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Assessment of geo-environmental hazards from non-traditional geotechnical construction materials

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1. INTRODUCTION

A tentative summary report offering some guidelines for using some non-traditional materials in situations where conventional materials would have been anticipated and studied geotechnically is presented, having in consideration their potential hazard to the environment.

Any attempt to promote secondary usage of residue is always welcomed, but, due to the potential geoenvironmental hazards associated with these products, comprehensive research has to be developed in order to supply the necessary garanties. Work has tried to concentrate on the uses of residue generated by some of mankind's numerous industrial activities, as we all know very well the tremendous burden our society already has in handling and disposing the amount of residue produced.

Due to the immenseness of the topic and to space limitations, the report herein presented does not try to cover all topics or residues known. Particularly, it has to be considered that, worldwide, there is not a homogeneity between the same type of residue as produced in equivalent industrial operations; variations of the original product/ore, as well as of the industrial/beneficiation process locally optimized to recover the end product, generate residue which may vary significantly, both chemically and physically, despite being identified inthe bibliograaphy by the same name.

It contains a significant amount of information taken from the experience of the authors in particular topics. The authors believe that further work has to be done in compiling important information in this immensely broad theme.

The report contains overviews of the characterization and evaluation of geotechnical and geohydrological problems related to the usage of following products:

- combustion residues,
- MSW and sludge ashes,
- paper industry sludge,
- phosphogypsum,
- used tires,

as well as it briefly addresses a major geotechnical problem related to the usage of mine tailings as construction materials for it's own disposal areas, as upstream tailings dams.

In this latter topic, it is our understanding that a special effort has been done not to conflict with the work being developed and published by ISSMFE TC7 - Waste Disposal.

Non-Traditional Construction Materials include all residue generated in industrial processes, energy production utilities, mining and beneficiation activities, being non-profitable end products which were routinely disposed. A major effort to reuse/recycle these materials helps the preservation of natural resources, and minimizes the need of disposal areas.

The potential environmental impacts of such uses cannot be forgotten, and the proper analysis of the potential geo-environmental hazards generated has to be included in the feasibility and design studies, using as reference the existing standards. It is believed that further development in standards for environmental assessment and quality assurance systems are required (Hartlén, et al 1996).

Particular uses of many different by-products are, at this time, being studied in different parts of the world. Knowledge is already available in many topics; it is worth noting that a broad international experience has been gathered in the use of distinct industrial residue in road construction as substitutes for natural aggregates.

Finally, it shall be noted that contributions being presented by SubCommittees SC 1, SC2, SC6 and SC8 are directlly related to this topic, and complement this work.

2. TESTING METHODOLOGY

The environmental evaluation of a secondary material considered for utilization should be based on the extent of contaminant release expected to occur during the lifetime of the product itself, or the facility in which it will be used. In the particular case of tailings dams, environmental harm can be caused by the release of impounded material and supernatant liquids if a failure of the structure occurs.

It's compatibility with the local aquifer has to be determined with relation to the components that may leach out. Consideration of the release rate of all contaminants present in the material has to be analyzed, including percolation and diffusion processes due to the natural permeants present in the soil profile.

Quality control standards and assurance programs are essential to maintain product quality and to avoid undesirable environmental impacts. Quality control testing for leaching characteristics, important physical parameters and durability shall be carried out at defined time intervals (Hartlen, et al 1996).

Many different countries in the world already have specific regulations on the utilization of distinct residue, which could be used as reference for new regulatory efforts (Bialucha, 1994).

Physical properties are routinely tested any time a material has its use planned for a certain future known behavior. These physical properties include the basic behaviors of permeability, compressibility and shear strength, under static and, eventually, dynamic conditions.

All routine standardized soil mechanics, road construction and structural testing are used. In the specific case of residue, care has to be taken as the material has been produced under certain specific conditions, which may suffer changes during the long term use it is bound to. For example many residue are produced under reducing conditions, and when exposed to air may oxidize, changing its properties. Hartlen, et al (1996) present Tables with the physical properties and test methods used in Germany to determine suitability of construction and demolition wastes for geotechnical applications, and with the ASTM, DIN or other methods specified for determining the properties of granular and solidified residue.

The main environmental impact from reuse of secondary materials is the potential of mobilization and leaching of hazardous substances into the subsoil or aquifer; all toxic elements inherent within their matrix have to be properly analýzed. Solubility controlled leaching test (batch or column test) are normally used for coarse grained materials, and tank leaching tests when diffusion controls the expected behavior. Other routine testing includes pH, specific conductance, the latter being a measure of total dissolved solids.

Regulatory tests are listed by Hartlen, et al (1996); the chemical composition of the leachant shall represent the real field worst conditions expected, including acidity due to acid rain conditions. Some particular secondary materials, as phosphogypsum, contain radiological characteristics which also have to be properly accessed previous to use (Lopez and Seals, 1992; Kumbhojkar, 1992).

Dredged materials, which are simply composites of geotechnical materials naturally occurring, sometimes contain contaminants from agricultural, urban, or industrial sources; special dredging and post-dredging handling and management techniques may be required to dispose and use these materials.

3. CHARACTERIZATION AND EVALUATION OF GEOTECHNICAL AND GEOHYDROLOGICAL PROBLEMS RELATED TO COMBUSTION RESIDUES

3.1 *Geotechnical Utilization*

a. *Material Description*

Sustainable development in terms of conservation of natural resources and minimization of environmental impacts often calls for the recycling or reuse of products. In construction technology, residues of various types can be used, potentially saving millions of tones of natural materials annually. The benefits of this conservation of nature is difficult to specify but it is obvious that it will mean a lot to future generations. Even if the utilization of various residues from industry means conservation of natural resources, it is often disputed due to the increased risk of pollution.

Ashes, slags and desulfurization products are the solid residues of combustion at power plants using solid fuels, such as coal, peat, and wooden chips.

Ashes

Ashes from the combustion of coal are a cohesionless material, prevalently consisting of vitreous particles. The grain size distribution ranges between that of silt and coarse sand. In its dry state, ash is prone to dusting and can hardly be compacted. Hence, to be able to handle it, wetting is necessary to combat the dusting. A certain amount of the water (to be specified in each case) should be mixed in by intense agitation producing an aggregate that is not prone to dust. If not hosting pozzolanic properties, e.g. introduced by lime additives, the aggregates can be destroyed by drying and moderate kneading.

Slags or bottom ashes from the bottom of the combustion units are cohesionless materials corresponding to coarse sand or gravel.

Flue gas desulfurization products

Several types of flue gas desulfurization products are generated depending on the type and state of the residue. Chemically, the differences in composition are merely a matter of oxidation state - sulfite/sulfate with different proportions of water bound to the crystals. However, the composition is also very much affected by whether there is a recollection of fly ash prior to the desulfurization or not. If not, the fly ash may dominate both the composition and the physical properties.

Energogypsum is a sulfate product generated from the desulfurization of flue gases by washing them with a limestone slurry. It is a cohesionless material, typically in the form of fine sand. At this wet desulfurization, the ash is usually precollected and can be used or disposed of independently. Energogypsum is useful as secondary raw material in the manufacturing of plaster, plaster-cardboard plates and admixture to cement. For geotechnical purposes, the product is mainly useful as a component for stabilization.

When using the semi-dry desulfurization method, only a portion of the fly ash is precollected. The fly ash that is not collected acts as condensation nuclei for the precipitation of calcium sulfite obtained in the course of desulfurization of the flue gases. The stepwise, spontaneous conversion of sulfite to sulfate has not yet been confirmed in practice. The grain size distribution of the product corresponds to silt to fine sand. For geotechnical purposes, it is suitable only as a stabilizing component.

Collection of dry FGD-products from fluid combustion uses all the fly ash as condensation nuclei, i.e. without any precollection. The result is a product with properties very much influenced by the fly ash. Hence, the grain size distribution is analogous to that of fly ash, silt-medium-sized sand. In contrast to the semi-dry desulfurization product, this product contains mainly sulfates. However, as much as 10% CaO may be present. When moistened, the product shows pozzolanic, or even hydraulic, properties. Therefore, the product is often suitable as a stabilizer in other products.

Stabilizates

For geotechnical purposes, ash may be stabilized in a similar way as soils by using additives and blending. Cement is the most common additive for stabilizing ashes. The amount of additive must be determined through tests taking into account the future geotechnical utilization. In the absence of slag components in the ash, 2 to 3% of additive is usually sufficient to obtain a hardening structure, but as much as 5-15% may be necessary for some ash types, especially if high strength and low permeabilities are foreseen as necessary.

Normally, a mixture of ash and energogypsum will not solidify, even after a good compaction. However, mixtures containing ashes from lime-rich coals may represent the exception. If no solidification takes place in course of time, additional admixtures of lime may be necessary for the stabilization, 2 to 5% of lime usually being enough. Even if water is consumed in the hydration, it is usually sufficient to determine the optimum moisture content by the Proctor compaction procedure. At moisture levels below the optimum for compaction, hydration will be limited and the solidification hampered. Moisture levels exceeding the optimum for compaction by more than 3%, may be sufficiently high to cause bad compaction and even the risk of liquefaction.

The typical ratio of ash and energogypsum is 3/2. However, for specific applications, the ratio of additives should be tested in order to get the feasible stabilizate strength and permeability. Like in soil stabilization, the strength increases with time, most hardening taking place during the first 28 days after compaction.

Some mixture of fly ashes with semi dry FGD's will solidify in time, even in the absence of additives. Introducing and additive may improve the characteristics, a typical additive being cement. However, as demonstrated by tests, lime may be an equal or even better additive. The charge of additive should be selected on the basis of tests taking into account the purpose of the stabilization. The typical ration of ash/FGD-product is 2:1 or 1:1. The optimum moisture content may be determined by the Proctor compaction test.

FGD-products from fluidized bed combustion, using carbonates as sorbents could be possible to use as stabilizers as they are. If having hydraulic properties, they will solidify when moistened, even without additives. A higher moisture content than the corresponding for optimum compaction, according to the Proctor curve, is normally necessary for sufficient hydration. The moistened product solidifies rather rapidly, making it necessary to be processed within 1-4 hours.

b. *Material Geotechnical Properties*

As demonstrated above, geotechnical utilization will comprise ash fractions, mixtures of ash fractions and various stabilizers. Basic information on geotechnical properties are collected in table 1 and the corresponding utilization potential in table 2.

TABLE 1. Important geotechnical and environmental properties and their relation to basic waste types after compaction.

Properties	Coarse grained	Fine grained	Sludge	Hardening products
Geotechnical parameters				
Permeability	High	Medium	Medium-low	Low
Compressibility	Low	Medium	Very high	Very low
Strength/ bearing capacity	High	Medium	Very high	Very high
Environmental parameters				
Relative source strength	Medium	High	High	High
Leachability	Medium	High	High	High
Contamination transport	Medium	Medium-high	Medium-high	Low

TABLE 2. Utilization potential of basic waste types (and disposal).

Utilization	Coarse grained	Fine grained	Sludge	Hardening products
Road embankments	Yes	Yes, conditionally	No	Yes
Structural fills	Yes	Yes, conditionally	No	Yes
Sealing layers	No	Yes,	Yes,	Yes
		conditionally	conditionally	
Drainage	Yes	No	No	No
Disposal	Should be avoided	Yes, conditionally	Yes, conditionally	Should be avoided

3.2 *Environmental and Health Hazards*

a. *Potential Impact Situations*

In view of the environmental concern, the most important risk situation with combustion residues is the transport of certain trace elements with the leachate, especially arsenic, cadmium, copper, chromium, lead, mercury, selenium and zinc. In some cases even radioactive elements could be involved, not only associated with the leachate but also with gaseous emanations, e.g., radon. The leaching rate is normally very slow resulting in a continuous leaching for hundreds or thousands of years. As a matter of fact, only a small fraction of the total content - 1-10% - of most of the trace elements may ever be leached out.

The most obvious leaching is that of salts like sulfates and chlorides. Compared to the trace elements they are often quite readily washed out. In a perspective of 100 years or so, they could be reduced to some few per cent in the fill.

Salts and elements are mobilized by water percolating through the deposit or fill. The leaching process is very much governed by the pH of the leachate. Since the solubility of many of the elements mentioned is high both in the low and the high pH-range, stable conditions close to the neutral will generally inhibit leaching.

b. *General evaluations*

Slags and bottom ashes

In most cases slags and other products discharged from the bottom of the combustion units, including spent bed materials at fluid bed combustion, are relatively harmless since very little of the volatile elements are collected in these products. However, they are generally very pervious and could easily be leached out. Therefore, the products should be subjected to studies on their leaching properties and to monitoring in the field. In general, the transport rate of harmful elements, such as copper, reaches the level of kg/year only at big deposits, i.e. in the order of 100,000m^3 or more.

Fly ashes

Flue gas solids, collected by electrostatic precipitators or bag filters, contain a lot of condensed elements on their surfaces. A minor fraction of these elements are possible to extract by ordinary leaching with water, even if pH often reaches high levels. Normally, the content of trace elements such as copper and cadmium exceeds the natural background levels by a factor of 10. The leachate concentrations, however, may exceed the corresponding natural levels by factors of 100-1000. Even so, the total leachability is normally less than some few per cent of the total content of the element in question.

The permeability of most fly ashes are close to the limit when the leachate production rate of an ash fill will be governed by the properties of the ash rather than by the rain precipitation rate. Since the precipitation rate is very much dependent on the climatic conditions, it is impossible to make general statements but in humid, temperate climates the leachate production will be in the order 100-200 mm/year. In drier climates, the production will be lower but more seldom below 25 mm/year. In wetter climates, it will probably not exceed 500 mm/year in most cases.

Even if the permeability is lower in fly ash than in bottom ash and slag, the total leaching rate of salts and trace elements will be higher from fills of fly ash than from fills of slag. It soon reaches the level of kg/year for trace elements and tones/year for sulfate, but seldom tones/year for trace elements. The neutralizing capacity of fly ashes from combustion of coal, peat and wood can high enough to maintain high pH-values (pH 9-12) for long periods of time.

Desulfurization products

Both wet and dry methods are used when collecting sulfur dioxide from flue gases using different kinds of sorbents. The wet method uses a slurry or a liquid of the sorbent and the dry method a pulverized solid product, commonly lime or limestone. In the latter case the residue, the flue gas desulphurization product or FGD product is always dry but in the former case it could be both dry and wet, i.e. in the form of pulver or a sludge. In most cases, the end-product contains unused lime or limestone plus sulfates or sulfites. If the fly ash is not fully collected in a prefilter, the FGD will also contain some fly ash, up to 80%.

The leaching characteristics of a desulfurization product is similar to those of a fly ash. The alkalinity is high, concentrations of sulfate and some trace elements are relatively high, and the leaching rate will remain relatively constant for many years. Also the permeability is about the same as in fly ash. Hence, the total transport from fills with desulfurization products are about the same as for fly ash fills.

Stabizates

By using the pozzolanic properties of some fly ashes, fluidized bed combustion residues and some desulfurization products, it is possible to achieve a gain in strength of the products. Sometimes Portland cement has to be used in relatively small quantities. This hardening, like in concrete, influences the leaching properties of the waste. In most cases it reduces the hydraulic conductivity thereby reducing the leaching rate by one or several orders of magnitude. This process is known as solidification or physical stabilization. Sometimes it may also reduce also the leachability of certain elements in the product, i.e. chemical stabilization.

Stabilization can be used also for other waste types. If the combustion waste has pozzolanic properties and can be used as a stabilizing agent when mixed with other wastes, it could be a positive way of utilizing the product.

3.3 *Recommendations for Geotechnical Applications*

a. *Needs of Precaution Measures*

Using combustion residues in structural fills etc. will always constitute a risk to the environment. In most cases the risk is very small but the risks should always be assessed and minimized. Environmental impact assessments with the object to identify and possibly the risks could encompass:

- a laboratory test of the leaching properties of the waste,
- calculations of the discharge of salts and harmful trace elements to the environment including the water balance of the structural fill,
- calculations of the total loads of harmful substance to the sensitive habitats of the surrounding environment including all artificial sources and the natural background.

For slags, bottom ashes and FBC-residues, the impact assessment could be conducted on a general basis, i.e. on a national or regional basis covering the conditions for the most sensitive areas or regions. This assessment could form a basis for a general permit and for specification of the conditions for the general permit, e.g. the precaution measures and the monitoring programs to be applied.

General impact assessment studies could also be conducted in order to specify what combustion wastes should be excluded from permissions to be used as structural fills etc., e.g. certain condensate residues.

For ashes and FGD-products, impact assessment studies should be carried out on an individual basis, for a specified producer or a specified utilization object. In the former case it is essential to cover all utilization categories, e.g. those 4 described above. The permit or the conditional permit could be restricted to a certain utilization category.

For stabilizates, impact assessments should be performed on an individual utilization case basis. The conditions for a possible permit could be related both to the wastes, the stabilizing agents and the utilization object.

b. *Regulatory Aspects*

In most countries regulations are based on a normative legislation meaning that all separate discharges of harmful substances must not exceed certain concentration limits are set with due concern to all natural and human activities resulting in discharges of the substances, and to the general sensitivity of the environment. Since the sensitivity can vary within broad limits and many different activities can be involved, the limits can not be generous if following the precaution principle. If not accompanied by special restrictions on certain areas, the normative approach will lead to a common rise of concentration levels and to the leveling out of those levels.

The alternative to a normative principle is a relative principle, meaning that concentration levels could be raised as a percentage of either the natural or the existing background level. This may lead to the concentration of human activities to certain areas or regions where a given additional discharge causes a small relative discharge, leaving virgin land untouched. The risks with such an approach is evident. Therefore it is common that the permission to discharge of harmful substances is also regulated according to the sensitivity and the total load of all the discharges of the area, an additional principle that could also be applied with the normative approach.

With relation to the residues from combustion, it is essential that all aspects are covered in the environmental assessment even if they are very difficult to compare. The impacts of the alternatives (e.g. disposal as a landfilling and the loss of natural reserves when using natural materials, etc.) and the impacts of different transport works are probably the most difficult to treat.

3.4 *Examples on Successful Utilization of Coal Fly Ash*

a. *Stabilization of Open Pit Backfilled Clayey Coal Spoils*

In Tertiary, brown coal basins, claystones are the frequently occurring as overburden to the coal seams. When mining the coal in open pits, they are deposited in piles as spoils, the thickness of which only occasionally exceeds 100 m.

In a freshly tipped spoil layer, the fragments of strongly overconsolidated, weakly lithified claystone are prevalent. The average size of the fragments is typically 100-150 mm and the maximum size does not normally exceed 500 mm. The amount of fragments smaller than 10 mm is typically below 20%. In this condition, the spoil has the nature of gravel and is considerably permeable.

The percolating precipitation causes a slaking of the fragments resulting in softening of their surfaces and due to the weight of the overburden, the porosity decreases. The depth at which this occurs depends on the lithification degree of the fragments and on the time elapsed from the spoil tipping. Normally the depth is 10-15 m below surface, in exceptional cases even deeper. An exception is given by lenticular inclusions of strongly lithified claystone, conserving the void spaces even at considerable depths. However, they are not continuos and thus, they do not significantly affect the permeability.

Thus, building up the spoil pile, provides for a change in material structure of the pile resulting in a clayey soil overlain by a gravely soil. Under these conditions pore pressure could be built up in the heap. However, mixing fly ash into the fresh spoil material will fill the pores between the claystone fragments and thus facilitate the pore pressure dissipation.

Figure 1 shows the results of triaxial tests carried out as strain rate corresponding to that of a granular soil. It is obvious that the shear strength envelope of the claystone spoils without as additives is curved by the action of the induced pore pressure. The angle of internal friction at a low angle of internal friction of a gravely soil, at high stress values it corresponds to a non-drained test of a fully saturated clay. The effective angle of the shear strength of remolded clay made of claystone materials about 15° . It is obvious that admixtures of ash of up to 25-20% into the spoil material, even in the case of rapid loading (the spoil is tipped rather rapidly), will provide a sufficient pore pressure dissipation.

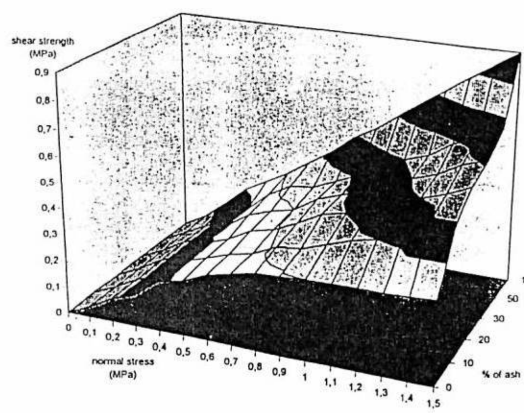

FIGURE 1. Results of triaxial tests carried out on stabilized lignite spoils

Clayey tipped spoil in 10-15 m thick surface layers are usually considerably compressive, the deformability modulus typically ranging between 2 and 10 MPa. The ash additive will usually not improve the strain characteristics of the claystone spoils. The permeability of the surface layer is in the order of $1*10^{-10}$ to $1*10^{-7}$ m/s and it is only slightly altered by adding ash. In the absence of ash additives, the permeability of deeper layers of the tipped spoil is typically lower than $1*10^{-9}$ m/s.

b. *Sealing Layers for Dry Covers on Waste Landfills*

The objective of a dry cover on a waste landfill is to protect the environment from hazardous emissions such as dusting and liquid leachates. This mission has to be fulfilled for centuries to come. Therefore special efforts must be made to protect the cover (and the waste deposit) from erosion, frost, drying out, root penetration and human penetration etc. This is normally accomplished by using a thick protective layer above the barrier which has the function to cut off the water percolation and occasionally also the gas transports. Usually the barrier itself is referred to as the sealing layer.

In order to significantly reduce the percolation of atmospheric precipitation, the permeability of a cover on a waste deposit has to be less than $1*10^{-9}$ m/s in most climatic conditions. It could be more pervious if a drainage layer is introduced reducing the hydraulic gradient over the sealing layer and the time during which water percolates through this layer.

Cement-stabilized fly ash/dry FGD, in Sweden known under the trade name Cefyll, has been successfully used as a sealing layer on a sulfidic waste rock pile. The Cefyll is made by mixing fly ash/dry FGD product with 8-13% cement. The high cement percentage was used when a less reactive product was produced at the power plant and the low value when the product properties were normal. It was grouted into a 0.25 m thick bed of crushed rock aggregates (50-70 mm). Due to this aggregate bed, all shrinkage cracks formed during the hardening process (lasting for months) were confined to the pores of the aggregate and did not propagate all through the layer. The Cefyll layer was covered by 2 m of glacial till as a protective layer. The covering was completed in 1989.

The water and oxygen transport through the cover has been monitored almost continuously since 1989. The small scale permeability was found to be in the order of $1*10^{-9}$ m/s which actually equals or even exceeds that of the full scale permeability as found by measuring the discharge from the controlled single outlet of the deposit. In fact, the percolation has been much lower than expected. In another waste rock heap, adjacent to this one, compacted clay was used as a sealing layer. On this heap, the full scale permeability was found to be 3-5 times larger than the small scale permeability.

The reason for the low, full scale permeability of the Cefyll layer is believed to be the capillary barrier effect that is automatically achieved by having the capillary Cefyll layer constructed on a coarse waste (capillary breaking) on a relatively high slope (15 m) providing for high suction forces in the upper part of the heap. The negative pore pressures result in a partly unsaturated Cefyll layer with a hydraulic conductivity lower than the saturated conductivity, c.f. figure 2. this effect is confirmed by the substantially higher oxygen transportation rates found in the Cefyll layer relative to the clay layer.

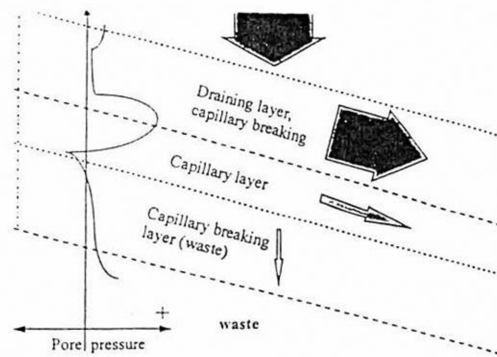

FIGURE 2. The dry cover applied on the waste rock and the basic principle behind the capillary barrier.

4 CHARACTERIZATION AND EVALUATION OF GEOTECHNICAL AND GEOHYDROLOGICAL PROBLEMS RELATED TO THE UTILIZATION OF MSW AND SLUDGE ASHES

4.1 *Utilization of Municipal Solid Waste Ashes as Construction Material*

Technological development and the extraordinary rhythm of increase in world population in the last hundred years, from 1 billion inhabitants at the end of last century to the present 6 billion, are responsible for a remarkable growth of waste production. The domestic waste production per capita nowadays in the United States exceeds 1.6 kg/day; there is no direct relationship between technological-economic development and the amount of produced waste, the most relevant difference lying in waste composition.

Furthermore, the number of inhabitants of urban centers per hundred world inhabitants has reached from 5 in 1800, to 40 at present time; the intensification of the urbanization rate is even more remarkable in underdeveloped and developing countries; for example 75 out of 100 Brazilians live in cities (IPT, 1995). Therefore, larger amounts of waste are being produced in increasingly concentrated urban spaces; land disposal of municipal wastes involves larger and more distant areas as cities grow.

New trends for solid waste management aim at the decrease of disposal quantities by means of reduced production and recycling. Incineration is a thermal technique of waste treatment with a view to recycling, which results in the modification of toxicity characteristics and the reduction of volume to be disposed of.

The basic process consists in burning materials for a given time at high temperatures, over 900^0C, mixed with an adequate amount of air (IPT, 1995). The wastes to be incinerated can be fluid, solid, or semi-solid (sludge). The combustion reduces organic compounds to their mineral constituents, mainly gaseous carbon dioxide, water vapor and inorganic solids, i.e. ashes. Water vapor can be recovered for energy production. Ashes are collected at the bottom of the incinerator - slag or bottom ashes - or in the gas filters for the gases generated by combustion - fly ashes, lighter than the bottom ashes; normally, the bottom ashes represent 75 to 90% of all produced ashes.

The advantages of incineration are: drastic reduction of volume to be discarded, and therefore, of the necessary space for landfilling; reduction of hazardousness and environmental impact by detoxification, that is, destruction of bacteria, viruses and organic compounds; and possibility of energy recovery, since part of the consumed energy can be recovered for vapor or electricity generation. The drawbacks are high costs, need of qualified manpower, operational problems and emissions of dioxine and furan types.

Ashes consist basically of mineral matter, unburned carbon and metals, including heavy metals, among which the most frequent are lead and cadmium, originated mainly from batteries, electronic equipment and some plastics. Fly ashes have higher metal content than bottom ashes. By the final disposal in landfills, the possibility of groundwater contamination by soluble metals present in the ashes leachate should be accounted for. According to US Classification System ashes can be classified as well graded mixtures of silty sand and gravels with traces of organic matter, the average water content being around 50%. Ashes are considered cohesionless, but exhibit apparent cohesion when wet; high CBR values and some swelling in the presence of water have also been reported (Maher et al, 1992).

The first incineration unity started to work in 1874 in England. In Australia only 1% of domestic waste is incinerated; in the USA and Neatherlands this percentage lies around 15%; in Japan and in Italy it reaches 80% (Samarin, 1993). In 1898 the first waste-to-energy incinerator started to operate in New York City (Maher et al 1992). In Brazil, the first domestic waste incinerator was installed in Manaus in 1896 (IPT, 1995).

According to Maher et al (1992), experience accumulated progress for almost one century in the United States and researches in progress since the end of the 70's have shown that solid municipal waste incineration is economically interesting because of energy recovery and technically superior to other methods of hazardous waste treatment. The authors mention that in 1985 in the United States there were already 60 incinerators for energy production in operation, 18 in construction and 31 in advanced stage of planning; and that in the year 2000, 16 to 25% of all the country's municipal waste is expected to be incinerated.

Important questions about incineration of MSW are how to use the ashes and how to recover energy more efficiently and economically. Researches indicate the utilization of the ashes as aggregate for Portland or bituminous concrete in several applications in civil construction, or as aggregate for soil improvement and road construction; to a lesser extent, the employment as additive in soil stabilization has also been studied.

Ashes properties depend strongly on waste composition, but heavy metals contents are more related to chemical mechanisms that occur at combustion and to the presence of certain non metallic compounds in the original waste.

As ashes present some limitations as engineering material, the more significant of which are high water and organic matter contents, they must be mixed to other materials such as natural aggregates or soils. These technical inadequacies are more pronounced in fly ashes than in bottom ashes, which present lower fines content, lower water absorption, lower expandability and fewer adverse reactions with Portland cement. Lime must be added to fly ashes to control the fines.

Maher et al (1992) investigated the engineering properties of a mixture of ashes with Portland cement and sand at varied proportions in order to assess the possibility of recycling the 375 tons of ashes produced per day in two municipal waste incinerators in the State of New Jersey. Unconfined compressive and tensile strengths of the mixtures were determined in function of curing time. A meaningful reduction of resistance and rigidity with increase of ash content was observed.

The authors list several satisfactory in situ applications such as the construction of an experimental reef in the Long Island Sound with large blocks made of 15% Portland cement and 85% ashes by weight; the resistance of the submerged blocks increased with time (compressive strength was 1372 psi after 358 days of exposition to salt water, which means as increase of 397 psi relative to resistance before submersion). Twelve projects in the Chicago area used lime and ashes in the construction, respectively, in bituminous concrete and in a mixture with lime and asphalt.

The authors also mention experiments carried out in other countries: 80% of the bottom ashes resulting from municipal waste incineration in Paris is utilized in landfill and road construction. In Koeln, Germany, 80% of the parking lots and roadways built since 1974 have used municipal waste ashes as granular material in pavement base. Ashes are also used as additive for soil stabilization in Europe; in Japan MSW ashes are used as additive for clinker in cement manufacturing.

The crucial question which arises when considering reusing MSW ashes for civil engineering practice is the release of toxic substances in the air and groundwater. The solubilization of heavy metals can be intensified by salts and acids present in the ashes. Proper design should assure encapsulation and stabilization of metals and post-construction monitoring of leachate.

Estimates of MSW energy content have been researched in order to evaluate energy-generating alternatives. Energy content of a material is the amount of heat released during its incineration; it can be determined by equations or experimentally by calorimetry. Materials with high energy content need less fuel to be fired.

Usually 70 to 90% of MSW consists of five elements: paper, glass, food, plastic and metal. To calculate MSW energy content by the modified Dulong Equation, which is the most used procedure, percentages of carbon, hydrogen, oxygen and sulfur. Ali Khan & Abu-Ghararah (1991) propose a new equation based on percentages of food, plastic, paper and rubber. The authors used information about domestic waste from 86 cities in 35 countries to compare energy content values obtained by both equations. Estimates were similar (the proposed equation results in values 1 to 10% higher); furthermore, the proposed equation is easier and faster to use.

The authors also conclude that paper and plastic contribute with 50 to 70% of the total MSW energy content. Domestic wastes from underdeveloped or developing countries such as India, Pakistan, Bangladesh, Sudan and Taiwan present lower energy content (2800 to 3700 KJ/kg), from one third to half than from developed and highly industrialized countries such as United States, Finland, Denmark, Norway, Belgium, Austria, and Sweden (7000 to 11600 KJ/kg)).

Apparently it may deduced from the above that, whereas underdeveloped and developing countries hardly ever properly dispose of domestic waste in manner to protect the environment, larger amounts of superfluous waste and dilapidation of natural resources, both expressed by high percentages of paper and plastic, are characteristics of developed countries.

4.2 *Utilization of Sewage Sludge Ashes as Construction Material*

Disposal of sludge from wastewater treatment plants is increasingly troublesome in highly populated cities, due to the scarcity of proper sites and the intensified concern about the environmental hazards. Incineration can be a feasible alternative, since it results in a reduced volume of inorganic, odorless and inert ashes about 10% of the original bulk of sludge (Tay and Show; 1991; Tay et al, 1991). The amount of ashes to be disposed of is considerable though, which has enhanced the interest in researching recycling applications. A promising possibility is the utilization of sewage sludge ashes as fine aggregate in concrete for general practice in civil engineering such as construction of roads and building and shore protection.

In Long Island, for instance, 250,000 tons of sewage sludge ashes are generated per year, the high volume, the limited space available for landfilling and the restrictive environmental standards had already led to attempts to employ Long Island ashes in the protection of concrete blocks for shore protection works. Khanvilbardi and Afsahri (1995) studied the physical characteristics of Long Island ashes in order to evaluate both the technical feasibility of using them as fine aggregate for Portland concrete and the consequent environmental impact. The ashes were obtained from a wastewater treatment plant that generates an average of 10 m^3 of ash per day.

According to organic-impurity tests those ashes proved to be inorganic. Extraction procedure toxicity and leaching tests indicate that the material is nonhazardous since sulfate and chloride contents fall well bellow EPA limit values. This material according to USCS would be classified as sandy silt; with grains 100% finer than a #4 sieve and 38% finer than a #200 sieve; this particle distribution does not fulfill ASTM requirements for fine aggregates used in concrete, therefore sand-ash mixtures with a maximum of 30% ash content by weight were investigated thenceforth.

The average 28 day compressive strength, 28,5 N/mm^2 for concrete without ashes, decreased in 15% for ash content of 10%, and further 7% for ash content increasing from 10 to 30%; the strength values of all mixes were superior to 20 N/mm^2: in spite of the fact that concrete compressive strength decreases as ash content increases, design resistance (20 N/mm^2) is achieved for ash contents below 30%. Concrete mixes with 30% ashes presented tensile, bond and flexural strength values equal to 74%, 78% and 85% of those obtained for concrete without ashes, respectively, 3,2 N/mm^2, 7,2 N/mm^2, and 4,4 N/m^2. The skid resistance shows an improvement with ash addition. The authors also observe that, despite the ashes absorbing water, unlike plastic soils, they do not show undesirable volumetric changes.

Differential scanning calorimetry tests were carried out to study the role of sludge ash in the microstructure of concrete and its potential impact on durability. Results seem to show that part of the entrapped water in the ash skeleton (originated by the relatively high water content of ash prior to mixing) which neither came into contact with cement nor reached directly with it, will affect adversely concrete resistance and durability.

Artificial lightweight aggregates have been made of sewage sludge, such as dewatered sludge fired in brick kilns at 1050^{0}C, dewatered sludge-clay mixtures fired between 1070^{0}C and 1095^{0}C, or sludge ash pelletized and fired between 1060^{0}C and 1110^{0}C.

Tay et al (1991) investigated the utilization of incinerated dewatered sludge-clay mixtures for the production of coarse lightweight aggregate for concrete. Digested and dewatered municipal wastewater sludge from Cingapura, with solids content ranging from 25 to 35%, was blended with red clay constituted mainly of halloysite. Mixtures with dry clay/sludge ratio by weight of 10%, 20%, 30% and 40% were fired in a brick kiln at 1050-1080^{0}C for about 40 hours. The ashes thus produced were crushed and graded according to typical aggregate sizes.

The material is an angular aggregate with open surface pores. The specific gravity is a little higher than that of normal dense aggregates, and decreases from 2,82 gf/cm^3 to 2,77 gf/cm^3 as clay content increases from 10 to 40%. The bulk density increases from 622 kg/m^3 to 660 kg/m^3 as the clay composition in the same range, thereby complying with ASTM limit for lightweight coarse aggregates. The water absorption is low, slightly greater than 6% for all investigated clay contents, when compared to the usual values of 5 to 25% for light aggregates. The pH values indicates the desirable characteristics of alkalinity. The chemical compositions consist basically of potassium, iron, calcium and aluminum. Clay content must exceed 20% to assure that sulfate and chloride contents are within acceptable limits.

The concrete properties of workability, compacting factor, air-dry density, shrinkage, water absorption and compressive strength were determined for five concrete mixtures made of Portland cement. natural sand as fine aggregate and incinerated sludge-clay mixtures as coarse aggregate, at different aggregate fine-coarse ratios and percentages of clay in the coarse aggregate. At the optimum fine-coarse aggregate ratio of 1:1.5, the 28th day unconfined compressive strength varied from 23.9 N/mm^2 for 10% clay content to 31 N/mm^2 for clay content of 40%. The minimum value recommended by ASTM is 15 N/mm^2.

The high aggregate porosity indicates potential characteristics of fire resistance and thermal isolation, though eventual loss of mechanical resistance. The authors conclude that the incinerated mixture of sludge and clay is a potential material for the production of light concrete aggregate; the maintenance of long term properties should be verified.

A successful former experience has been reported in Brazil. Souza et al (1978) researched production of lightweight aggregate from sewage by sintering sludge pellets with subsequent fragmentation and classification according to ASTM standards. The digested sludge of a sewage treatment plant was dewatered and air-dried, mixed to recirculation powder and disintegrated. The mixture was then pelletized, dried and sinterized. The sinter was fragmented by a rotor, crushed to diameters below 25.4 mm, stabilized and classified by a system of sieves. Tests were carried out relative to aggregate characteristics (grading curve, unit weight, organic matter, clay lumps) to paste at normal consistency (water content and compressive strength) and to hydraulic concrete. Results point out to a satisfactory performance of the aggregate in hydraulic concrete: the authors also carried out studies which showed that the proposed use of digested sludge is economically more advantageous than mere disposal in landfills or incineration by conventional methods.

Brick making is another possible application of sludge ashes. Trauner (1993), with a view to recycling the 32 dry metric tones of ash daily originated from municipal sludge incineration in the city of Indianapolis, researched the physical characteristics of bricks produced at four clay-ashes ratios and fired at temperatures below and above the vitrification temperature of the ash. Other alternative aggregates, such as coal fly ash, blast furnace slag and mining tailings, have been employed in the making of bricks; the use of sewage waste in brick making started in 1889, in Manchester, England.

Trauner investigated weight loss and shrinkage by oven-drying and by firing, density before and after firing, unconfined compressive strength, water absorption, freezing-and-thawing resistance and leachability. The ash-vitrification temperature was between 1060^0C and 1120^cC. Bricks with ash content of 0, 10, 20, and 30% were tested; for each ash content 4 bricks were fired at 1040^0C, and four at 1120^0C.

It was observed that the higher the ash content, the higher the weight loss and the lower the shrinkage by oven-drying: the water retained in the ashes is not available to produce a workable mixture with the clay, but it evaporates. In full-scale production, this would mean an additional energy demand to evaporate the extra water contained in ash bricks. On the other hand, the higher the ash content, the lower the loss of weight and the higher the shrinkage by firing: volatile compounds were removed from the ashes during the sludge incineration, at 870^0C; only the clay contributes with volatile compounds during firing of bricks.

Firing temperature showed no remarkable effect on eight loss. However, shrinkage for bricks fired to 1120^0C was greater than for those fired to 1040^0C: salts in the ash probably lower the melting temperature of the clay-ash mixture, increasing consolidation with increasing ash content.

Finally, greater ash content resulted in a slight increase in total weight loss, practically regardless of temperature. No clear relationship was observed between total shrinkage and ash content. Density of bricks previously to firing and final density of bricks fired at 1040^0C decreased with increasing ash content: final density of bricks fired to 1120^0C presented the same behavior, but not as clearly. The unconfined compressive strength decreased with increasing ash content, more noticeable at firing temperature to 1040^0C. Water absorption and freeze-and-thaw weight loss increased in function of ash content for firing to 1040^0C and decreased for 1120^0C.

Metal leaching tests were carried out; as there are no industry standards for bricks regarding leaching of metals, the author compared metal contents of extracts for ash bricks to those of bricks without ashes fired at the same temperature; no general trend could be defined based on the results.

The work indicates that addition of ashes to bricks fired beyond ash-vitrification temperature apparently provides unexpected resistance to weathering without environmental drawbacks. The author remarks that the utilization of sewage sludge ashes in bricks should be regarded as an opportunity for cost reduction. Brick making costs are relatively low when compared to other clay applications, such as paper and porcelain, the benefits of raw-materials replacement are not significant as in the case of coal fly ash. The meaningful advantage lies in the reduction of municipal economic and political problems associated to sewage sludge disposal. in 1992 a brick plant successfully produced full-scale ash bricks with 8% by weight of municipal sludge ash from a major city in the southern United States, which showed to be technically feasible and economically attractive both to the plant and to the municipality.

Other known possibilities in utilization of sewage sludge ashes in brick production are sludge clay (40% in weight of dry sludge). sludge ash with clay 50% in weight in ashes), pulverized ash mixed with cement. The products present low thermal conductivity and high fire resistance.

Sludge ashes can also be reused as filling material. Hartlén (1994) studied the utilization of bottom ashes in road construction and the associated environmental impact, with a view to recycling the 250.000 to 400.000 tons annually produced in Sweden. According to the author, 70% of this material, after screening and magnetic separation, can be considered as a possible substitute for gravel. A test road was built in 1988, 500 m long and 9 m wide, divided in 6 sections of 80 m; it was an internal circurlation way at the incineration plant, used by about 300 heavy trucks pre day. The ashes were applied underneath the bituminous layer and in the embankment slopes. To assess the environmental impact, leachate was collected from different embankment sections. The properties of bottom ashes change with time due to drainage, carbon dioxide uptake, hydrogen production and iron oxidation; the product gets more stable and less expansive; there ashes before, fresh ashes, one-month aged ashes were investigated. The bearing capacity was determined by falling weight deflectometer tests. Results were promising: the difference between the reference and the best sections with ashes is within the error of the measurement. Compaction in the field caused a minor crushing of particles; the content of fines was just slightly increased, thus not compromising the draining characteristic of the material.

A filling work was performed under a bridge abutment. Pressiometer tests indicated stiffness comparable to that obtained in compacted sand fills, which led the author to believe that probably chemical reactions resulted in hardening. Laboratory diffusion tests were carried out to assess environmental impact; it was observed that contents of salts and metals in the leachate decrease rapidly with time; and that the leachate specimens collected in the field showed lower pH value than those obtained from laboratory tests.

The authors concludes that sorted bottom ashes can be utilized as a natural aggregate. and after compaction result in an embankment with good bearing capacity. The associated environmental impact is limited. The main recommendations are that ashes must age at least 2 to 4 months use. the magnetic material must be separated. ashes should not be used near groundwater catchment areas; and that the road must be covered with impervious asphalt to reduce leachate formation.

Since the utilization of wastes is very promising in road construction, in coastal protection and in restoration of degraded areas, Company Cementa from Sweden developed the Cefill concept of stabilization, based on the mixture of a waste product with an adequate cement and some additives. The desired properties are low permeability and low leachability, besides good physical characteristics. Several wastes have been tested in the Cefill concept: fly ashes from coal combustion, waste incineration ashes, oil ashes and industrial dust. So far two stationary factories and two mobile stations have been established in Sweden manufacturing Cefill from coal fly ashes. Carlsson and Marcusson (1989) list documented uses of Cefill.

Tay and Show (1991) studied the feasibility of using dewatered sludge mixed with lime and incinerated to produce a cementlike material. Dewatered wastewater sludge collected from a sewage treatment plant was oven-dried at 105^{0}C to achieve a solids content of at least 95%, crushed and fixed with varied lime percentages. The mixtures were pulverized to 250-350 μ by an ultra-centrifugal mill and incinerated in laboratory under several conditions: the resulting ashes were pulverized to a maximum diameter of 80 μ. Physical, chemical and mechanical characteristics of the resulting cement were determined according to ASTM specifications.

Sludge-lime mixtures with ratios 1:3, 1:1 and 3:1 by weight were fired for half an hour at 1000^{0}C, 1100^{0}C and 1200^{0}C. The effects of firing duration ranging from half an hour to six hours on the compressive strength were also investigated. Sludge cement and Portland cement are constituted by four major oxides: silica (SiO), alumina (AlO), lime (CaO) and iron oxide (FeO), which combined represent, respectively, 80 and 90% of the total weight. The main difference between sludge cement and Portland cement are the relative percentages of these oxides: Portland cement has a higher percentage of lime and lower alumina and iron oxide. The chemical composition of sludge cement is within the limiting values, except for CaO and SO contents. Cement made of sludge has little pozzolanic activity, higher water requirement and quick setting. The authors understand that sludge cement, with a sludge-lime proportion of 1:1, fired at 1000^0C for four hours, can be used in civil construction for general masonry works.

Wise et al (1994) argues that sludge composting and incineration, both followed by land disposal, are currently the only two feasible sludge disposal methods given the present technical and political conditions; they feel that composting is a better solution because of lower capital costs and relatively small carbon dioxide release as compared to incineration, and production of a potentially useful by-product. The authors investigated the suitability of soil-compost mixtures as a landfill cover material.

Sludge incineration can be regarded as part of the process of sludge treatment. The complete process comprehends mechanical pre-treatment, anaerobic stabilization, direct or indirect drying, incineration with energy recovery, treatment of waste gases and, finally, releasing of ashes and treated waste gases; if possible, there should be recycling of the ashes. One of the largest and most modern incineration units in Europe, built in Berlin (Uhde GmbH, 1994) for the incineration of sludge from the waste treatment plant, is the milestone in solid and semi-solid waste management.

Research and applications of sludge ashes as construction material should be encouraged and intensified, without losing sight, however, of effects on the environment. In spite of the fact that most applications involve combination with cement, which presumably encapsulates the ashes preventing solubilization of toxic components, particularly heavy metals, there is nowadays technical and scientific tools to provide more through analyses and more solidly grounded courses of action

5 CHARACTERIZATION AND EVALUATION OF GEOTECHNICAL AND GEOHYDROLOGICAL PROBLEMS RELATED TO THE UTILIZATION OF PAPER INDUSTRY SLUDGES

5.1 *Introduction*

The pulp and paper industry generates large quantities of sludge from wastewater treatment. The sludge is typically landfilled, at considerable cost. A number of beneficial reuses of paper sludge have been considered, including as a soil material. Paper sludge has been used in the United States as a soil material for construction of landfill caps and for daily cover in active landfills, and in mine reclamation projects as it can be compacted to low permeabilities and can substitute clays in landfill covers.

Paper sludge ashes have studied in Japan as raw material for blocks and soil stabilizing agents, and as artificial soil for planting slopes (Nagasaka, et al 1996). Leaching test results reported acceptance to environmental quality standards, except pH which varied between 8 - 12.

a. *Sludge characteristics*

Paper mill sludges typically consist of organic and inorganic solids, plus water. Typical solids contents range from 20 to 45 percent after dewatering (NCASI, 1989);being equivalent to water contents ranging between about 120 and 400 percent.

Primary sludges resulting from sedimentation of untreated wastewater generally contain wood fibers as the principal organic component. The inorganic component, also referred to as ash, can consist of kaolinite, calcium carbonate, titanium oxide and other materials used in pulp and paper production (NCASI, 1989). Clay is usually the principal component of the ash. Solids from secondary sludges resulting from sedimentation of biologically treated wastewater are typically microbial biomass. The term "combined sludge" refers to a mixture of primary and secondary sludge. Because the sludge comprises primarily wood fibers and clay it has also been called "fiber clay".

The organic content of paper mill sludges range from about 30 percent to more than 90 percent (NCASI, 1989). Sludges with high ash contents and low organic contents are usually associated with the production of fine papers and with the production of de-inked pulp from recycled paper.

The physical behavior of paper mill sludges is similar to peats and highly organic silts and clays. Paper mill sludges are highly compressible, and water content is a useful indicator of compressibility. For preliminary evaluation of paper sludge materials, correlation developed for pears can be used to estimate compression index (MacFarlane, 1969):

$$C_c = 0.01w$$

where C_c = compression index,
w = water content, expressed as a percentage

Moo-Young and Zimmie (1996) present a relationship between the compression index and the organic content:

$$C_c = 0.027\ O_r$$

where O_r is the organic content determined at 440^{0}C.

Large, continuos secondary compression should be anticipated for paper sludges, similar to peats.

The hydraulic conductivity of paper sludge is a function of the sludge's organic content, degree of consolidation, and decomposition. The hydraulic conductivity of paper sludge and peat decreases as the ash content of the material increases and the organic content decreases. For preliminary evaluation of paper sludge materials, the following relationship can be used to estimate hydraulic conductivity at low confining pressures of about 34 kPa;

$$k = 10^{(0.022\ Or\ -\ 8.03)}$$

where k = hydraulic conductivity, cm/s,
0_r = organic content, expressed as a percentage

Hydraulic conductivity of paper sludge and peat is sensitive to small changes in confining pressure, since these materials are highly compressible. Confining pressures in laboratory tests, therefore, need to be carefully selected to model field conditions. The hydraulic conductivity is also time dependent, apparently the result of long term secondary compression.

Work done by Moo-Young and Zimmie (1996) shows that hydraulic conductivity (cm/s) can be estimated from the organic content from the equation:

$$O_r = -5.5 \log k$$

The hydraulic conductivity of paper sludge is affected by decomposition and freeze thaw cycles. As the organic solids decompose, the organic content of the sludge decreases and its hydraulic conductivity decreases (Moh-Young et al 1996). Freeze thaw cycles adversely affect the hydraulic conductivity of paper sludge (Moo-Young, 1995); however, the impact of freeze thaw cycles has been found to be less severe than it is for compacted clays.

It appears that the shear strength of paper sludge is frictional, similar to the shear strength of peats (MacFarlane, 1969). Measured friction angles are high compared to inorganic soils and are a function of organic content. Charlie (1977), for example, reports that the friction angle of two paper mill sludges increased from about 45° at 30 percent organic to about 65° at 60 percent organic.

b. *Research and case histories*

Numerous studies have been conducted to evaluate paper mill sludges for use as a soil substitute (NCASI, 1989; NCASI, 1990; Moo-Young and Zimmie, 1995; Zimmie and Moo-Young, 1995, Floess et al., 1995, Moo-Young and Zimmie, 1997). Paper mill sludge have been used to cap landfills in Wisconsin, USA since 1975 (Stoffel and Ham, 1979; Pepin, 1985).

The National Council of the Paper Industry for Air and Stream Improvement NCASI constructed four test pads in 1987 to evaluate the performance of paper sludge as a hydraulic barrier in landfill caps (NCASI, 1990). Two cells were constructed using paper sludge barrier layers; the other two cells were constructed with clay barrier layers to provide a baseline. Provisions were made for collecting and monitoring runoff and run-through, conclusions derived from the test pads are:

- the sludge consolidated as much as about 30 percent, with most consolidation occurring during the first year .
- measured runoff from the sludge test pads was similar to that from the clay test pads during the first year. Thereafter, runoff from the sludge test pads exceeded runoff the clay test pads.

- after the first year, measured run-through in the sludge test pads was less than the run-through in the clay test pads.
- combined sludge from primary and secondary treatment performed better than did sludge from only primary treatment.

Beginning in the late 1980's, Erving, MA,USA, conducted a comprehensive study on the use of their sludge as barrier layer material in landfill caps (Aloisi and Atkinson, 1991). Six test plots were constructed to evaluate the performance of Erving Paper Mill's sludge as hydraulic barrier in landfill caps. Both primary and combined sludge were evaluated. One of the test pads was constructed with clay as a control. The test pads included provisions for monitoring and collecting runoff and run-through. Conclusions derived from the test pads include:

- the hydraulic conductivity of the sludge decreased with time. The measured hydraulic conductivity of the combined sludge decreased by about one order of magnitude.
- the measured hydraulic conductivity of the primary sludge decreased to about one-third of its initial value. The presence of fine colloidal material in the secondary sludge was used to explain better performance of combined sludge.
- the clay test pad showed significant deterioration due to freezing and thawing. The sludge, however, showed improved performance over the first winter.

In 1991, a full scale demonstration project was completed using Erving Paper sludge as barrier layer material in the cap of the 1.8 ha Hubbardston, MA, USA, municipal landfill (Aloisi and Atkinson, 1991; Floess et al, 1995). The paper sludge barrier layer was thickened to 0.9 m in lieu of the standard 0.45 m of clay. The sludge was placed and compacted using low pressure tracked dozers. A paper mill roller was used for compaction and to smooth the sludge surface. The paper sludge barrier was covered with 0.15m of sand and 0.30 m of vegetative-support soil.

Laboratory hydraulic conductivity testing of sludge Shelby tube samples obtained shortly after completion of the barrier layer indicated variable hydraulic conductivities, averaging about 3×10^{-7} cm/s. Sampling and testing of sludge samples performed nearly two years after completion of the cap indicated an average hydraulic conductivity of 4×10^{-8} cm/s, a decrease of about one order of magnitude. This comparable to the performance of the test pads.

Sludge from the International Paper Company, Hudson River Mill, Corinth, NY USA was used as the barrier layer material in the cap of this town's municipal landfill (Floess et al, 1995). Cap construction was completed in 1995. An extensive investigation was performed to evaluate the sludge's characteristics and to demonstrate its suitability as low permeability barrier layer material. This investigation included geotechnical centrifuge tests to simulate rainwater infiltration over a 30 year period. The paper sludge barrier was thickened to 0.8 m in lieu of the standard 0.45 m of clay. An additional 0.45 m of paper sludge was added above the barrier layer for frost protection.

In addition to use as a barrier layer material, paper sludge blended with sandy soil and fertilizer has been used as a topsoil amendment in landfill cap (Floess, 1995).

5.2 *Quality Control*

Important indicators of paper sludge characteristics are water content and organic content. These index parameters are useful for quality control in construction projects, since they provide an indication of the variability of the sludge material being used, and they can be used to estimate the sludge's permeability, compressibility, and strength, considering that Atterberg limits and routine compaction control using standard Proctor tests are not meaningful.

Low permeability paper sludge barrier layers in landfill caps have typically been constructed by spreading the sludge in approximately 25 cm lifts using a low ground pressure dozer. The lift is then rolled smooth to shed water using a paper-mill roller pulled by a dozer or other tracked vehicle. Provided that the sludge is rolled smooth, it readily sheds water and does not dry out and become dusty like clay. Cap construction with paper sludge can proceed under a broader range of weather conditions than can clay-cap construction. It is not necessary to conduct in-place density testing, since the compactive effort merely serves to eliminate voids and to smooth the surface of the paper sludge.

5.3 *Summary*

Paper mill sludge has successfully been used as a soil material, mostly for construction of landfill caps and for use as cover in active landfills. Paper sludge with more than about 50% ash typically has a hydraulic conductivity less than 1 x 10-7 cm/s, and is therefore suitable for low permeability barrier material. Performance of test pads indicates that paper sludge may be superior to conventional clay since the hydraulic conductivity of the sludge tends to decrease with time. The hydraulic conductivity of clay test pads was found to increase with time as a result of freeze-thaw cycles.

In addition to use as low permeability barrier material and as topsoil amendment, paper sludge may also have application as frost protection material over conventional clay landfill caps.

Use of paper sludge as soil material can be difficult because each sludge is different and depends on the paper making process, and the wastewater treatment process. Beneficial use of paper sludge is also complicated by chemical contaminants in the sludge. Each sludge contains different contaminants and has differing concentration of contaminants. The chemical constituents of a particular paper sludge need to be carefully evaluated prior to considering its use as a soil substitute.

Regulatory hurdles also make it difficult to beneficially reuse paper sludge. Although regulators tend to be receptive to using paper sludge, it is time consuming and costly to obtain regulatory approvals.

6 CHARACTERIZATION AND EVALUATION OF GEOTECHNICAL AND GEOHYDROLOGICAL PROBLEMS RELATED TO PHOSPHOGYPSUM IN CONVENTIONAL CONSTRUCTION

6.1 *Introduction:*

Many areas in the world are encountering shortages of suitable natural aggregates. In addition, processing and handling operations have continuously increased the cost of conventional aggregates and the resultants products. As a consequence of this shortage, the need to obtain and evaluate various synthetic aggregate for the construction industry has never been more urgent.
To date, one possible source of aggregate has been largely overlooked, this material being phosphogypsum, which, herein, is defined as a by-product of the fertilizer industry's wet acid product of phosphoric acid from phosphate rock deposit. As indicative of its name, "phospho" refers to its industrial origin and "gypsum" indicates its predominate composition.

Currently, only 14% of the total produced phosphogypsum is reprocessed and utilized. Due to the level of impurities found in phosphogypsum and an abundant supply of natural gypsum, the practical use of this solid waste by the construction industry has been limited to 0.5% of the total production. Nearly 58% of the world wide production of phosphogypsum is being stored or stockpiled and the remaining 28% is being discharged into the ocean.

As a measure of the magnitude of stockpiling problems, central Florida alone is estimated to have a stockpile that will exceed one billion tons by the year 2000 while India has 40 millions tons annually and Turkey has 3 million tons annually. Serious storage and environmental pollution, aesthetic appearance, and economical factors have increased the demand for finding solutions other than simple land disposal.

In view of these factors, many studies were undertaken to ascertain the engineering characteristics of plain phosphogypsum and phosphogypsum based cement mixtures and thus evaluate its suitability as an aggregate or other base material for construction materials (Lopez and Seals, 1992; Kumbhojkar, 1992).

Engineering properties investigated included strength characteristics and their relationships under different placement technique; geotechnical properties; effect of curing type, curing age and testing conditions on strength properties; durability in terms of internal sulfate attack; and corrosion protection. Additionally, use of phosphogypsum as cover material of its own stacks have also being studied (Patel et al 1996), determining its hydraulically conductivity properties when compacted.

6.2 *Nature And Source Phosphogypsum*

Phosphogypsum is a by-product of the manufacture phosphoric acid from phosphate rock. Although there are several methods of producing phosphoric acid, including the thermal method, hydrochloric, and nitric acidulation, the sulfuric acidulation of phosphate rock (mostly referred to as "wet process") is most commonly used throughout the world. In this method, the phosphate content of the rock is converted by the concentrated sulfuric acid to phosphoric acid and calcium sulfate in a series of mixing tanks.

Calcium sulfate's by-product, phosphogypsum, is then separated from the phosphoric acid by filtration. In general, each 1000 kg of phosphoric acid is associated with the production of 4500 - 5500 kg of phosphogypsum. In obtaining high phosphoric acid recovery, there are presently several advanced methods that are being used around the world. These processes are: dehydrate, hemihydrate, and hemidihydrate.

The dehydrate method is widely used. It requires a relatively low capital cost, has a relatively low production cost and has great flexibility in using various qualities of phosphate rock. This method is capable of producing an acid from which uranium can be extracted. The dehydrate process produces 28-30% phosphoric acid; and dry phosphogypsum's production is about 4900 kg for each 1000 kg of phosphoric acid produced.

This gypsum can not be used for either the wallboard or cement industry without pretreatment or cleaning. It requires washing, lime neutralization, calcination, and granulation to assist in solids handling and feeding of the cement kiln.

The hemihydrate process produces 40-52% phosphoric acid and yields 4300 kg of dry phosphogypsum for each 1000 kg of phosphoric acid generated. This gypsum has a higher $CaSO_4$ content and lower levels of impurities when compared to dehydrate gypsum. The capital and production costs are higher for the hemihydrate process. The higher costs are somewhat balanced by the more pure product and some energy savings. Presently there is no fully developed method for extracting uranium from this process acid. This type of phosphogypsum still requires some washing, lime neutralization, and granulation before it can be used in wallboard or cement production.

The hemidehydrate procedure combines the advantages of the dehydrate process with the requirement of clean gypsum residues as produced by the hemihydrate method; there are a number of installations of this process in Europe and Japan. This method generates 40-50% phosphoric acid. The gypsum produced by this method still requires some washing, lime neutralization, and because of its dehydrate nature, it also requires calcination and granulation. This process is presently the least used of the three processes due to its higher capital investment, production, and maintenance costs.

6.3 *Experimental programs:*

a. *Engineering Characteristics of Unpurified Plain Phosphogypsum*

The composition analysis, as shown in table 1, indicated that it consists primarily of calcium sulfate, up to 93% as seen in table 2. Sand, phosphate, fluoride, and organic constituents add the remaining percentage. The pH value of phosphogypsum ranged from 3.1 - to 5.5.

By its nature phosphogypsum contains a number of heavy metals which are potentially toxic elements. Investigations available indicate that trace elements are usually not leachable in any significant amount, and their concentrations are usually lower than EPA's definition of toxicity.

Radioactive minerals are incorporated in phosphogypsum, and issues of potential groundwater contamination and radiological effects must be addressed. Lopez and Seals (1992) mention that persons working on the disposal stacks continuously receive an annual gamma radiation dose well below the occupational exposure limit.
Kumbhojkar (1992) reports that studies done in Florida to detect if phosphogypsum leachate from roads could affect the quality of groundwater and concluded that there could be an increase of sulfate, Ca and Ra-226 levels if hydrogeological conditions were favorable. The sealing of roadways by impermeable layers effectively eliminated the contamination of groundwater in the area around the studied roads.

The external gamma radiation of a phosphogypsum pavement was found to be about 50% lower than the old asphalt pavement, and also, was less than the original ground cover. Radon radiation from phosphogypsum concrete as reported by Kumbhojkar (1992) indicates that the maximum radon daughter concentration collected in a specially constructed room with no windows and air-tight door was less than the working level specified by state for remedial action. It also showed that the

TABLE 1. Typical Dehydrate, Hemihydrate, and Hemidehydrate Phosphogypsum Analysis (Carmichael 1985).

Composition (%)	Dehydrate Phosphogypsum (DH)	Hemihydrate Phosphogypsum (HH)	Hemidehydrate Phosphogypsum (HDH)
CaO	32.50	36.90	32.20
SO_3	44.00	50.3	46.50
P_2O_5	0.65	1.5	0.25
F	1.20	0.8	0.50
SiO_2	0.50	0.7	0.40
Fe_2O_3	0.10	0.1	0.05
Al_2O_3	0.10	0.3	0.30
H_2O	19.0 (approx.)	9.0 (approx.)	20.0 (approx.)

The addition of stabilizing materials, such as Portland cement, is one method of overcoming this deficiency.

TABLE 2 Composition Analysis of Raw Dehydrate Phosphogypsum

Element compositions	Percentage (%)
Gypsum	85.0-93.0
Phosphate	0.2-1.7
Fluoride	0.4-1.3
Sand	1.4-8.4
Soluble salt	0.1-5.3

TABLE 3. Physical Properties of Dehydrate Phosphogypsum

			Sieve Size (%Pass)			Permeability(cm/sec)	
Variable	Percentage gypsum	Specific gravity	40	60	200	Modified Proctor density	Standard Proctor density
Average	89	2.40	93	88	51	$4.5*10^{-5}$	$5.9*10^{-5}$
Range	85-93	2.40	93	87-88	49-53	$4.7\text{-}4.3*10^{-5}$	$7.6\text{-}4.2*10^{-5}$

TABLE 4. Geotechnical Properties of Dehydrate Phosphogypsum

	Maximum Dry Density (kN/m^3) and Optimum Moisture %		Lime Bearing
Variables	Modified Proctor	Standard Proctor	ratio (LBR)
Average	15.88 at 14.1	14.94 at 16.8	26

Range	15.72-16.15 at 14.01-14.1	14.87-15.02 at 16.6-16.8	22-29

TABLE 5. Geotechnical Properties of Dehydrate Phosphogypsum

	Plate Modified E (MPa)			Total Deflection at 1000 Repetition (mm)		
Triaxial (1)	Soaked (2)	Dried (3)	Optimum (4)	Soaked (5)	Dried (6)	Optimum (7)
$\varnothing = 49.0^0$;C = 0.0	155.82	267.66	199.404	5.520	1.260	2.207

concentration levels were directly proportional to the relative humidity and inversely proportional to ambient temperature.

The grain size distribution depends on the process and degree of grinding the rock used. Table 3 presents some results. The geotechnical properties of unpurified dehydrate phosphogypsum are shown in tables 4 and 5.

The results indicates that the dehydrate phospogypsum is a highly compressible material, and that its strength properties can be greatly improved by increasing the compaction energy. Compressive strength of 37.9 MPa (achieved under a compaction pressure of 248 MPa) is comparable to the compressive strength of good quality concrete and hence, utilization of phosphogypsum in certain applications such as building bricks and blocks, and road construction appear feasible. Dehydrate phosphogypsum specimens under soaked condition generally disintegrated when there were low - compaction pressures, and in most instances when impact compaction was used. These and other tests indicate that plain phosphogypsum has limited applications when wet conditions are to be anticipated.
Shear Strength parameters of compacted phosphogypsum at Standard Proctor energy and at optimum moisture content indicate drained friction angles varying from 43.5 to 50 degrees, without any cohesion intercept (Lopez and Seals 1992).

b. *Engineering Characteristics of Cement Based Phosphogypsum - Based Concrete Mixtures*

Hydration, physico-mechanical and carbonation studies have been carried out on calcium sulfaerluminate (C_4 A_3 S), calcium (C_5 S_2 S) and only dried (CS) synthesized by single firing at 1200^0 C.

The effects on setting and mechanical properties of partly refined boro-and phosphogypsum mixed with Portland and trass cement were studied and compared with Portland cement containing high grade natural gypsum.

The formulation of a cementitious binder based on calcined phosphogypsum, fly ash, hydrated lime and Portland cements were investigated and discussed. Strength properties and hydration of the cementitious binder studied at room temperature and temperature and at 50, 70, and 85^0 C in over 90% RH. are presented. It was found that the compressive strength of the cementitious binder was remarkably enhanced at 50^0 than 27^0 C.

The hydration of the cementitious binder as studied by differential thermal analysis and scanning electron microscopy glowed that the early age strength in the cementitious binder was due to the hardening of calcined gypsum and the hydration of Portland cement while later age strength development was ascribed to the formation of attringite and CSH.

6.4 *Conclusion:*

Information gathered during the course of the literature review lead to the following conclusions:

- Evaluation of Geotechnical properties indicate that Phosphogypsum is a good to fair base material for building elements, building block, tiles, etc. Phosphogypsum can be used as suitable aggregate for construction and in concrete.
- Apart from energy saving, the use of phosphogypsum assists in the reduction of the cost of the raw material. The clinking process, and the cement produced.
- Large scale utilization of phosphogypsum and by

products also contributes to the reduced exploitation of natural resources. The decreased generation of CO_2 during firing can contribute to the reduction of the green house effect.

- The partly refined boro-and phosphogypsum can be used in place of natural gypsum for Portland and trass cements.
- Systems containing up to 80% phosphogypsum can be very effectively employed in the manufacture of performed building elements.
- The cementitious binder containing equal proportions, of calcined gypsum and fly ash and small quantities of hydrated lime and Portland cement attained higher strength than the cementitious binder containing hydrated lime and no Portland cement.
- The presence of calcium sulfate does not adversely affect the long-term properties of the cement-based mixtures containing phosphogypsum.
- Phosphogypsum is a highly compressible materials and its strength properties can be greatly improved by increasing the compaction energy.
- Phosphogypsum can be used in agriculture as a soil amendment or conditioner.
- Plausibility of using highly compacted phosphogypsum as a radiation shielding material.

In addition it was found that there is still a need for more research due to the following limitations:

- Lack of enough data about the durability of the ettringite containing cements.
- No clear evidence that hydration of samples used had taken place.
- Variation in the curing temperature between 50^0 and 70^0 as reported for attaining maximum strength.

7. CHARACTERIZATION AND EVALUATION OF GEOTECHNICAL AND GEOHYDROLOGICAL PROBLEMS RELATED TO THE UTILIZATION OF USED TIRES

Each year, millions of tires are consumed throughout the world. Disposal of this material creates problems in the environmental' s preservation; because of their chemical composition, tires are combustible. For several years, this material has been re-used in the civil engineering. There have been made research projects, mainly in France, and several field works were concluded with success.

Tires can be used in two different forms in embaankments: as material of the embankments body, in substitution to the soil, or as reinforcement material of the soil. Even more, there have already been tests that proved that compacted soils mixed with rubber chips have lower hydraulic conductivity values, in certain types of permeants. Work has also been done in the use of ground tires for organic compound containment in soil-bentonite cutoff walls (Park et al 1996), and, after pyrolysis, use of carbon black as an additive in hot mix asphalt concrete (Park and Lovell 1996).

Use of tire chips isolated in a soil matrix eliminates the compaction difficulties that appear when whole tires are used. Tires have the particularity of being reinforced with cables of natural, artificial or metallic fibers, which make them more efficient when used as reinforcement soil.

Extensive tests have been made in the Laboratoire Central des Ponts et Chaussés, in France. (Cartier et al 1989; Long 1996), determining the mechanical characteristic of isolated elements of the tires, laterals and the wheel- work's band. Obtained results are:

- maximum tensile strength of the wheel-work's band equals to 56 kN, with standard deviation of 24kN.
- the two laterals of a tire show practically the same tensile strength, varying between 17 kN on samples least reinforced. Obtained mean value was 25kN, with standard deviation of 10kN.

The adherence tire-soil varies with the tensile of the tire element that is immersed in the embankment, the acting confining pressure, soil type, and with the way that the tire elements are disposed inside the embankment.

Tires can take part into the embankment body, piled up, underneath the uppermost compacted soil. The advantage of using in this manner is its low density, around of 0,4, near four or five times smaller than the density value of the compacted embankments, decreasing the surcharge above the natural soil. This kind of the embankment had already been made in Haute-Savoie (France), in the bridge abutment in a swampy region (Perrin et al).

An experimental embankment was constructed to evaluate the performance of this use of tires. The embankment was constructed with column of tires reaching 2 meter high, above a layer of coarse material of 0,50m, disposed above diameter of 1,10m and weight of 60kg.
One double structure of geotextile and welded wire mesh was disposed above the tires, with the purpose of not letting the soil penetrate into the tire. Two types of pavement were used: one rigid of reinforced concrete with 0,30m thick, and one flexible with a thickness of 0,50m. Observations showed that the area constructed with the rigid pavement had very small settlements, while in the flexible pavement the differential settlements were relevant.

In the work, the tires were tied in columns of five and pre-compressed. The instantaneous settlement, which is most important in these structures, was eliminated in this arrangement; settlement values were predicted as 0,5m for a column of 10 tires. The embankment presented unit weight of 3,5kN/m^3, value which is lower than conventional embankment.

Between the tires and the transition slab a welded wire mesh covered with geotextile was disposed. The experience in the Calvi channel (Haute-Savoi), was the first in the world and used 2000 tires. Work finished in 1989, and has not presented prejudicial deformation in the pavement.

The design of reinforced soil with tires must be conceived in the same way as the soil nailing, using the same design hypothesis presented by Vidal, H. (1966). Case histories of tires as embankment reinforcement were presented by Oberti,O,F. et al (1955) for two different embankments; one of them being a hazadours waste storage operated by France Decehts. In Brasil, there is a road embankments, constructed with tire reinforced soil, in João Melão Highway that joins Castelo Branco Highway with Avaré city.

Bayal, G et al (1992) has given another utility to the tires rubber. In areas contaminated by waste disposal it was necessary the use of suitable impermeable liner to prevent the contamination of the groundwater. The authors made experiences to determine the efficiency of using a mixture of fine particles of rubber, with varying lengths, and clay to construct a bottom liner of compacted soil. Tests were also made in samples obtained by the fly ash-rubber mixture.

The author has made mixtures with different percentages of rubber, and standard Proctor compaction tests to determine the mixture's optimum water content and the maximum dry density. The compaction curve for clay (kaolinite) - rubber mixture were obtained with pure kaolinite, 4%, 7% and 10% of rubber added to the kaolinite. The rubber -fly ash mixture were: pure ash, 3%, 6% and 9% of rubber added to the ash.

The addition of rubber in the two mixtures decreased slightly the maximum dry density of the mixture and increased its optimum moisture content.

Infiltrometer and permeameter tests were made in samples compacted at two per cent wet of optimum to achieve lower hydraulic conductivity particles. After the compaction, vacuum was applied to saturate the samples. In the clay-rubber mixture results indicated that the addition of rubber didn't increase the hydraulic conductivity of the mixture significantly when water was the permeant, indicating good interaction of kaolinite and rubber, with the rubber not causing development of larger pores or extra cracks in the mixture. When permeant was gasoline, the addition of rubber decreased the hydraulic conductivity values. This happens because the rubber in presence of gasoline swells, decreasing the conductivity of the mixture.

When the mixture was of rubber with ash the results reached were similar. For a mixture with 9% of rubber, the conductivity was three to four times larger than those of pure fly ash, when the permeant was water. With gasoline permeation, the hydraulic conductivities of rubber added mixtures decreased up to one sixth of the value obtained for pure fly ash.

When gasoline was used as the permeant a significant decrease in hydraulic conductivity values were observed for mixtures with rubber, the utilization of waste rubber as a liner additive in large quantities will provide and alternative to the old tire disposal.

8 CHARACTERIZATION AND EVALUATION OF GEOTECHNICAL AND GEOHYDROLOGICAL PROBLEMS RELATED TO MINE TAILINGS

Tailings consist of the barren residues of ores left after the commercially sought minerals have been removed; some typical grainsize curves for tailings are shown in (Blight and de Mello 1997). Each year the international mining industry processes hundreds of millions tons of earth and rock to extract minerals; a large portion of ore is waste material, which is mostly deposited hydraulically in dams. These dams are among the largest structures ever built by mankind.

Tailings dams constructed by the upstream method were initially conceived by miners as a lower cost alternative to downstream construction, as its shell usually consists of the coarser fraction of the tailings as deposited hydraulically. The separation of the coarser shell material and the finer slimes can be done by a natural beaching/sedimentation process or by cycloning. Sometimes dozers are used to shape and compact the shell. The slimes are the bulk of the waste material having a grain size of fine sand to silts, and occasionally clays.

Tailings dams are particular structures raised over many years or decades, with little control of the geotechnical engineers responsible for the original concepts and project; the exact location of the slimes-shell interface separating completely different materials and behaviors in loading, is unknown and unknowable.

The major structural concern when designing a tailings dam is the stability of its slopes, as the shell is continuously raised over a portion of slimes (Blight and de Mello 1997). It is recognized that the slimes, and sometimes the shell, are loose and contractive, generating positive pore pressures during loading and in rapid shear solicitation, as earthquakes. These loading pore pressures are related to the rate of dam raising, which is a function of ore processing, the length of beach, time of desiccation, existence of minute coarser layers and/or internal drainage, and consolidation properties of the slimes.
The resulting positive porepressures can cause liquefaction and lead to a flowslide, even in static conditions.

In the analysis of static slope stability of these dams there is not yet a consensus regarding the proper shear strength to use. Ladd (1991) addresses the problem of stage construction and the stability evaluation of dams and fills, and lists, together with Carrier (1991), groups of engineers that follow and believe that the analysis should be done with consolidated-drained shear strength parameters, and those that recommend use of consolidated-undrained parameters.

Considering that there is no way to avoid designing and constructing upstream tailings dams, due to economical analysis and decisions, it is usually recommended that consolidated-undrained analysis and verifications are done, as "an effective stress analysis inherently assumes slow failure with complete dissipation of shear induced pore pressures" (Ladd 1991). This reflects the truth that "undrained conditions will generally prevail during actual failures that entails significant displacements".

Ladd argues against the use of consolidated-isotropic-undrained triaxial compression tests, recommending anisotropic (Ko) consolidation direct simple shear and extension tests using the Recompression or SHANSEP techniques. Poulos et al (1985) recommend that the undrained steady state shear strength should be used to analyze the stability of dams composed of saturated contractive sands, accepting factor of safety simply grater than one in this analysis. Carrier (1991) proposes that both verifications are done, as when dealing with cohesionless materials which are not strongly contractive the conventional factor of safety could be lower than the accepted value in situations where safety estimated with steady state shear strength arrive at an acceptable value.

The question that remains is how to properly define if a material, cohessionless or cohesive slimes, will behave in a contractive way during shear, which is equivalent to define the need to run an undrained strength analysis. Carrier (1991) presents a very elegant methodology, using a ternary diagram developed by Scott and Cymerman, to display the sand-like (dilative) and clay-like (contractive) regimes of a gives soil or tailings, as a function of its water content. in this diagram simple calculations help determining if the in situ tailings consists of independent sand particles suspended in a matrix of fines and water, or of fines and water trapped within a sand structure.

With this important knowledge, it is easier to decide which stability analysis has to be done.

Among the important topics to be presented related to the characterization and evaluation of geotechnical and geohydrological problems related to mine tailings it was decided to briefly present a discussion of a topic the authors consider of fundamental importance; in the referred Symposium held in Santiago, Chile in October 1996, many other relevant topics are addressed, including the attention needed to avoid percolation of contaminants eventually present in the tailings to the aquifer. In this particular case special liners may have to be installed prior to tailings disposal.

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