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Evaluation of Waste Sludge as Landfill Cover

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Synopsis

The objective of this paper is to examine the material properties of paper mill sludge (PMS) and construction sludge (CS) as landfill cover materials. Hydraulic conductivity, physical and engineering properties, and chemical analysis of effluents were investigated to evaluate the suitability of PMS and CS for cover application. X-ray diffraction and scanning electron microscopy analyses have been carried out to evaluate the mineralogical and microfabric arrangement of PMS and CS samples. The test results indicate that both PMS and CS fulfill the landfill cover requirements and encourage their utilization as alternative materials.

Keywords: hydraulic conductivity; landfill cover; shear strength; x-ray diffraction; scanning electron microcopy; waste sludge

1. Introduction

The dense population in urban areas of Japan due to limited space, shortage of natural resources and rapid industrial growth have resulted in a huge amount of wastes generation, and thrown considerable challenge for effective disposal. Kamon and Katsumi, (1994a) reported that there are several paper mill industries in Japan that generate considerable amount of sludge up to 1.15 million tons every year. Further, the amount of construction sludge (CS) has reached a level of 10 million tons per year due to slurry excavation works involving shield tunnels, cast-in-place concrete piles and diaphragm walls. In most cases, these materials are harmless, and hence it is possible to recycle them using dewatering and stabilization techniques. The amount of CS recycling when compared with the total generation is low (2%) since CS sludge contains fine particles that are difficult to dehydrate. In view of the above reasons, disposal of both PMS and CS has thrown considerable challenge due the difficulty in securing dumping sites. Thus there is a need to develop new methods for treatment and recycling of wastes to produce valuable reusable resources.

Currently PMS and CS are considered as industrial waste sludges (similar to waste waster treatment sludge) and they are disposed into the landfill either directly or after incineration. In near future, the landfill sites are expected to be exhausted and hence new measures have been taken for the reuse of wastes including PMS and CS in an effective way. Even though few investigators reported the use of PMS and CS for geotechnical applications (Kamon and Katsumi 1994b; Kawachi et al. 1996; Tsukada and Ogawa 1996; Kamon et al. 1999), no study on the use of PMS and CS for landfill cover applications has been reported in Japan. The scarcity of natural clay sources and usage of synthetic materials for landfill applications have increased the overall cost of waste disposal. Also, the importance of landfill cover and its related study has paid little attention in Japan. The measurement of consolidation and hydraulic conductivity relationships for highly compressible waste sludge materials is challenging due to the associated low effective-stress range, large strains, low shear strength and lengthy consolidation process. In this paper, an attempt has been made to explore the possibility of using PMS and CS as landfill cover materials by evaluating their geotechnical as well as chemical properties. Hydraulic conductivity, chemical analysis of effluents, shear strength and consolidation, X-ray diffraction (XRD) and scanning electron microscopy (SEM) tests were carried out to evaluate the suitability of both PMS and CS for landfill cover application.

2. Background

2. 1 Properties of PMS and CS

Moo-Young and Zimmie (1996a) reported that the water content of PMS varies from 150 to 268%, whereas the organic content values is high (ie. Up to 56%). Inview of the presence of fibers and high initial water content, PMS pose problem in determining liquid and plastic limits using the standard laboratory testing procedures. However Moo-Young and Zimmie (1996b) succeeded in obtaining Atterberg limits of Erving paper sludge at wet condition. Kraus et al. (1997) performed hydraulic conductivity tests on three PMS, whereas Moo-Young and Zimmie (1996b) carried out an extensive study on seven PMS and their test results can be summarized as follows. PMS contains high moisture content, highly compressible and behaves as an organic soil. PMS showed a significant reduction in void ratio, and the variation in strength properties mainly depends on the organic and water contents. The presence of 40 – 50% clay at high water content showed low hydraulic conductivity less than 10^{-7} cm/s that increased the PMS application as landfill cover (Kraus et al. 1997). A two-year study carried out by Floess et al. (1995) on fresh fiber clay sludge showed low hydraulic conductivity (6 x 10^{-7} cm/s), and attracted its usage in U.S. landfills. An extensive chemical analysis on PMS has demonstrated that its use in the cap system does not produce contaminants beyond unacceptable level. A series of centrifuge model tests on PMS and field trials showed that PMS is non-hazardous, and its behaviour is similar to clay (Zimmie and Moo-Young 1995). In Japan, the improved material of CS has been successfully used in the construction of embankment (3700 m^3) along the bank of Tone river (Ogawa 1995). In view of the proven applications of PMS and CS and reduction of wastes disposal cost, the use of unconventional materials is strongly encouraged if they satisfy the established landfill criteria.

2. 2 Landfill cover

Recently several innovative technologies have been developed in the field of waste landfill containment system, and final cover is one of the critical components of landfill. The main functions of final cap system is to reduce the amount of leachate generation due to infiltration of water into the landfill, control the release of gases from the landfill, and protect humankind by providing a physical separation between the waste and environment. Figure 1 shows a typical sketch of landfill containment and cover systems as suggested by Koerner and Daniel (1997). Several researchers brought out the application of natural earth materials or geosynthetic clay liners in landfill (Daniel 1995). The geotechnical aspects of landfill cover system have been reviewed and reported by several researchers (Benson and Khire, 1995). The U.S. landfill liner and cover regulations states that the hydraulic conductivity of final cover system should be equivalent or less than 1 x 10^{-7} cm/s.

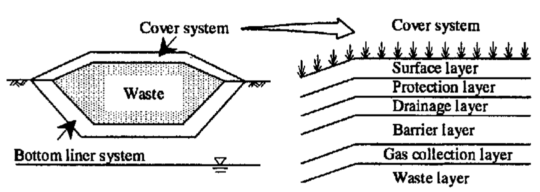


Fig. 1 Components of landfill containment and cover systems

3. Experimental Procedure

The physical and engineering characteristics of PMS and CS samples obtained from the local companies in Japan are given in Table 1. All the tests were carried out as per JGS (Japanese Geotechnical Society) standards. The hydraulic conductivity of sludges was evaluated using flexible wall permeameter, and falling-head procedure was used. For the above tests, five PMS samples of 100 mm diameter and 30 mm height were prepared with different water contents (53%, 75.7%, 114.5%, 136.1% and 157.9%). Whereas in the case of CS, samples with water contents of 10.5%, 20.1%, 26.6%, 32.7% and 40.9% have been used. Samples were prepared by placing three layers of sludge in a specially prepared mould, and a light hammer was used to compact each layer with 6 to 8 blows. The samples were carefully placed in the hydraulic conductivity cell with a layer of non-woven fabric sandwiched between filter papers (Fig. 2). A low confining stress of 30 kPa was applied for all samples,

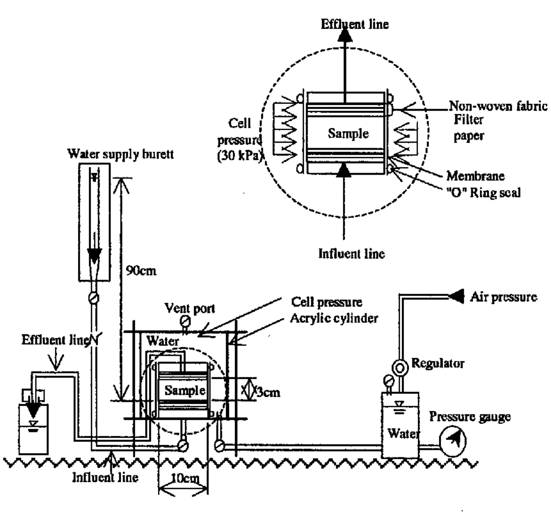


Fig. 2 Schematic diagram of hydraulic conductivity experimental setup

which is the practical approach to simulate the highest permeability in the field (Moo-Young and Zimmie 1996b).

PMS tends to form flocs which develops a coarse structure and that cannot be easily pulverized at dry state. In addition to that, PMS pose problem in determining liquid and plastic limits of PMS using the standard laboratory testing procedures is difficult (Kraus et al. 1997). However, falling cone method was used to estimate the PMS liquid limit, and there was no difficulty in obtaining the plastic limit for Japanese PMS (Kamon et al. 1999). Further compaction tests were carried out to examine the relationship between dry unit weight and molding water content of PMS. The presence of fibers and tissues results in problems to carry out standard testing procedures during trimming and cutting of samples, and the same aspects were noted by Moo-Young and Zimmie (1996a), and Kraus et al. (1997). The proctor test was performed from wet side since sludge at optimum water content state is dry, stiff and unworkable. In view of workability, a high water content usage in PMS is desirable when it has to be used as landfill cover material.

The behaviour of PMS depends on its chemical constituents generated during paper making and waste water process. The chemical components of sludges differ in concentration and they should be carefully evaluated prior to its use as soil substitute. A limited chemical analysis was carried out to study the heavy metals concentration such as lead (Pb), cadmium (Cd), chromium (Cr) and zinc (Zn). In the case of PMS, additional tests of dissolved oxygen (DO) and total organic carbon (TOC) were carried out to evaluate their impact on the hydraulic conductivity. It has been reported that organic degradation of PMS results in increasing the amount of clay content (kaolinite) with time, and decreases hydraulic conductivity. The sample heavy metals concentration was measured using Inductive Coupled Plasma (ICP). The chemical tests were carried out as per JLT-13, Environment Ministry of Japan. The characteristics of sludges and their hydraulic conductivity performance depend on the microfabric arrangement and compositional aspects such as kaolinite, feldspar and organic materials such as fibers and tissues. Hence, there is a need to evaluate the mineralogical and microfabric arrangement of PMS and CS. Air dried samples were used for X-ray analysis, whereas wet and dry PMS samples were further analyzed for microscopic study.

4. Results and Discussions

4. 1 Geotechnical properties

The basic properties of PMS and CS are given in Table 1. All the tests were carried out from wet side, and air drying process was used to obtain samples of appropriate water content required for testing. The presence of high kaolinite content in PMS increases the specific gravity to a maximum value of 1.79, which is consistent with the range of values highlighted by previous investigators (Moo-Young and Zimmie 1996b). The liquid limit of PMS was high (132.5%), and the compaction test results indicate optimum moisture content of 74% (Fig. 3). Also, the organic content of PMS was quite high (63.7%). The optimum moisture content of PMS is higher, but the maximum dry density is lower when

Table 1 Properties of PMS and CS

Properties	PMS	CS
Water content (%)	132.5	337.2
Organic content (%)	63.7	6.2
Particle density (g/cm^3)	1.79	2.68
Liquid limit (%)	325 - 335	46.5
Plastic limit (%)	106 - 117	28
Optimum moisture content (%)	74	18.2
Heavy metals analysis (mg/L)		
Pb	≤ 0.01	≤ 0.01
Cd	≤ 0.01	≤ 0.01
Cr	≤ 0.01	≤ 0.01
Zn	≤ 0.01	≤ 0.01

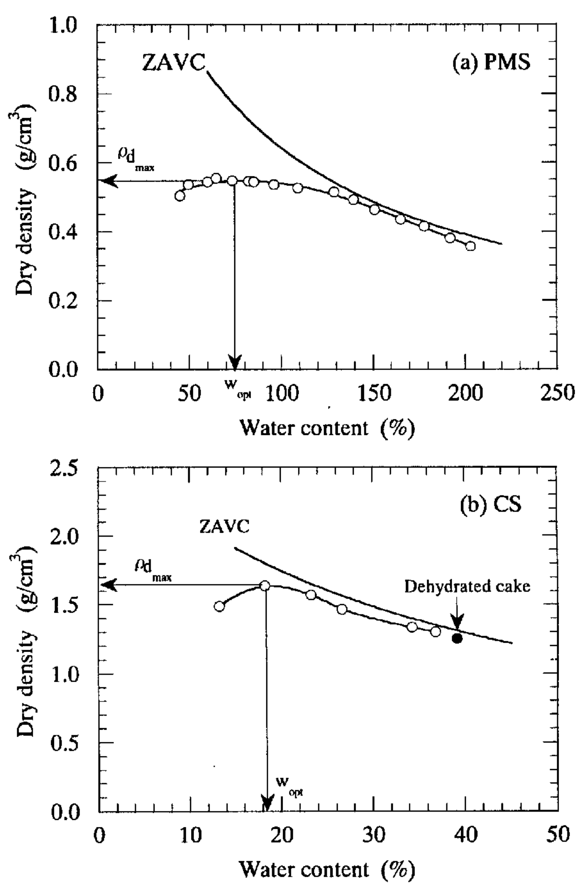


Fig. 3 Compaction curves of PMS and CS

compared with compacted clays. The properties of Japanese PMS compared well with the earlier studies carried out by Moo-Young and Zimmie (1996b). Comparing with PMS, the natural water content of original CS was quite high (337.2%), and the measured values of liquid limit (LL) and optimum moisture content (OMC) were 46.5% and 18.2% respectively (Fig. 3). As expected, the original condition of bentonite slurry used in construction works has been altered with site conditions, which results in CS with lower values of LL and OMC. However, the organic content of CS is low (6.2%) when compared with PMS (63.7%).

4. 2 Shear strength and consolidation

The utilization of sludges for landfill cover applications need a reasonable prediction of settlement since the presence of fibers and high water content of PMS can alter the cohesion as well as strength parameters. Consolidated undrained triaxial tests with pore pressure measurements were carried out to examine the shear strength behaviour of waste sludges. Remolded PMS and CS samples with water contents of 148.8% and 21.5% were used respectively (Fig. 4), and different confining pressures of 30, 60 and 120 kPa were applied to evaluate the effective angle of internal friction and cohesion. In the case of PMS, the measured values of cohesion and internal friction angle are 3.9 kPa and 40.5° respectively. PMS samples do not yield any sharp yield point, and it is difficult to determine the failure condition from stress-strain curves. Hence, failure at a reasonable level of 15% strain has been arbitrarily selected. The obtained results compare favourably with the earlier data of PMS and water treatment plant sludges (Wang et al. 1991; Moo-Young and Zimmie 1996a). The results of CS indicate cohesion and angle of internal friction as 3.6 kPa and 34.1° respectively (Fig. 4). The pore pressure (A_f) at failure stage of PMS and CS specimens indicated values of 0.65 and 0.36 respectively. In view of the high water content and A_f values, PMS exhibits high organic soil or slightly over-consolidated clay behaviour. However, effective friction angle (ϕ) is quite high as much as 40.5°, which is typical value for compacted gravelly soil. The high value of ϕ is mainly attributed due to the presence of organic fibers and tissues present in the PMS. Quiroz and Zimmie (1998) carried out an extensive study on the variation of undrained strength in a PMS landfill cover system using field vane shear test, and they observed tension cracks of considerable depth around the failed slope areas of old landfill. Their results indicated that the undrained strength of PMS stable slopes range from 12 to 35 kPa, whereas

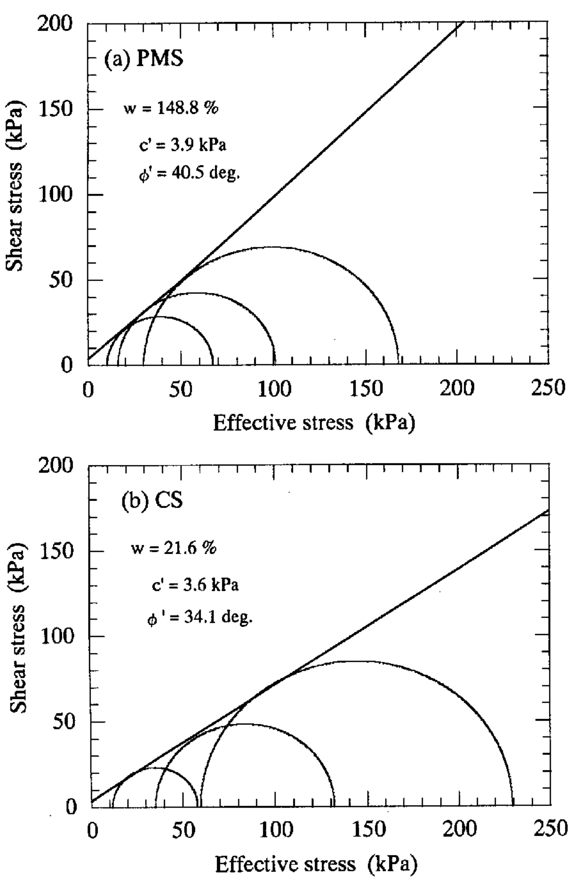


Fig. 4 Shear strength of PMS and CS

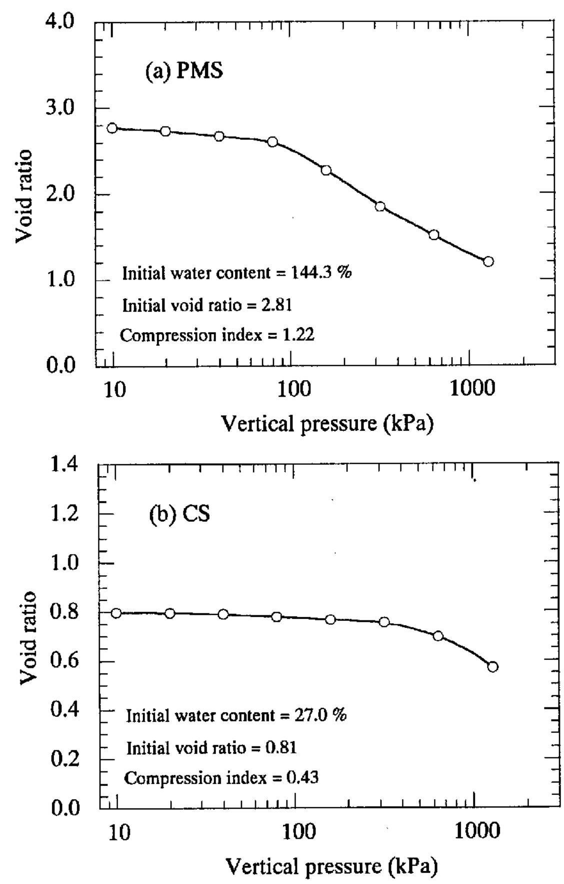


Fig. 5 Consolidation properties of PMS and CS

failed zones measured values less than 10 kPa. However, the PMS and CS samples used in the present study showed undrained shear strengths of 38.2 kPa and 31.1 kPa respectively. As highlighted earlier, the presence of fibers and tissues in PMS matrix enhance the strength even at higher water contents.

The results of one-dimensional consolidation tests conducted on PMS and CS samples are shown in Fig. 5. PMS sample showed a large reduction in void ratio from 2.81 to 1.20, and the measured compression index was 1.22. It has been observed that high strain values were measured at higher applied stresses, and this could be due to larger reduction in the void ratio of PMS samples. The obtained results are comparable with the earlier test results of PMS and water treatment sludges that showed similar consolidation behaviour (Wang et al. 1991; Moo-Young and Zimmie 1996b). In the case of CS, initial void ratio has reduced from 0.81 to 0.60, whereas the compression index was estimated as 0.43 respectively. The above test results indicate that PMS is highly compressible when compared with CS. Further, research is necessary to bring out the influence of organic decomposition on the strength and consolidation aspects of PMS since the tested materials are intended to be used as landfill cover material for long term. However, the results of earlier investigators showed that consolidation effect significantly improves the hydraulic conductivity of PMS, and organic degradation does not affect the performance of PMS (Quiroz and Zimmie 1998). The gain in strength due to consolidation as a result of overburden pressure is far greater than any strength loss due to organic decomposition.

4.3 Hydraulic Conductivity

The main criteria for using PMS and CS in landfill cover applications can be evaluated for the hydraulic conductivity requirements. The variation of hydraulic conductivity of PMS and CS with respect to time is shown in Fig. 6. The lowest hydraulic conductivity of PMS occurred at 136 % (wet of OMC), whereas CS showed minimum HC at 27%. It has been observed that the initial marginal increase in HC can be due to consolidation effect of samples. Eventhough PMS samples initially showed hydraulic conductivity close to 10^{-5} cm/s, ultimately it has reached a stable trend with low HC of 10^{-6} to 10^{-7} cm/s. It has been reported that initially PMS does not fulfill the landfill cover requirement of HC (Moo-Young and Zimmie 1996b). However, the effect of consolidation induced settlement leads to a decrease in HC that increases the strength with time (Moo-Young and Zimmie 1996b).

Under low effective stress, the decrease in void ratio of PMS due to consolidation and dewatering results in the reduction of HC to an acceptable value. The field test results of Kraus et al. (1997), and

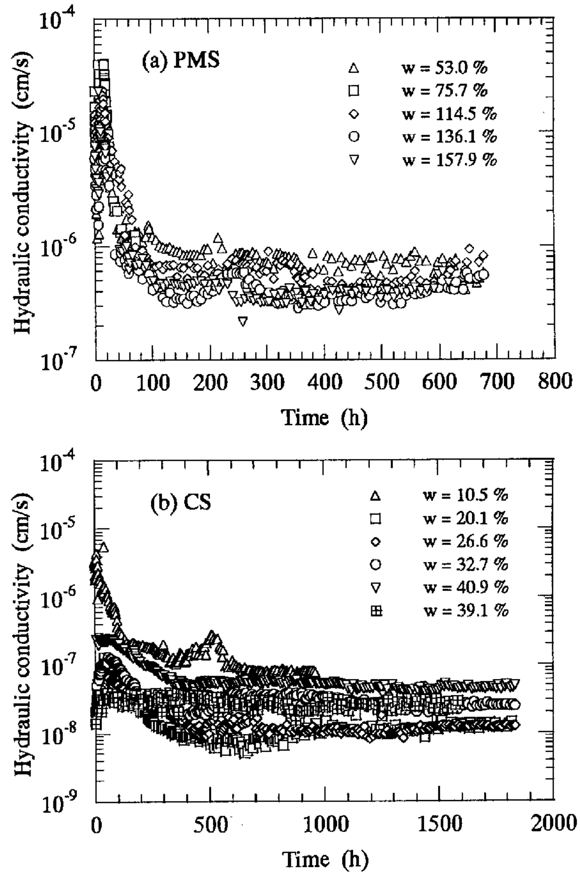


Fig. 6 Hydraulic conductivity of PMS and CS

Quiroz and Zimmie (1998) showed no increase in HC even after 8 years. This means that organic decomposition does not have any adverse effect on the HC and long-term performance of PMS landfill cover. However, it is suggested to cover PMS immediately with drainage and vegetative support layers to avoid any desiccation and shrinkage cracks formation. It is interesting to note that the hydraulic conductivity of CS showed better results when compared with PMS (especially for samples with water contents of 20.1%, 26.2%, 32.7% and 40.9%). The test results showed a promising sign for the application of PMS and CS as daily cover in active landfill, and barrier layer in the final cover system.

4.4 Chemical Analysis of Effluents

Figure 7 shows the variation of hydraulic conductivity with the cumulative mass of released TOC. A drop in the hydraulic conductivity of PMS with sudden increase in the release of TOC has been observed at L/S of 8. This indicates that the gradual decrease in organic degradation of PMS under anaerobic condition results in a sharp drawdown in HC, and thus satisfies the landfill cover requirement of hydraulic conductivity on long run. Eventhough the gradual release of heavy metals concentration in

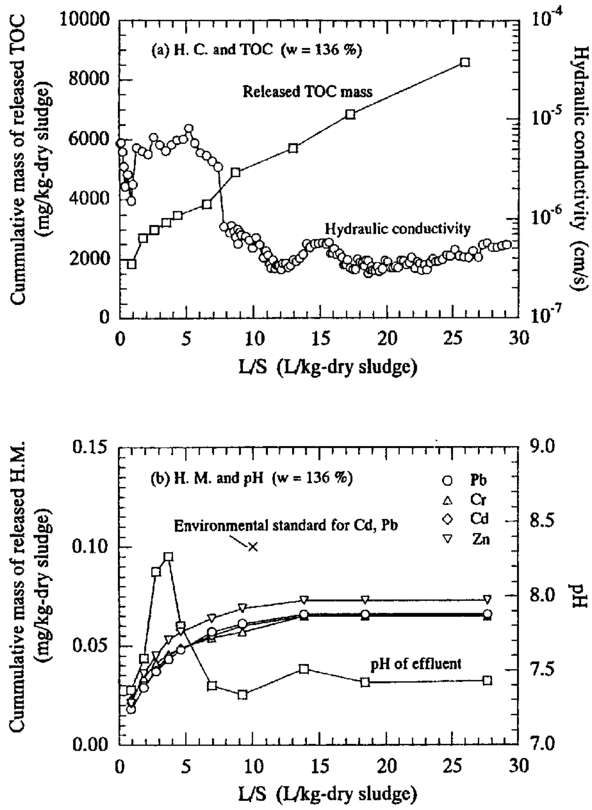


Fig. 7 Chemical analysis of PMS effluents

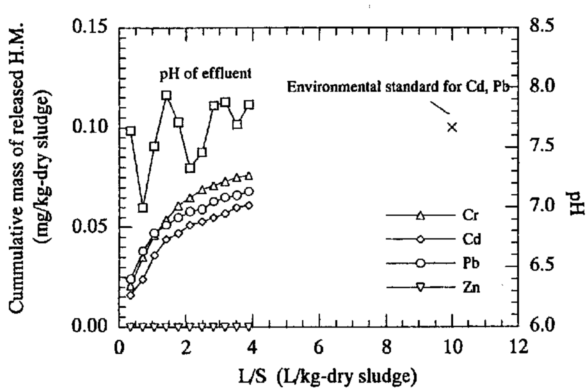


Fig. 8 Chemical analysis of CS effluents

PMS showed a sharp increase in the pH at the initial stage, a sudden decrease in pH at L/S of 3 has been noticed. At the same point, the release of heavy metals showed a stable trend, and the measured concentrations are well within the environmental standards. In the case of CS, the measured heavy metals concentration is low when compared with PMS, and the pH of effluents falls near the neutral condition (Fig. 8). Both PMS and CS results indicated that the ionic concentration in leachate samples is less and the environmental impact of heavy metals is insignificant (Kamon et al., 1999). The above results indicate that DO level of both PMS is an indicator of organic degradation since it affects the HC of samples. In view of the above reasons, it is expected that the environmental impact of metals release due to leaching is not a serious concern.

The above results reveal that the chemical constituents measured in PMS samples were within the environmental standards, and the application of PMS and CS as landfill cover in field does not cause serious environmental risk. Also, the above aspect is not critical in the case of landfill cover when compared with landfill liners as reported by Daniel (1995). In addition to that the test results of Moo-Young and Zimmie (1996b) indicated that organic degradation do not significantly affect the long-term performance of PMS landfill cover. However, a better understanding of the biodegradation of PMS in landfill cover applications through long term study is necessary before arriving any firm conclusion.

4. 5 XRD and SEM analyses

Figure 9 (a) shows the XRD analysis of PMS, which indicated the presence of kaolinite and calcium carbonate as dominant minerals. The results of Moo-Young and Zimmie (1996b) also supported the above aspect by indicating the presence of similar minerals

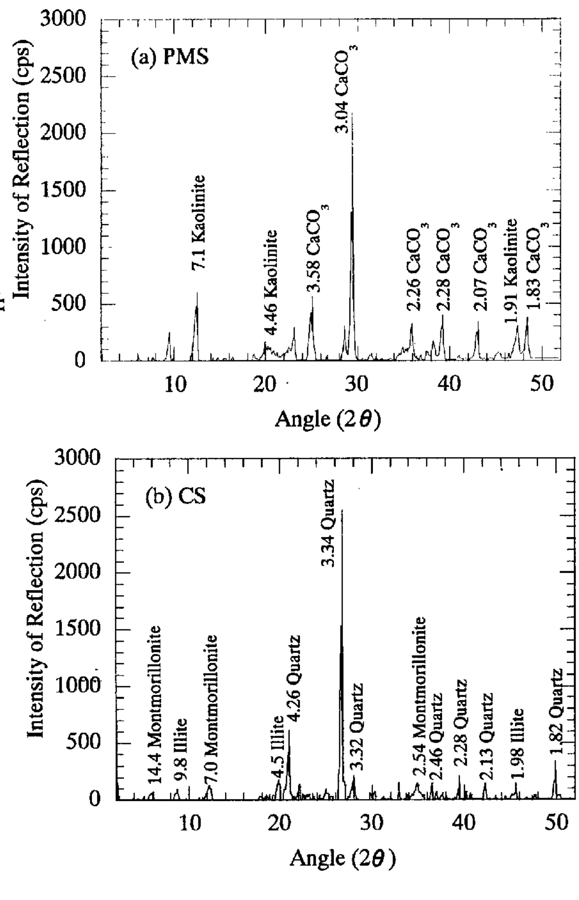
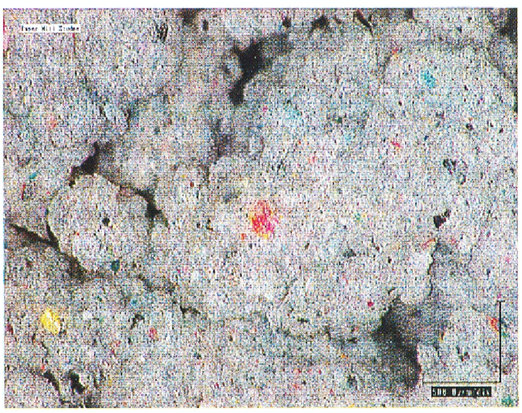


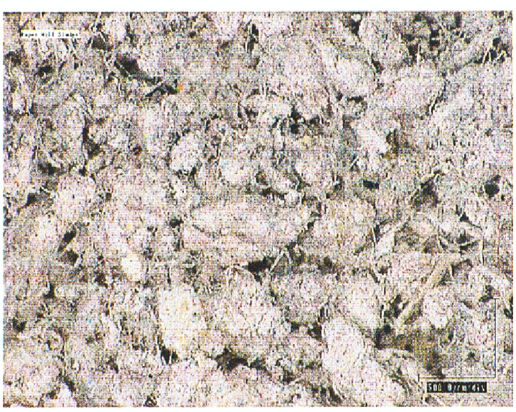
Fig. 9 X-ray diffraction patterns of PMS and CS

in PMS, and the behaviour of PMS is the same as highly organic soil. Further the XRD pattern of CS indicates the dominance of montmorillonite, illite and quartz minerals (Fig. 9 (b)). In view of the site conditions, the original composition of waste has been changed as seen in the XRD pattern of CS. Hence the mineralogical aspects of both PMS and CS should be examined to evaluate the long-term performance of sludges in the field.

Figure 10(a) shows the microscopic view of PMS at wet condition, and the presence of homogeneous lumps consisting organic fibers and tissues can be seen. On compaction, the embedded fibers and tissue materials of lumps results in the formation of compacted cover system that improves the engineering behaviour of PMS. A similar observation has been reported in organic soils that indicated that the fibers acting as reinforcing elements and results in higher shear strength (Franklin et al. 1973). The use of dye and other materials in paper making process results in small colour spots on the PMS lumps. Whereas PMS under the dry condition indicates shrinked mass of lumps with a clear view of organic fibers (Fig. 10(b)). It has been established that the laboratory testing of PMS under the dry condition for evaluating its characteristics should be avoided since PMS loose its plasticity. In view of the above, it has been suggested to carry out all tests from wet side, and the above aspect has been pointed out by Moo-Young and Zimmie (1996a). The microscopic view of PMS samples, which confirm the presence of well knit, form of organic fibers and organic tissues respectively. It has been reported that the behaviour of PMS is expected to be similar as peaty soils (Edit et al. 1981), and further study is necessary to bring out the role of fibers and its decomposition effect on the performance as cover materials (Al-Khafaji, 1979). Under the overburden pressure, pores between the PMS particles are expected to be decreasing and thus reduce the hydraulic conductivity with time. The above micrographs indicate that fabric arrangement of PMS play a major role in the engineering behaviour of PMS.



(a) Wet condition



(b) Dry condition

Fig. 10 Microscopic view of Paper mill sludge

5. Summary and Conclusions

The utilization of PMS and CS materials as final cap system not only saves the landfill space, but also disposal cost significantly. Since PMS and CS are considered as waste products, landfill owners have to pay little or no cost. The chemical analysis of PMS and CS, and results of effluents collected from the hydraulic conductivity tests indicated that the concentration of heavy metals and TOC were within the Japanese regulatory standards. As reported in Kraus et al. (1997), the environmental impact of PMS usage in landfill cover system is not a serious concern. The use of PMS and CS as landfill cover materials provides significant pollution control, ecological, and economic benefits in comparison with the utilization of traditional barrier caps such as compacted clays and geosynthetic materials including geosynthetic clay liners (GCL). The test results strongly encourage PMS and CS sludges utilization in the barrier layer of cover system, and the above experimental work leads to the following conclusions.

- CS indicated low HC values that indicated better results of HC than PMS. In view of the low organic content, it is an added advantage for using CS in the field without much problem. The chemical analysis of both PMS and CS samples indicated that they do not cause any environmental impact on long run.
- In view of negligible contaminant presence, CS can be used confidently in the field with out concerning its chemical impact on environment. The effect of organic degradation does not affect the PMS performance as cover material since the overburden pressure with time outweighs the above factor.
- The presence of fibres in PMS plays a major role in the strength increase especially at higher water content. Also, the effect of consolidation in PMS due to overburden pressure is expected to increase its efficiency as barrier system.
- The performance of PMS as landfill cover is expected to improve with time. However, organic

matter biodegradation, reduction of organic matter with time, and influence of organic fibers and tissues on the engineering behaviour of PMS should be considered to evaluate its long-term performance in the field. However, further study is needed to evaluate the above aspects in detail.

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要　旨

近年，我が国では廃棄物処分場における残余年数の切迫等により，廃棄物の有効利用が積極的に行われている。そのような状況下，本研究では廃棄物である汚泥材料の廃棄物処分場カバー材としての適用性を検討するものであり，汚泥材料として製紙汚泥および建設汚泥に着目した。室内試験では，汚泥材料の工学的諸特性，透水試験，圧縮試験，およびせん断試験を実施することでカバー材としての安定性を検討した。さらに，廃棄物の有効利用に伴う環境影響評価として，透水試験後の排出液中の有害物質含有量分析を行っている。結果として，製紙汚泥，建設汚泥とも有効利用に伴う環境適合性は満足しており，さらにカバー材として要求される機能を十分に有していることを明らかにした。

キーワード：透水係数，処分場カバーシステム，せん断特性，X線回折，電子顕微鏡，汚泥