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Geotechnical characterization of water treatment plant residuals

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ABSTRACT

GEOTECHNICAL CHARACTERIZATION OF WATER TREATMENT PLANT RESIDUALS

by
Zhengyuan Xia

Evaluation of engineering properties of water treatment plant (WTP) residuals is a critical part in predicting their behaviors in monofills. In this study, ten WTP residual samples were collected from ten water treatment plants across the United States. Their general chemical/physical and geotechnical properties including liquid and plastic limits, compaction, shear strength, permeability and durability characteristics were determined.

It was observed that the geotechnical properties of WTP residuals are influenced by various factors such as mineral particle composition, organic content, type and amount of chemical additives, and time of aging, etc. Based on this study, the behavior of WTP residual can be primarily attributed to a unique floc structure developed due to their colloidal properties and high ion concentrations. This highly oriented floc structure plays an important role in the development of cementation and thixotropic hardening and has significant influence on the geotechnical properties of WTP residuals.

WTP residuals exhibit low durability characteristics. They usually have low strength at low solids content. Aging, which is believed to be a process in which floc water escapes with the reorientation of floc particles and the development of cementation, has a tendency to improve the strength. The levels of development of strength of different residuals have a wide range which is also believed to be related to thixotropy and cementation developing properties. Coefficients of permeability are all low, of the order of 10^{-6} - 10^{-7} cm/s. The compressibility is very high due to the high water retaining ability and

the deformation of floc structure. Low swelling ability and the high pseudo pre-consolidation pressure of these residuals, may be caused by the development of the inter particle bond due to thixotropic hardening.

GEOTECHNICAL CHARACTERIZATION OF WATER TREATMENT PLANT RESIDUALS

by
Zhengyuan Xia

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APPROVAL PAGE

GEOTECHNICAL CHARACTERIZATION OF WATER TREATMENT PLANT RESIDUALS

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CHAPTER 1

INTRODUCTION

1.1 General

Each year several million tons of residuals are produced by water treatment facilities in the United States. Handling and disposal of these residuals have always been important considerations in protecting environment. Due to the stringent environmental regulations, the problem of how and where to dispose of these residuals has received great attention in the recent past.

Water treatment plant residuals (or sludges in some references), hereinafter referred to as WTP residuals, are sludge type materials produced from filter backwashing, coagulation, and softening processes during water treatment. These residual materials have long posed problems of management and disposal. The disposal of these residuals has grown into a formidable challenge for the water industry, especially in light of the current emphasis on clean environment. (Hsieh et al., 1992)

In the past years, the disposal of WTP residuals has included direct discharge of these into sanitary sewers or streams landfilling, and ocean dumping with or without prior dewatering, and incineration. However, some of these alternatives are no longer feasible because of the current regulations that limit the direct discharge of wastes into water courses. These regulations include the Water Pollution Control Act Amendments of 1972, (WPCAA), the Clean Water Act (CWA), and Ocean Dump Ban Act (ODBA). The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as the Superfund, also affects the disposal of WTP residuals. Under Superfund, liability is "joint and several", which means anyone who can be shown to be responsible for even a fraction of the harm can be made to pay for the contamination. If a water utility disposed of its residual at a municipal solid waste landfill, and if toxic compounds were found in this landfill, the water utility could be liable for cleanup based on its use of the landfill, even if its residue did not directly cause the problem. So it is obvious that the monofill will become a future trend for ultimate disposal of WTP residuals. (Hsieh et al., 1992; Cornwell et al., 1987, 1992)

At present, landfilling and land application of water treatment residuals are the logical alternatives because of their environmental and economical advantages over other methods.

1.2 Scope and Objective of Research

New Jersey Institute of Technology (NJIT) has been awarded a contract by the American Water Works Association Research Foundation (AWWARF) to study the physical and chemical properties of the WTP residuals. (Hsieh et al., 1992) The results of this study will be utilized to design, construct, and operate a monofill for ultimate disposal of WTP residuals.

Samples of WTP residuals were collected from ten treatment facilities. Geotechnical testing involving identification and classification tests, compaction tests, water content tests, specific gravity of solids tests, direct shear tests, unconfined compressive strength tests and consolidation tests were conducted. Environmental experiments performed include general physical and chemical tests, cation exchange capacity tests, and TCLP tests. Methods for geotechnical tests are listed in Table 1.

The objective of this research work is to determine geotechnical properties of various types of water treatment residuals. Results of this study will help to develop the design, construction, and operation criteria of WTP residuals monofill.

1.3 Structure of Thesis

Following this introductory chapter, Chapter 2 starts with the literature review of the research work performed on the geotechnical properties of WTP residuals. The previous work conduced in NJIT on this subject is briefly reviewed. Other developments in this research area are also presented in that chapter.

Chapter 3 is devoted to a brief introduction of water treatment process and a discussion on the composition and structure of WTP residuals.

Chapter 4 contains the results obtained from this study. Discussions on these findings regarding the characteristics of WTP residuals are presented.

Finally, summary, conclusions, and suggestions for further studies are presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

Geotechnical properties influencing the design and performance analysis of WTP residuals landfill include mainly solids size distribution, compaction behavior, compressibility, strength, and durability. The present state of knowledge of these properties generally falls into two categories of untreated and treated WTP residuals. Since this study focuses on the behavior of landfilled WTP residuals in natural conditions, knowledge on untreated WTP residuals is of interest for this study. Since available information regarding studies on WTP residuals is very limited, studies on treated WTP residuals, wastewater treatment sludges, industrial sludges, and clay materials will also be reviewed for reference, comparison, and interpretation purposes.

In one of the early studies on this subject, Raghu et al. (1986 and 1987) performed modified Proctor compaction tests on a lime/alum/polyamine type residual obtained from Jersey City Water Treatment Plant at Boonton, New Jersey and a lime type residual from Three River Water Treatment plant at Fort Wayne, Indiana. Compaction curves exhibited typical one-hump shape. For the Jersey City residual, the optimum water content was about 65 percent and the maximum dry unit weight was about 51 pcf. The corresponding numbers for the Fort Wayne residual were 28 percent and 84.5 percent respectively. Environmental Engineering & Technology, Inc. (1989) reported the results of standard Proctor compaction test on a coagulant sludge that had been stored at a water plant in Oklahoma for an extended time. The test results also showed the typical one-hump compaction curve. Optimum moisture content and maximum dry unit weight were approximately 17 percent and 105 pcf (pounds per cubic foot), respectively. Wang et al. reported the engineering behavior of one iron and two alum coagulant WTP residuals in

1992. Test results indicate that the residuals are extremely plastic and highly compressible. The compaction curve for the iron type residual exhibits typical one-hump shape, whereas that for the alum residuals shows no peak. In 1993, Wang et al. reported the compaction behavior of an alum type WTP residual. The compaction curve is not that of the typical one-hump curve. Instead, the dry density decreases with increasing water content from a maximum near zero water content.

Raghu et al. (1986 and 1987) conducted conventional consolidation tests to determine the coefficient of permeability of the two WTP residuals mentioned above. The coefficients of permeability were found to be in the order from 10^{-6} to 10^{-7} cm/s. Using the method of dewatering under different pressure differentials, Knocke and Wakeland (1983) investigated the compressibility of four sludges--alum (low density), alum (high density), conditioned alum, and lime sludges. They reported that the average coefficient of compressibility for the first three alum sludges ranged between 0.94 and 0.97, whereas that of the lime sludge was 0.79, indicating the lime sludge to be considerably less compressible than the alum sludge. Wang et al. (1993) reported the permeability characteristics of an alum water-treatment residual treated separately with a slaked lime and fly ash. Results showed that, for both the treated and the untreated residuals, the permeability-versus-void ratio relationship can be expressed as a power function as opposed to an exponential function. Under the same void ratio, the treated sample was noted to have a greater permeability than the untreated one. It was found that within the void ratio of approximately between 7 and 17, the coefficient of permeability varies from about 3×10^{-8} to 8×10^{-6} cm/s for untreated residual samples. Alvi and Lewis (1986) reported a study on industrial sludges generated from steel manufacturing. Primary consolidation was found take place in relatively short time, and the secondary compression was the dominant mode of compressibility. A pseudo preconsolidation effect was suggested which was considered to be caused by thixotropic phenomenon and cementation.

Available information on the shear strength characteristics of WTP residuals concentrates mainly on the undrained strength with regard to sludge handleability (or workability). Raghu et al. (1986) conducted unconfined compression and direct shear tests on a lime type residual obtained from Fort Wayne, Indiana at a dry density of 84.5 pcf and a moisture content of 28 percent. A value of 9.6 psi was obtained for the unconfined compression strength. An angle of internal friction of 28 degrees and a cohesion of 2.5 psi were determined from a quick (UU) direct shear test. Most other studies used the vane shear test method to determine the strength (Cornwell et al., 1990).

Novak and Calkins (1975) studied five sludges using a torvane and reported 0.04 tsf to be the minimum undrained shear strength for easy handling of the sludge. This minimum shear strength value is about 2.5 times lower than 10 kPa (0.104 tsf) currently used in Germany and Netherlands for determining the acceptability of WTP residuals for disposal in a landfill (Cornwell, 1990). Using both a torvane and a viscometer, Huang (1979) presented, among others, a relationship between the undrained shear strength and solids concentration for two sludges.

It was pointed out by Knocke and Wakeland (1983) that WTP residuals exhibit marked increase in strength due to thixotropic hardening. However, very little information on the thixotropic behavior of WTP residual is currently available. Alvi and Lewis (1986) suggested that in sludges the attractive forces due to cementation dominate over gravity forces. Wang et al. (1992) tested one iron and two alum coagulant WTP residuals and found that the samples were highly sensitive and thixotropic. Compared with the iron sample, the alum samples tested were more plastic and compressible, and had higher undrained shear strength at the same solids content.

In 1993, Wang et al. reported the shear strength behavior of an alum type residual both untreated and treated with additives. It was found that the additives improve the shear strength considerably. The untreated residual had a high effective angle of internal friction, but the undrained shear strength was low, especially at high water content. Both the untreated and the treated residuals were sensitive and highly thixotropic.

Reports about the study on the durability of WTP residuals are scarce. Most previous work in this area focused on dewatering by freezing/thawing. Ferrell et al. reported in 1970 a study on the design of facilities for dewatering alum residuals by natural freezing. Logsdom et al. (1971) studied the effective dewatering freezing rate. It was suggested that high freezing rate causes effective dewatering and residuals could be effectively frozen in thin layers on a flat surface. Vesilind et al. (1990) presented a conceptual model for freezing of WTP residuals that helps to explain the improvement of dewaterability of WTP residuals by freezing.

A classification of water in WTP residuals of four types of is suggested by Vesilind (1990). This classification seems to be widely used in explaining some of the geotechnical properties of WTP residuals. Martel et al. (1991) reported a pilot-scale study of alum residual dewatering in a freezing bed. Based on the study, freezing method is a very effective technology for dewatering alum residuals with a volume reduction up to 96 percent.

Since WTP residuals may contain high organic content, volatile substances and chemical additives, the proper method of moisture determination has become a concern. Raghu et al. (1986 and 1987) observed a loss of volatile solids when a residual sample obtained from Jersey City Water Treatment Plant was oven dried at 110°C. It was suggested necessary to oven-dry the WTP residuals with high volatile solids contents at 35°C to determine the moisture content in order to prevent the solids loss. Alvi et al. (1986) performed a serious moisture content tests on steel industrial sludges and concluded that the moisture content of sludge could be appropriately determined at a standard temperature of 105°C which is conventional used for most soils.

Efforts were made to improve the workability of WTP residuals so that they may be used for construction. Raghu et al. (1987) evaluated the feasibility of using a WTP residual collected from Jersey City Water Treatment Plant as a liner for sanitary landfills. It was found that the residual met all the criteria imposed by New Jersey Depatrment of Environmental Protection for use as sanitary landfills. Sockanathan (1991) reported that a sludge-sorbond mix can be compacted in the field provided the mix was allowed to dry for 4 days and that it can used as sanitary landfill liner.

The preceding account indicates that the current knowledge on geotechnical properties of WTP residual is limited. For the effective design and performance analysis of WTP residual disposal landfills, determination and understanding of its fundamental properties are essential. In addition, the potential use of stabilized WTP residual as a construction material can only be evaluated with the understanding of the necessary geotechnical properties.

CHAPTER 3

THE WATER TREATMENT PROCESS AND THE COMPOSITION AND STRUCTURE OF ITS RESIDUALS

3.1 Water Treatment Process and its Residuals Production

In water treatment plants, residuals are most commonly produced in the following treatment processes: presedimentation, coagulation, softening, sedimentation and filtration (filter backwash).

After surface waters are withdrawn from water courses containing a large quantity of suspended materials, presedimentation is the first step to reduce the accumulation of solids in subsequent units. The settled material generally consists of fine sands, silts, clays, and decomposed organic products.

The next process is so called coagulation where aluminum and iron salts are generally used to accomplish the removal of colloidal particles. Chemical reactions of both these salts are similar. After chemical reaction, alum and iron flocculate with water impurities and form insoluble aluminum and iron hydroxides. Approximately 0.44 pounds of chemical residuals are produced for each pound of alum added. Alum residual leaving the sedimentation basin generally has a suspended solids content of 1%. Out of this, 20-40% are volatile and the remainder are inorganic clays or silts. Alum residual from sedimentation basin may include large numbers of microorganisms, but generally does not exhibit an unpleasant odor. The residual flowrate is often in the range of 0.3 to 1% of the treatment plant flow. (Cornwell et al., 1978)

The residuals from softening by precipitation with lime ($Ca(OH)_2$) and soda ash (Na_2CO_3) vary from a nearly pure chemical to a highly variable mixture. However, many of plants surveyed were softening surface supplies, which produce a highly variable material. In this case, softening was often carried out in conjunction with chemical coagulation and therefore, may contain large quantities of silts, clays, and precipitated metal coagulants.

All water treatment plants that practice filtration produce large volumes of washwater containing a low concentration of suspended solids. The volume of backwash water is usually 2 to 3% of the treatment plant flow. The solids in the backwash water resemble those found in the sedimentation units. Since filters can support biological growth, the filter backwash may contain a large fraction of volatile solids than solids from sedimentation basins. Any suspended solids present in the water will produce an equal amount of residual. The amount of residual produced per turbidity unit is not as obvious.

Generally speaking, the water treatment plant residuals consist of fine sands, silt, clays, precipitated metal coagulants, conditioning agents, and organic matter.

3.2 The Composition of Water Treatment Residuals

As discussed above, residuals from water treatment processes are composed mainly of soil particles, chemicals, organic materials, and water. The source of the soil particles and organic materials is the colloidal and suspended materials in water sources. Chemicals are added during water treatment process.

Surface waters generally contain a variety of colloidal impurities that cause the turbidity and color. These impurities include inorganic and organic solids, ions, and microorganisms, etc. Colloids are substance whose particle sizes range from about 1nm (1nm = 10^{-6} mm) to 1μm (1μm = 10^{-3} mm) when they are mixed with water or other substance (Bohn et al., 1985).

3.2.1 Clay Mineral Colloids

Suspended inorganic solids are mainly clay fraction soil particles with a size range from 1nm (1nm = 10^{-6} mm) to 1μm (1μm = 10^{-3} mm). They are fine crystal mineral sheets resulting from the weathering products of rocks. Minerals of the clay fraction of soils commonly include the carbonate and sulfur minerals, the layer silicates, and various oxides. These solids usually do not take part or involve in any chemical reactions during water treatment processes.

The most abundant carbonate mineral is calcite ($CaCO_3$). Gypsum ($CaSO_4 \cdot 2H_2O$) is a sulfur-bearing mineral that occurs in soils usually found in arid regions. The most important secondary mineral in clay is layer silicate. When the particle size of this mineral is reduced to clay or colloidal size fractions, the influence of these minerals on the properties of the residuals is greatly enhanced. They will not only affect the plasticity and cohesion, swelling and shrinkage, but cation exchange capacity (CEC) as well. Other important constituents are so-called free oxide minerals such as allophane. Allophane is a general name for amorphous aluminosilicate gels. The composition of allophane varies widely but includes mostly hydrated Al_2O_3, SiO_2, and Fe_2O_3. Allophane may have a high CEC and a high surface area. Aluminum oxide (Al_2O_3) is called alumina. Clay contains a large proportion of it. Silicon dioxide (SiO_2) is called silica. Pure form of silica (usually called quartz) is extremely stable, for example quartz sand. (Bohn et al., 1985) But other modifications which consist of extremely small siliceous skeletons are far more reactive than ordinary quartz (Czernin, 1962). Layer silicates, allophane and the chemical additives from water treatment process can play important roles in affecting the properties of WTP residuals.

3.2.2 Organic Materials

Organic materials are mainly colloidal polymers called humus produced by the degradation of nonhumus materials undergoing enzymatic and chemical reactions. Humus is a complex mixture of brown to black colored amorphous and highly colloidal substance. It can hold up to 20 times its weight in water which prevents drying and shrinking. Humus helps to stabilize the structure by forming structural units called aggregates, which are similar to flocs. It also increases the cation exchange capacity of the soil. In general, 20 to 70% of the total CEC of many soils is due to the organic matter present in them. (Bohn et al., 1985)

The organic matter content in WTP residuals can be in some way determined by testing the total solids, the volatile solids and fixed solids contents. More discussion on the determination of these contents and other matters is presented in section 4.2 of this report.

3.2.3 Water

Water in WTP residuals can be classified into different categories. Vesilind (1979) classified the water in wastewater sludge into four categories: free water, floc water, capillary water, and chemically bound water. Vesilind et al. late (1990) presented another classification and set of definitions in which the water still was classified into four categories but with different names as: free water, interstitial water, surface water, and bound water. Huang (1979) classified the water in WTP residuals into six types in a study of sludge dewatering. By comparing the definitions between the old and the new classification of four types of water given by Vesilind, it can be found that these two classifications are very close. As far as geotechnical properties are concerned, Vesilind's old classification is considered proper for this study. The definitions of the four types of water are discussed below.

(1) Free water: This kind of water is not held to residual solids and is capable of moving freely by gravity. It is very easily removed by using dewatering equipment such as presses. Free water can also be removed by processes such as evaporation and drying due to weather, which would take a very long time. So, usually WTP residual samples collected from lagoons contain large quantities of free water, and the dewatered cake sample has very little free water.

(2) Floc water: This kind of water is free water trapped within the voids of the floc structure. Dewatered residual cake contains mostly floc water. Unless the floc surfaces are moved, the floc water trapped in them can not be removed. Significant quantities of energy, for example high remperature may be required to achieve floc water removal. This could be accomplished by processes such as heating, freeze and thaw, air drying and mechanical squeezing. Discussion on some of these processes will be presented elsewhere in this report.

(3) Capillary water: Residual sample from lagoon has a high capillary water content while dewatered residual cake usually has limited capillary water. The residual material above the water table in a lagoon is subjected to capillary action and hence contains capillary water. If this material is taken out of the lagoon and placed in a dry area, the capillary action in the residual will be destroyed. Then the capillary water will come out of the residual. The rate at which this water would flow out will be slow due to the low capillary-permeability of the residual. In due course of time, the surface on which the residual is placed will become moist. Also, vibration during shipping of residuals will try to force all of the capillary water and some of the floc water out of the residuals. Observations listed in Table 2 regarding the presence of water outside some of the samples could be attributed to the movement of capillary and floc water as explained in this section.

(4) Bound water: This kind of water is chemically bound (adsorbed) within the molecular structure of colloidal solids. Water molecules are held together by hydrogen

bonding. Due to the elliptical shape of these molecules, the centers of gravity of the positive and negative charges are not the same. So, the water molecules tend to assume a configuration such that their positively charged portions are close to the negatively charged surfaces of the colloids present in the WTP residuals. These water molecules are highly adsorbed and they can only be removed by thermochemical destruction of the particles. Great deal of energy has to be expended in breaking the bond between the water molecules and the negatively charged surfaces. This could be accomplished by heating the residual to a very high temperature or probably by applying a very large amount of electrical energy.

Change in the water content (solids content) of residual material is the greatest single cause of variation in the geotechnical properties. It will not only alter the floc structure and the particle sizes of the solids but also will change the ion concentration and complex formation within the residuals.

Generally, geotechnical behavior of WTP residual material is not only a function of the physical and chemical composition of its solid contents but also a function of the type, amount, and chemical nature of the pore fluids. As the structure and the solid content change, interactions between the solid and liquid phases such as cementation take place. These will affect the geotechnical properties such as compaction (handling), shear strength and permeability.

3.2.4 Chemicals

Chemicals added during the water treatment process are mainly softeners (lime, etc.) and coagulants (lime, alum, ferric chloride, and ferric sulfate, etc.). Some water treatment plants use lime as conditioning agent in dewatering process. They are used to promote colloid aggregation by destroying the forces that stabilize colloidal particles. When these destabilized colloidal particles move toward each other and become attached during the sedimentation or dewatering process, flocculation occurs.

3.2.5 Others

Raw water usually contains some metal ions like Ca^{2+}, Mg^{2+}, Fe^{3+}, etc. which cause hardness and impart color to water. During the water treatment process, hardness and color are removed by softeners. Colloidal particles are removed from water by the addition of coagulants which induce flocculation. Resulting residue may be retained in soils by cation and anion exchange, precipitation, weak electrostatic attraction and as a complex with organic matter.

3.3 The Structure of Water Treatment Residuals

Clay colloidal impurities in receiving water usually carry negative charges. Since like charges repel, these similarly charged colloids are held apart from each other by their electric charges and thus are prevented from aggregating into larger particles. When coagulant is added (like alum or ferric sulfate, etc.), it will dissociate to yield Al^{3+} or Fe^{3+} ions, which then hydrate to form a variety of aquametal complexes such as $Al(OH)^{2+}$, $Al(OH)_2^{+}$ and other polynuclear species such as $Al_8(OH)_{20}^{4+}$. These species are capable of being adsorbed at the surface of colloidal particles, reducing the surface potential.

The negative charges of colloids are neutralized by a swarm of positive ions in the solution called diffused double layer (DDL), resulting in the destabilization of the colloidal particles. The DDL imparts a net positive charge at the edges of the colloidal particles, so when these particles are very close together (for example during sedimentation or dewatering), this edge charge can participate in an edge-to-face linkage between particles to form a so called floc-structure (Figure 1) and this process is called flocculation. This structure is sometimes also called salt type floc-structure. Skeletons of floc structure are the clay mineral particles which are assembled to each other by secondary valence forces (Lambe, 1969). The floc structure is a highly oriented solids particle arrangement. Re-orientation of these particles will cause a unique phenomenon called thixotropy.

Water filled in pore spaces is called pore water. When the residuals are in fresh conditions (immediately after they are produced), pore water contains high concentrations of ions from chemicals added during water treatment. Change in pore water content will alter the concentration of ions in pore water, causing the development of cementation. Detailed discussions on cementation and thixoropy will be presented in the succeeding chapters.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Sample Collection

Samples of WTP residuals were collected from ten water treatment plants as shown below. Relevant information regarding these plants is summarized in Table 2. For convenience of discussion, symbols were assigned to each of the samples collected. These symbols are also listed in Table 2 and will be used throughout this thesis.

4.2 General Chemical/Physical Properties

Information on the general chemical/physical properties of the residual samples collected for this research is based on the work of Tian (1993). Major test results are shown in Table 3.

Total solids contents were determined as soon as samples were received or collected. A well-mixed WTP sample was placed in a weighing dish and dried to constant weight in an oven (Fisher, BLUE M) at temperature of 103 to 105 °C. Volatile solids were determined by placing the sample in a furnace and heating to a temperature of 550 ± 50 °C. The remaining solids represent the fixed solids, while the weight lost is due to the volatile solids. The results are presented in Table 3. It can be found that WTP residual sample collected have high level of volatile solids content. Usually the organic materials will be burned off into volatile matter under the temperature of 550 ± 50 °C while the inert soil minerals will remain as fixed solids. So it is believed that volatile solids content reflects the organic matter level to certain degree.

The cation exchange capacity (CEC) also servers as an important indicator of organic matter level in a different way. CEC is defined as the sum of the exchangeable cations of a WTP residuals expressed in milliequivalent for 100 gram of dry residual. The CEC value is dependent on the amount and type of organic matter and clay in residuals. Organic matter increases the CEC value. Usually from 20 to 70 percent of CEC of many soils is caused by organic matter (Bohn et al., 1985). CEC value also reflects the ability of a WTP residual to hold metals by several other mechanisms.

Soils vary in CEC from less than 1.0 to greater than 100 meq/100g. The average CEC of soil is about 10 to 40 meq/100g (Bohn et al., 1985). As shown in Table 3, the CEC of residual samples tested are much higher than those of soils. This indicates that WTP residuals usually have higher organic matter content than normal clay soils, and also may have higher ion concentrations. Major ion contents including iron, aluminum, calcium, sodium, and manganese in each residual samples tested by Inductively Coupled Plasma - Mass Spectrometry (ICP/MS) are also listed in Table 3.

4.3 Particle Size distribution of Solids

Particle size distribution of solids can be determined by sieve and hydrometer analyses.

4.3.1 Sieve Analysis

Most samples collected had a large percentage of solids (above 95%) passing No. 200 sieve (0.075 mm). Since sieve analysis is only applicable for soils with high percentages of particles passing No. 200 sieve, grain size determination by sieve analysis was not considered appropriate for WTP residuals and hence was not performed.

4.3.2 Hydrometer Tests

The hydrometer analysis utilizes the relationship of the velocity of freely falling solids in an infinite fluid medium with the diameter of the solids, the specific weights of the solids and the fluid, and the viscosity of the fluid. The relationship is expressed by Stokes' law. In the test, a known quantity of sample is dispersed in water in a cylinder and agitated thoroughly into a thin suspension. The change in density of the suspension at known depths is recorded as the solid phase settles out according to Stokes' law.

Tests were first conducted from the dry side according to the standards. The oven dried (105 °C) samples were broken by a rubber tipped pestle, then proper amount of the dried sample (50g in weight) is placed in a 1000ml cylinder. Water was added and the mixture was left overnight for thorough soaking. During testing, it was found that all the solids tended to sink to the bottom of cylinders quickly leaving clear water on top. It is believed that this could be attributed to the interparticle cementation occurring during the drying process which increased the size of solids by destroying floc structure and causing ion adsorption to solids particles. This phenomenon will be furtherly discussed in detail in section 4.7.

A solution of sodium hexametaphosphate $(NaPO_3)_6$ (recommended by the standard) with different concentrations (2%, 5%, 10%, 15%, 20%) was used as a dispersing agent (5% is the most commonly used concentration recommended by the standard). Also tests were run by altering the pH of the solution. But it was not possible to settle the solids from the suspension. This could be a fact that the cemented structure of the floc could not be altered by all of the above procedures.

Tests were then attempted from wet side. Fresh samples were mixed with water and agitated in order to disturb the interparticle bond. For most of the residual samples collected (except for samples JCD and FLD), the suspension of residual in water stratified into two layers instead of the solids settling down in accordance with Stokes' law. The suspension then became a fluffy material and a water-solids interface appeared in a few seconds. This interface moved down slowly pushing the clear water up and finally stabilizing at a certain level. It was observed that for samples JCD, PVD, NCD, MWD, SLD and SLDF, which have a predominant high lime content (Table 3), a white gel material was formed on top of the water-solids interface.

The dispersing agent $(NaPO_3)_6$ is most commonly used in hydrometer test for soil. This chemical is soluble in water up to 70% solution and has pH value of 7.2. It does not react chemically with most natural soils, but it neutralizes the charges on soil particle surfaces (usually negative charge) to prevent the particles from sticking together and creating large particles. When high concentrations of dispersing agent (up to 1:1 ratio to dry solids) were used, the water-solids interface still appeared but dropped more slowly and finally stabilized at a level higher than that of the suspensions with the addition of dispersing agent with no or low concentration. It seemed that dispersing agent could prevent aggregating to some degree, but was unable to stop the strong tendency of WTP residuals to reflocculate. Efforts were also made by adjusting the pH value with the addition of acid or basic solutions, but the suspension did not settle according to Stokes' law. We believe that this could be attributed to the thick and the stable DDL formed in the residuals due to the high ion concentrations caused by the chemicals added during the water treatment process. The dispersing agent probably was unable to alter this DDL and prevent re-flocculation.

On the other hand, it is believed by the authors that the high viscosity of gel material in some WTP residuals also plays a critical role in preventing the settling of solids according to Stokes' law. The gel material is formed due to the presence of lime (added as softener or conditioning agent) and silica in allophane (Czernin, 1962). The term "gel" is used to describe a cohesive substance of individual colloidal particles. This "mineral glue" could cause a so-called "hydraulic hardening", and contribute to the development of cementation (discussed further in section 4.1.8).

For normal soils, the DDL is usually very thin, so it will not interfere with the functioning of dispersing agent. In the production of WTP residuals, coagulants added to the suspended colloidal impurities in water neutralize the charges on the solids. In this process, a strong bond is created between the colloids and the chemicals resulting in a very stable DDL. It is very difficult to destabilize this DDL with the dispersing agents used for hydrometer analysis for normal soils. This inference, in our opinion, can be used to explain the difficulties experienced in the course of these studies during the hydrometer tests.

Hydrometer test for sample JCD could be conducted with a 5% dispersing agent solution. A typical grain size distribution curve obtained from this test presented in Figure 2 shows that this sample is composed mostly of silt-sized solid particles. This may be attributed to the high silt content in the receiving water.

Sample FLD had been aged in drying bed. It was in a dry, brittle solid condition when it was received. When it was broken into powder and mixed with water, the solids particles sunk down to the bottom of the cylinder very fast. A probable explanation for this occurrence is provided here. During the aging period when all the floc water was evaporated, the floc structure was destroyed. Thus the particle size was increased by the inter-particle bond caused by cementation, causing the particles to sink.

4.4 Specific Gravity of Solids Tests

The specific gravity of solids is defined as the unit weight of the particle divided by the unit weight of distilled water at 4°C. It is an important parameter which can be used to classify soils and to compute other soil parameters. This property is influenced by the chemical composition of the solids. In this test, removal of air from the sample can be accomplished either by applying a vacuum to the sample or by heating it. Since heating may result in loss of volatile solids, air was removed by the application of vacuum to the sample.

Values of specific gravity of solids of all the WTP residual samples are shown in Table 4. It ranges from 1.87 up to 2.71 with an average value of 2.51. Most of the primary soil minerals have specific gravities in the range 2.55 to 2.75 with a mean value of 2.65. The clay minerals generally have a slightly higher specific gravity value ranging from about 2.70 to 2.85 with a mean value of 2.75. It is found that specific gravity values of all residuals are less than those of clay soils. This is due to the fact that usually WTP residuals have high organic contents which will decrease the specific gravity. It can be observed that except for FLDM, WQD, JCD and RWA, the specific gravities of solids of all other residual samples are almost the same. They are in the range of 2.61 to 2.67.

As discussed early, the volatile solids content (showed in Table 3) generally reflects the organic content. It can be noticed that the specific gravity basically increases with the decrease in volatile solids content, i.e. the organic content. Sample FLDM has the lowest specific gravity value of 1.87 of all the WTP residuals tested. This could be attributed to its high volatile solids content (63.41%) and low iron content (0.038%). The sample was black in color which is caused by its high organic content. Residuals WQD and JCD have specific gravities of solids of 2.27 and 2.38 respectively. These are lower than the observed range of 2.61 to 2.67 and can be attributed to the high volatile solids present in these samples. Sample RWA has the highest specific gravity value of 2.71 of all the WTP residuals tested even though it has a high volatile solids content. The high value of specific gravity of solids in this sample is due to its high iron content, resulting from the addition of ferric chloride during the treatment process. It is to be noted that of all the residual samples tested, sample RWA has the highest iron content.

4.5 Liquid Limit and Plastic Limit Tests

The liquid limit is the minimum water content at which the soil will flow under a specified small disturbance. Plastic limit is the minimum water content at which the soil can be deformed plastically. These two parameters are used for classification of fine grained plastic soils. Since WTP residuals are plastic and fine grained, these limit tests were performed. These tests were conducted from the wet side, meaning that the water contents of the samples were gradually decreased. Usually, for normal soils, the procedure is to conduct the test by completely drying and adding water. This technique is referred to as one in which the test is performed from the dry side.

Results of liquid limit and plastic limit tests are presented in Table 5. It is found that WTP residual samples have higher liquid and plastic limits than normal silt or clay type soils. The residual samples which have high natural water contents usually possess high liquid and plastic limits. Samples which have low natural water contents have low values for these limits. This observation can be explained by the fact that the samples with high natural water content have a high water retaining ability which may be caused by high organic content and highly developed floc structures.

It can be noticed that sample JCD has a liquid limit of 329.2% which is about the same value as its natural water content of 329.2%. The sample was in a cake form at natural water content, but when it was squeezed, it became a paste without any strength. The authors believe that at its natural state, the sample possessed a floc structure with significant amounts of trapped water. When squeezed, the floc water came out and created a liquid condition. With no water added, the sample lost its shear strength. Thus the water content of the sample was at its liquid limit. The residual behaves like a sensitive fine-grained soil in the sense that the strength is reduced upon disturbance. So this phenomenon supports the contention that a floc structure forms during the dewatering process (discussed further in section 4.7).

The liquid and plastic limit values for sample MQD could not be determined because it had a high sand content. The residual was excavated from the lagoons and dumped in the drying bed. At that time, the material got mixed with sand in the underdrains. Sample FLDM is nonplastic, because the sample had been aged in drying bed wherein it lost most of the water. When the sample was received, it was in a dry, brittle condition, and did not exhibit any plasticity. Sample HWD has a high content of sand which was used as a drainage material in drying bed, so the plastic limit of that material could not be determined either.

4.6 Weight Loss Observation Tests

The moisture content of soil sample is usually determined in the laboratory by drying the sample in an oven at a temperature of 105°C. Since WTP residuals usually contain volatile substances and chemical additives, drying at high temperatures may result in loss of solids in addition to the loss of water. Hence, use of proper procedures for drying (without loss of solids) is critical for accurate determination of solids (moisture) content. In order to arrive at an acceptable drying temperature for determination of moisture content, the weight loss observation test was designed. In this, a series of moisture content tests was conducted on each sample at different temperature conditions. The results are summarized in Table 6.

It can be inferred from Table 6 that the samples with high natural water contents (initial water contents in tests) had higher weight losses than those with low natural water contents. Since the weight losses under room conditions (24±2°C) and under conditions of drying in low temperature oven (35-40°C) were very close to those under high temperature conditions (105°C), it can be concluded that drying at a temperature range of room temperature to 105°C will not significantly affect the moisture content determined. As a result of these tests, it was concluded that in laboratory testing, moisture contents of WTP residual samples could be appropriately determined at a standard temperature of 105°C. Alvi et al. (1986) performed similar tests on steel industrial sludge samples and came up with the same conclusions as the author regarding the procedures for drying.

4.7 Compaction Tests

In compaction tests, mechanical energy is applied to the soil to rearrange the particles and reduce the void ratio in order to increase the dry density by removing the air in the voids. Efforts to achieve high dry density are related to the moisture content (or solids content) of soil. For normal soils, the compaction curve (dry density vs. moisture content or solids content) is of one hump form under the same compaction energy exhibiting a well-defined peak. Therefore at optimum moisture content or solids content, maximum dry density can be obtained based on this compaction curve for a certain type of soil. Compaction tests for soils are conducted from dry side (from lower moisture content to higher moisture content). Usually soil samples are oven dried under a temperature of 105°C, then water is added and compaction test is conducted at a certain moisture content. Then other tests are conducted at increasing moisture contents by adding more water to the sample.

Compaction tests were performed from dry side for each WTP residual sample following the standard procedure. All compaction curves obtained were of the one hump form (Figures 3, and 4). Maximum dry density and optimum solids content values obtained from these tests are presented in Table 8. It is observed that the optimum dry densities are in the range of 5.4 to 14.64 KN/m^3 corresponding to optimum solids contents ranging from 50% to 80%. In all of these tests, the WTP residuals behaved as granular nonplastic soils.

While performing these tests, it was found that some residual samples behaved differently at the same moisture content approached from dry side and from wet side, in which samples at different moisture contents were prepared by air drying starting from their natural water contents. Therefore, standard compaction tests were also conducted from wet side. Residual samples were broken up and spreaded on big pans and stored in room. Samples were turned, mixed and spreaded periodically in order to keep the moisture loss pattern uniform. Under room conditions, samples were air dried.

Compaction tests were performed as soon as the samples became dry enough to be compacted. Results are presented in Table 7, and Figures 5 and 6.

It can be noticed that some curves do not exhibit the characteristics of one hump form (Figure 5). Instead, the dry density increases with the increasing solids content, and thus the compaction curves exhibited a monotonously increasing pattern of curves. Such moisture-density or solids content-density relations are rarely observed in normal soils. This phenomenon could be attributed to the floc structure of WTP residuals and cementation occurring in them upon loss of water. During drying, the floc water is gradually removed from floc spaces. Edge-to-face bonding is gradually lost and pore spaces collapse. The flocs are held together to form a new inter-particle bonding. Finally floc structure gets destroyed while the particle size increases leaving behind a dry sandy material. Due to this, the dry density increases with decreasing moisture content.

On the other hand, some of the ions (Ca^{2+}, Al^{3+}, Fe^{3+}, etc.) which were in a soluble state in the floc water (they may be in aquametal complex form) may be adsorbed in solids particles during drying process. New inter-particle bonding with increasing particles sizes occurs. This phenomenon is called cementation (Scott, 1980). The "mineral glue" which causes "hydraulic hardening" is also believed to contribute to cementation development

When the samples are rewetted after drying to certain degree, water can not break the strong adhesion due to inter-particle bonding to recreate the original floc structure. Thus the residual sample behaves like a silt or a sand. So all compaction test results from dry side exhibit behavior similar to those of normal sandy soils. This pattern of behavior was observed on water treatment samples by other researchers also (Wang et al., 1992).

The phenomenon discussed in the previous paragraph is similar to thixotropy characteristics exhibited by certain types of soils. Thixotropy is the loss in strength resulting from the reorientation of soil particles. Even after a long period of time, full strength is not restored (Scott, 1980; Lambe et al., 1969). Thixotropic hardening is defined as an isothermal, reversible, time-dependent process occuring under conditions of constant composition and volume, whereby a material stiffens while at rest and softens or liquifies upon remolding (Mitchell, 1976). WTP residuals exhibit thixotropic hardening which refers to an increase in strength due to cementation and reorientation of floc structure. This process is irrecoverable, as it caused by the change in inter-particle bonding. The edge-to-face type bonding of floc structure of WTP residual exhibits a highly oriented particle adhesion pattern. When the floc water is removed, particles are reoriented and bonded together to form larger size particles. This irreversible process is noted in the compaction tests from dry side. The compaction curves from these tests not only differ in forms from those from wet side, but also have higher optimum dry density and optimum solids content values. This is due to the fact that larger particles (resulting from reoriented floc structures) have higher density. These exhibit characteristics similar to those of sands and possess water retaining ability than those with smaller particle sizes (corresponding to the original floc structure).

It can be noticed that the compaction curves from wet and dry sides differ not only in form (one-hump or increasing) but also in the range of solids contents in which tests can be performed. The optimum dry densities and optimum solids contents also differ. Usually the compaction curve from wet side is flatter than the one from the dry side. The optimum dry density for tests done from wet side is higher than that from dry side. As explained earlier, the increase in dry density can be attributed to the thixotropic hardening and cementation developing in WTP residuals. These processes are influenced by the clay mineral properties, the type and the amount of chemicals added, dewatering methods, initial solids contents, organic and metal contents etc. As explained in the following paragraphs, the amount of thixotropic hardening and cementation may be predicted by a comparison of their compaction behavior from wet and dry sides.

Figures 7 to 15 present a comparison between the compaction curves from both wet and dry sides for some of the residual samples tested. They can be roughly divided into three categories.

(1) Samples JCD and RWA: Compaction curves differ not only in form, but in the solids content range in which the residuals can be compacted, and the optimum solids contents and dry densities (Figures 7 and 8). This type of residual samples may have the highest level of thixotropic hardening and cementation development.

(2) Samples MQD, PVD, SLDF, SLD, NCD, and HWD: Compaction curves are all of one hump type; but the curves from wet side have a wider range of solids contents in which compaction can be performed. The optimum values from wet and dry sides are still different but much closer than those obtained in JCD and RWA samples. These residual samples also have medium levels of thixotropic hardening and cementation development. (Figures 9, 10, 11, 12, 13, and 14)

(3) Sample MWD: Pattern of compaction curves, the ranges of solids contents in which compaction can be performed and the optimum values from wet and dry sides are all very close (Figure 15). This residual sample may have a very low level of thixotropic hardening and cementation development.

4.8 Freeze/Thaw Tests

If WTP residual is dumped in monofills, it will be subjected to cycles of freezing and thawing. In order to determine the stability of the residuals under these conditions, freeze and thaw tests were conducted. Cylindrical specimens of diameter 33 mm (1.3 inches) and length 71 mm (2.8 inches) were prepared from each residual sample at its original (natural) condition. If the samples were very wet and could not be compacted in the condition in which they were received, they were air dried under room conditions. Then the specimens were stored in the freezer at a temperature of $-5\pm0.5^{o}C$ for 24 hours. After this, the samples were allowed to thaw under room conditions for 24 hours at a temperature of $24\pm 2^{o}C$. This 24+24 hours cycle of alternate freezing and thawing was repeated 12 times (i.e., twelve cycles), continuously for each specimen. The weight loss and volume loss experienced by the samples at the end of 12 cycles were recorded and presented in Table 9.

It was observed that all the samples experienced weight loss and volume reduction during the testing; cracks formed on the surface of most of the samples; the surface of the material became dry, loose, crispy, and even scaled off. Specimens experiencing large reductions in volume and weight loss percentages could hardly remain intact after the testing and some of them fell apart.

From the results of these tests, it can be inferred that the weight loss after twelve cycles is influenced by initial water content. Specimens with high initial water contents experienced high losses in weight while low weight losses were observed for samples with low initial water contents. This indicates that major cause of weight loss during freeze/thaw is the moisture loss caused by evaporation. There could also be other contributing factors to this phenomenon such as loss of organic matter. Volume loss is high for samples with high initial water content. The presence of organic matter tends to increase the volume loss by reducing the potential for cementation development.

Sample MQD had a high initial water content of 549.4% (15.4% solids content). It experienced a relatively small volume loss of 20%. But the corresponding weight loss was high (80%). This can be due to the fact that water was removed from the voids and shrinkage started to develop. Cementation developed and prevented significant volume loss. The very small organic content of this sample was quite conducive to the occurrence of this phenomenon, since organic matter tends to prevent cementation. The above observation is valid for all the samples tested except for WQD, PVD and RWA. The significant volume losses of RWA, and WQD can be attributed to the reduction of development of cementation due to their high organic contents. So there is insufficient bond to resist the disturbance to which the structure of the solid particles is subjected to by ice crystals forming in the pore spaces (Martel, 1991). The other interesting thing is that these two samples happened to be the only samples among the ten tested residual samples in which ice crystals were observed on the surfaces of specimens during the first and the second cycles when the specimens were taken out from the freezer after twelve hours. This phenomenon indicates that the structure of these two samples has very low resistance to freeze and thaw. Freeze/thaw seems to be a very promising alternative for dewatering and volume reduction for these two samples.

4.9 Wet/Dry Tests

WTP residuals in monofills are also subjected to alternate wetting and drying. The durability of WTP residuals to the above phenomenon is investigated by conducting wet/dry tests. Cylindrical specimens of diameter 33 mm (1.3 inches) and length 71 mm (2.8 inches) were prepared from each residual sample at its original (natural) condition. If the samples were very wet and could not be compacted in the condition in which they were received, they were air dried under room conditions. Then the specimens were stored in a low temperature oven (60±2°C) for 24 hours followed by another 24 hours in a moisture chamber (28±2°C). This 24+24 hours cycle was repeated for 12 times, i.e., twelve cycles, continuously for each specimen. The weight loss and volume loss were recorded when tests were finished and shown in Table 10. It can be observed that the weight and the volume losses followed patterns similar to those for freeze and thaw.

It was observed that all the samples experienced weight loss and volume reduction during the testing and the values are very close to those obtained by freeze/thaw tests. Cracks formed on the surface of most of the samples and the material became dry, brittle, and hard. Specimens made of some of the residual samples broken into chunks (JCD) or loose, crispy, and sandy material (MQD, WQD, RWA, and HWD) while the specimens made of sample PVD, MWD, NCD, SLDF and SLD remained intact.

The specimens made of sample FLDM collapsed because the residual sample had been aged in lagoon. When it was received, it was in a dry, brittle chip state without exhibiting any plasticity. Sample was broken to a powder form and mixed with water in order to make specimens. Since sample essentially was nonplastic with very little cohesion, it disintegrated into a powder upon wet and dry testing.

On the other hand, sample SLD, which is also an aged sample like FLDM, remained intact after wet-dry tests. The study of the reasons for this is very enlightening. It was noticed that when this sample was received, it was still in a paste form. It was soft, sticky, and plastic which indicates that the sample was still holding most of its floc water that somehow was not removed from floc spaces during the aging period. Based on its compaction and unconfined compression strength characteristics, it seems that Samples SLD and SLDF exhibit quite similar behavior. It is interesting to note that while SLD is a sample aged for about a year, SLDF is a fresh sample. When sample SLDF was received, a large amount of standing water was observed on the surface of sample. This indicates that the sample had a high free water content. Thus it is appropriate to believe that during the aging period while sample SLD was in lagoon, the water removed was mainly free water and capillary water. By the time it was collected, most of its floc water was still trapped in the pore spaces. Thus aged sample SLD still behaved like its corresponding fresh sample SLDF.

Further study as to why samples PVD, MWD, NCD, SLD and SLDF remained intact revealed that these samples have high calcium contents and relatively low volatile solids' contents (Table 3). In these samples, gel formation was observed during hydrometer testing (discussed in section 4.3). From these observations, it can be concluded that hydraulic hardening that may have developed probably improved the durability and stability of these samples. Among them, samples PVD, SLD, and SLDF not only remained perfectly intact, but had very smooth surfaces without any cracks. By examining Table 3, it can be noted that these three samples had the least volatile solids content, i.e., the lowest organic content. It was also noticed that when these two samples were collected or received, they were of a light color (gray and greenish gray respectively) instead of the normal black or dark brown color. During the wet/dry process, most of the floc water was removed and cementation was developing very well without the interference of organic material. On the other hand, carbon dioxide present in air could have caused hardening of lime to a stone-like material.

Sample MQD has a very low volatile solids content and a high aluminum content. It can be inferred that cementation was highly developed during both the freeze/thaw and the wet/dry testing due to its relatively very low volume loss even though it had the highest initial water content. But the specimen was unable to remain intact. This is due to its high sand content. The sand from the underdrains in the lagoon got mixed with the residual during excavation from lagoon. Because sand is a very stable silicate mineral (quartz) without any electrostatic attraction, ionic cementation will not occur.

Sample JCD has a high calcium content. But the sample broke into chunks after wet/dry testing. It was observed that the surfaces of these big chunks were still smooth. This could imply that the cementation and hydraulic hardening were well developed, but the process was interfered by the presence of relatively high organic matter (volatile solids content up to 34.45%).

4.10 Direct Shear Tests

The direct shear test is designed to investigate the shear strength in order to predict the bearing capacity and slope stability.

Standard direct shear tests were conducted on specimens made of each residual sample at the water contents as close as possible to the natural water contents. This will be close to their liquid limits but within the plastic range (water content range between liquid and plastic limit). As the residual in the monofill undergoes drying, cementation develops. This increases the shear strength making the residual denser and more stable. It can be stated that at the time the residual is dumped in landfill, it has the lowest strength and stability due to its high water content. So this critical situation was chosen to be investigated in the direct shear tests. When the water content is lower than liquid limit, sample is in a nonplastic state and is unable to be made into specimen. Thus residual samples at natural water contents lower than liquid limits were air dried under room conditions. This was carried out until their water contents were above their liquid limits and specimens were then prepared for testing. The results are included in Table 11.

It can be noted that the cohesion values of these samples are generally very low and they increase if the water content is decreased. This is because that at a water content close to liquid limit, residual sample still has sufficient amount of free and capillary water, and cementation between particles has not begun to develop. Thus the higher the water content, the higher the free water content, and the lower the cohesion value. Broadly speaking, the cohesion of colloidal material particles is caused by "gel" materials (Czernin, 1962).

Sample JCD has an extraordinary high cohesion value even though it has a high water content. This is perhaps caused by its high thixotropic hardening and cementation which has been discussed in section 4.7.

It should be pointed out that the friction angle values obtained from these tests actually do not reflect the friction between solids particles in the case of WTP residuals. The flocs and not the individual particles are sheared in these tests. During the movement of one floc over the other, floc water escaping from the pores, acts as a lubricant and reduces the friction between the flocs. Organic matter also tends to lubricate the floc surfaces reducing the friction between them. The friction angle values for most samples are in the range of 15 to 25 degrees for most samples. Samples WQD and RWA have low friction angle values due to their extremely high water contents. The low friction angle of sample MQD could be caused by its sand impurity and the friction measured is that between the floc and the sand. Sample FLDM has the highest value of friction of all the samples. This is because the aging effect had increased the particle sizes and hence the friction.

4.11 Unconfined Compression Tests

The unconfined compression test is used for obtaining the shear strength of residual samples to predict their stability in landfill. Tests were conducted at different solid contents to investigate the effects of drying and aging.

Cylindrical specimens of diameter 33 mm (1.3 inches) and length 71 mm (2.8 inches) were made for each residual sample at different water contents from wet side. Load was applied in vertical direction on each specimen at controlled rate until the failure was reached. The strength vs. solids content curves for these samples are plotted in Figures 16 and 17, and their main characteristics, parameters and other data for interpretation are listed in Table 12.

The strength vs. solids content curves fall into two categories: increasing type and one hump type. They are plotted in Figures 16 and 17 respectively. It can be observed that generally samples exhibiting increasing type patterns can reach very high strength levels, for example, samples SLD, SLDF, NCD, and FLDM (Table 12). This could be caused by well-developed cementation. On the other hand, these samples usually have low plasticity indices. Plasticity index is indicative of the range of water contents over which the sample is in plastic condition. Clays with low plasticity indices will have a low volume change potential associated with the change in water content. That is low plastic clay soils will experience small reductions of volume due to removal of water. This phenomenon can be observed from the wet/dry and freeze/thaw tests in which the residual samples experienced low weight and volume losses and remained intact after testing. Thus the cementation develops uniformly and thoroughly. Also, since the volume changes are small, the structure experiences very little disturbance, resulting in high strength. Unconfined compression strength is an undrained strength. Soils with low plasticity possess higher undrained shear strengths than those with high plasticity. The residuals have low or no plasticity and hence they exhibit high unconfined compression strengths.

The strength vs. solids content curve of sample MWD does not present an increasing pattern although it has a very low plasticity index of 4.0. The testing could be conducted over a very limited range of solids contents ranging from 82.5% to 91.3% with the optimum solids content of 88.6%. By examining its compaction curves from both wet and dry sides (Figure 15) as discussed in section 4.7, it can be noted that these curves are similar in form with close optimum solids content and optimum dry density values. All these indicate that this sample just behaves like a normal silt-clay type soil. This sample has some organic content and the amount of chemicals added during treatment is quite small. This means that the ion content available for cementation is limited. The organic content hinders cementation development. Due to this, there is very low thixotropic hardening.

Clays with high plasticity indices have a high volume change potential associated with the change in water content. That is highly plastic clays soils experience large reductions of volume due to removal of water. Thus the difference in dry and wet strengths is very high for such soils. This phenomenon can be observed in residual samples JCD, PVD, WQD and RWA. The strength increases at first with increase in solids content. Then, the strength starts to decrease with decrease in solids content. Thus the strength vs. solids content curves exhibit one pattern. As discussed in section 4.7, sample JCD and RWA may have high cementation development due to their dramatical difference of compaction behavior between wet and dry sides. But these two samples did not exhibit high strength as expected. It could be noticed that they have high plasticity values which cause the increasing pattern of compaction curves from wet side. This could mean that the cementation develops very gradually during the drying process due to the high floc water content. But because the shrinkage tends to increase, the particle bonding will develop unevenly, and thus causes micro fractures and cracks throughout the specimens. So the strength, which is influenced by macroscopic behavior, does not increase when the solids content reaches a certain degree. Thus strength is not only related to the degree of cementation development, but also to plasticity.

4.12 Consolidation Tests

When soil is subjected to pressure, the stress between the mineral skeleton (effective stress) will increase as the pore water drains out. This process is called consolidation. The amount of water that flows is related to the pressure and the soil properties. The rate of this flow is related to the coefficient of permeability K_v. With increasing loads, voids decrease. This is reflected by the compression index C_c. When the load is removed, soil skeleton will rebound, which will cause an increase in voids. This is related to the swell index C_s.

The consolidation tests were performed at initial water contents in the range between liquid and plastic limits, i.e., the plastic stage. This enabled the samples to develop effective stress as the pore water drained under loading. Sample FLDM was in the form of brittle pieces without exhibiting any plasticity when received, so it was ground to a uniform fine powder and sufficient water was added and the sample was soaked for two days in moisture chamber before testing. So the test was performed at a water content greater than that at which the sample was received. The results are presented in Table 13.

It was noted that the compression curves (settlement dial reading vs. log time) were not typical of the behavior displayed by ordinary soils. A group of representative compression curves for sample JCD is shown in Figure 18. All the compression curves show uniform settlements except for the one under the first load. These curves indicate high secondary settlements. As a result of this time-settlement behavior, the graphical techniques that are customarily used to determine the coefficient of permeability K_v, and compression index C_c are not directly applicable for this test. However, among these time-settlement curves, it can be noticed that the settlement curve under the first load (the lowest load) is of a different pattern than those for higher loads. It is smooth and shows the characteristics of typical settlement curve for normal soil except at the end of the curve. Here, a little drop, and a distinct break at approximately 3 hours duration of time followed by a relatively constant drop are observed (Figure 19).

The natural residual sample JCD was in hard cake form. In order to make specimens to fit the consolidation ring, residual cakes were broken and kneaded to obtain a uniform paste. Thus the floc structure in the cake was destroyed to a great degree. So some of the floc water was squeezed out and became capillary (even free) water that was held in between particles. Hence, the sample became a plastic paste material. During the initial few hours after first load was applied, the development of effective stress predominately contributed to settlement due to the drainage of free and capillary water. So the consolidation curve under first load resembles the pattern of normal soils.

As time went on and loading increased, the capillary and free water available for drainage became less and less, and the settlement caused by the development of effective stress was reduced by the development of floc structure. This floc structure is formed after the first load is applied, in the same manner in which the cakes were formed in mechanical dewatering process. Because this type of fine floc structure has a higher stability and pressure resistance than normal soil mineral skeleton, and the floc water has a higher pressure than the pore water in normal soils, it is more difficult to drain the floc water than the free or the capillary water. So the water expulsion process becomes more time-dependent than that for natural clayey soils. This effect is very well demonstrated by a high secondary consolidation under each load. It must be pointed out that the effective stress in floc material might probably be contributed partially by deformation and re-orientation of floc structure. According to the interpretation on thixotropic hardening by Mitchell (1976), remolding destroys the previously equilibrated system and causes particle displacement and reorientatiion. As a result, the balanced interparticle forces are disrupted. After remolding, the system will tend to return to the original equilibrium condition, possibly involoving particle reorientation or readjustment of the diffuse double layer or both. In view of this, the settlements under succeeding loads do not occur as smoothly as that under first load. So after first load, the normal effective stress theory does not apply and the consolidation behavior is quite different from that in natural clay soils. After testing was completed, the residual specimens in consolidation rings were in hard cake form just like the mechanically dewatered cake. This provided an evidence of a highly developed floc structure due to consolidation.

Therefore, it is considered proper to use the time-settlement curve under first load to determine the coefficient of permeability. Consequently, the value of K_v for sample JCD is computed to be in the order of 10^{-7} cm/sec based on the 50% consolidation time derived from Figure 19. Since K_v is in the range of clay soils, which is consistent with its colloidal formation, it was proved to be a suitable method. The low permeability of WTP residuals could be due to fine colloidal particles and tightly held floc structure and may be due also to the mineral gel that is seen to form (as discussed previously).

It should be pointed out that this K_v value determined does not represent the actual permeability property of WTP residual. The actual K_v value will be smaller, since drainage of floc water is more difficult than free or capillary water. On the other hand, this value may increase in a landfill, if the particle sizes increase by aging due to the development of cementation. Development of cracks due to weather conditions such as freeze/thaw and wet/dry will also contribute to increase the permeability of WTP residuals in monofills after a period of time.

In order to determine the compression parameters that are customarily used in ultimate settlement analysis, e-log p curves were obtained. For most natural soils, there is a well-defined feature on the curve which makes it easy to determine pre-consolidation pressure, and compression index C_c. However, in the case of WTP residuals, the e-log p curves do not exhibit the well-defined features in the vicinity of the maximum pre-consolidation pressure. But as shown in Figure 20, it is of a wide radius and appear somewhat similar to those of a stabilized or moderately disturbed soil. As a result, the accuracy in the determination of these parameters via graphical means may not be as much as those for natural clays. Nevertheless, values for pre-consolidation pressure P_c, compression index C_c, and swell index C_s were determined and presented in Table 13. Alvi et al.(1986) observed similar patterns of behavior based on the tests on steel industrial sludge samples and adopted similar techniques for the determination of these parameters.

A review of parameters presented in Table 13 indicates that the WTP residuals are highly compressible. The values of compression index C_c varies from 0.1 to 4.48. These values are considered close to those of highly compressible clay soils. The higher C_c values were experienced by samples JCD, PVD, WQD, and RWA, which had high initial void ratios and high water contents. These large C_c values, exhibited by the gross volume changes and settlements associated with loading increments, may possibly indicate drainage of floc water, development of effective stress and the re-orientation and deformation of floc structure.

The swell index values C_s are comparatively very low, ranging from 0.014 to 0.199, and falls within the range typical of natural non-plastic soils. Sample WQD has the highest compression index of 4.48 followed by a highest swell index of 0.199, which is still relatively much lower than its compression index value. This may be due to the thixotropy property of floc structure. As discussed previously, when floc water escapes, an inter-particle bonding develops in between the floc particles which causes an irreversible structural deformation. During the consolidation process, the floc particles become tightly bonded due to the deformation and re-orientation of floc particles under high pressure caused by the increasing loading and cementation due to the ions. This irreversible structural reformation prevents the rebound of the structure after removal of loading.

The calculated values for preconsolidation pressure ranged from 75 to 150 KPa. This may indicate that all samples have had a history of preloading, which is not true. When samples were made for consolidation testing, they were all in a hydrous state and could be molded easily to fit the consolidation ring without any indication of preconsolidation or cementation. So these high P_c values indicate that floc structure is reformed under loading, and in this structure, particles are bound by re-orientation and deformation of floc particles due to the collapse of the floc structure. Hence these preconsolidation pressures are pseudo values.

Sample JCD has the largest P_c and secondary consolidation values. This is due to its highly developed floc structure as a result of high thixotropic hardening. The hardening is caused by a time-dependent interparticle bonding due to its high aluminum and calcium content which cause the residual to be thixotropic.

In order to estimate the secondary consolidation, the secondary compression index C_α is determined, which is defined as $\Delta e/\Delta \log t$, where Δe is the change in void ratio and t is the time. C_α is usually independent of time and the thickness of soil layer. It is also independent of the load increment ratio, as long as some primary consolidation occurs. The ratio C_α/C_c is approximately constant for normally consolidated clays over the normal range of engineering stresses. (Holtz, et al., 1981) It is observed from Figure 18 that C_α values are almost constant for all load increments. Even though the plots under all load increments all have primary consolidation to a large (for the first load increment) or limited (for the rest of load increments) degrees, their slopes are almost parallel to each other and the ratio C_α/C_c is approximately a constant for a certain residual sample.

Usually the average value of C_α/C_c of organic silts is in the range from 0.035 to 0.06 (Holtz, et al., 1981). The values of C_α and C_α/C_c of residual samples are listed in Table 13. It can be seen that C_α/C_c values are all below 0.035. This could be caused by the high organic content in WTP residuals.

In the first load increment, there appears to be a predominant primary component of consolidation in addition to a secondary one. For the secondary and other load increments, it seems that there is practically no primary consolidation. The probable causes for this behavior have been discussed in the earlier section of this report.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Based on this research on the ten WTP residual samples, it can be noticed that the geotechnical properties of WTP residuals vary dramatically. It seems that each individual sample is unique. These characteristics are believed to be caused by many related factors including the type and quality of receiving water, the type and strength of hardness, the type of organic matter and content, water treatment process, type and amount of chemical additions, dewatering process and techniques, impurities (like sand that are mixed in drying bed), time of aging, even weather and climate, etc. But based on the limited tests conducted on these limited samples, some general conclusions and hypotheses have been made and presented in this section. Further studies on this subject are required to verify these findings.

Based on the tests of particle size distribution of solids, it can be concluded that sieve and hydrometer analyses are not suitable for the size determination of WTP residuals. WTP residuals are of colloidal sizes and are governed by flocculation theory. Advanced technologies such as those involving observation through an electron microscope are desired to determine the particle as well as floc sizes (Huang, 1979).

WTP residual sample usually has a lower specific gravity than that of clay. This is believed to be caused by high organic content and chemical additives. It was found that organic content tends to decrease the specific gravity while presence of iron tends to increase the specific gravity. Chemicals that are added during water treatment process may also increase the specific gravity.

Liquid and plastic limits of WTP residuals are generally very high, caused by their high water retaining ability. The plasticity of WTP residuals are believed to be strongly influenced by the floc structure of the residuals. As the material ages, floc water escapes and a different floc structure develops along with some cementation, decreasing plasticity. Usually aged samples tend to have low plasticity.

Moisture contents of WTP residuals could be in most cases appropriately determined at a standard temperature of 105°C with very limited influence on the accuracy of moisture content determination.

Based on the comparisons on the behaviors of compaction tests from both wet and dry sides, it can be concluded the WTP residuals usually have high thixotropic characteristics and can have highly developed cementation due to their fine colloidal sizes, high ion contents, and the unique floc structure. Thixotropic hardening which causes the increasing in strength during remolding is related to the highly oriented particle adhesion pattern. It can also be concluded from these tests that unless the solids contents of the WTP residuals are increased to certain degree (around 50%), it would be very difficult to compact them in the monofill. Some type of dewatering and /or reduction in water content will be required before the residuals can be dumped in the monofills in order to avoid handling and compaction problems.

WTP residuals generally have low freeze/thaw durability. The freeze-thaw characteristics of WTP samples are influenced by the initial solid content, organic content and the ions present. This indicates that WTP monofills may require a final cover constructed out of a material not susceptible to freeze and thaw.

WTP residuals exhibit better durability under wet/dry tests than under freeze/thaw tests. Wet/dry tests will increase the dry density for most WTP residuals and increase the strength for some residual samples due to the development of cementation and thixotropic hardening. Degree of aging of WTP residual is really dependent upon the quantity of floc water removed. The stability and durability of WTP residuals are related to their clay mineral types, lime contents, organic contents and cementation characteristics. Generally speaking, in WTP residuals, cementation can be well developed due to the high calcium, ferric, and aluminum concentrations present in floc water. Organic matter and other impurities (like sand) have a tendency to interfere with the development of cementation, decreasing the stability and durability. High lime content tends to increase the stability and durability due to the hydraulic hardening effect.

Based on the strength tests, it can be concluded that WTP residuals have low strength at low solids content, and the slope stability in landfill is more likely controlled by its solids content and organic content when it is dumped in a wet condition. Aging will improve the slope stability. Impurities like sand can also influence the shear strength. The strength of different WTP residuals developing during drying process may have a large range, and is dependent on thixotropy and cementation developing characteristics. Usually residuals with low plasticity will develop a uniform cementation and exhibit high strength while those with high plasticity will develop nonuniform cementation and exhibit low strength.

WTP residuals usually have low coefficients of permeability of the order of 10^{-6} - 10^{-7} cm/s due to their fine colloidal particle sizes. They also have large compressibility due to their high water retaining ability and the deformation of floc structure. The low swelling ability of these residuals is caused by their thixotropic hardening. The secondary consolidation takes a long time due to high organic content. The pre-consolidation pressure is a pseudo value which is caused by the development of inter particle bond during the depression of the floc structure under external loading.

APPENDIX

SUMMARY OF GEOTECHNICAL TESTS RESULTS

Table 1 Experimental Methods and Testing Instruments Employed

Test	Method	Instrument
Sieve Analysis	ASTM D421	US Standard Sieves
Hydrometer Test	ASTM D422	152H-Hydrometer
Specific Gravity of Solids	ASTM D854	Volumetric Flask 250ml
Liquid Limit/Plastic Limit	ASTM D4318	Liquid Limit Device (CL-205)
Standard Proctort	ASTM D698	Standard Mold and Hammer (CN-415)
Freeze/Thaw	ASTM D560	Kenmore 64831 Freezer
Wet/Dry	ASTM D559	Fisher Blue M Oven
Direct Shear	ASTM D3080	Direct Shear Device (D-300)
Unconfined Compression	ASTM D2166	Unconfined Compression Device (U-580)
Consolidation	ASTM D2435	Consolidation Device (C-320A)

Table 2 Information Summary of Water Treatment Facilities and Residual Samples

Sample	Residual Type	Name of the Facility	Water Source	
			Type	Name
JCD	Lime	Jersey City Water Treatment Plant at Boonton, New Jersey	Reservoir	Rockaway River and Boonton Reservoir
PVD	Lime	Little Falls Treatment Plant at Clifton, New Jersey	River	Passaic River
WQD	Ferric	Wanaque Water Treatment Plant at Wanaque, New Jersey	Reservoir	Wanaque Reservoir
MWD	Lime	Minneapolis Water Works, Minneapolis, Minnesota	River	Mississippi River
MQD	Alum	Manasquan Water Treatment Plant in Monmouth County, New Jersey	River/Reservoir	Manasquan River and Manasquan Reservoir
HWD	Alum	Haworth Water Treatment Plant at Harrington Park, New Jersey	reservoir	Hackensack River , stored in four reservoirs
NCD	Lime	Ellwood City Treatment Plant in Ellwood City, Pennsylvania	River	Slippery Rock Creek
RWA	Ferric	West River Water Treatment Plant in Woodbridge, Connecticut	Lake	Lake Gaillaud
FLDM	Alum	Bradenton Water Treatment Plant in City of Bradenton, Florida	Lake	Lake Manatee
SLD	Lime	South County Plant in St. Louis, Missouri	River	Mississippi River
SLDF	Same as above	Same as above	Same as above	Same as above

(To be continued)

Table 2 Information Summary of Water Treatment Facilities and Residual Samples

	Impurities in Water Sources (Yearly Average Value) (Yearly Range)							
Sample	Turbidity (NTU)	Color (PCU)	Taste/Odor (Threshold Odor No.)	Iron (ppm)	Manganese (ppm)	Hardness ($CaCO_3$ mg/L)	Trihalomethane (ppb)	TOC (mg/L)
JCD	1.93 0.5-6	22.08 10-30		0.1	<0.02	68.5 40-70	Not Detected	
PVD	5-75	25-100		1.3	0.11			
WQD	1.33 0.75-2.5	17 0-20		0.103 0.05-0.16	0.045 0.01-0.06	47 170-230		
MWD		43 10-100	<10	0.12 0.05-0.15	<0.01	171 170-230		
MQD	6-300* 2-4**	5-500* 60**		0.7-5.0* 1.0**	0-0.03* <0.13**	60* 30**	100-400* **	
HWD	3	25				120		
NCD	2-100		2	0.5	0.06	150	8.5	
RWA	1.2	26	5	0.15	0.08	25	0-300	3.2
FLDM	1.5-25	176 100-400		0.25		71.9 40-110	400-600	15-25
SLD	21	12		0.169	0.013	167		
SLDF	Same as above	Same as above		Same as above	Same as above	Same as above		

* Manasquuan River; ** Manasquan Reservoir

(To be continued)

Note: This information is based on the data provided by individual treatment plants and may not be complete

Table 2 Information Summary of Water Treatment Facilities and Residual Samples

	Water Treatment Process and Chemicals Added (Yearly Average Value)				
Sample	Main Water Treatment Processes	Lime (ppm)	Alum (ppm)	Ferric Chloride (ppm)	Coagulant Air and Others
JCD	Aeration, flocculation, sedimentation, filtration, chlorination	1 ppm as softener			Cationic polymer, alum
PVD	Prechlorination, flocculation, sedimentation, multiple media filtration, chlorination		as coagulant		Polymer activated carbon
WQD	Pretreatment, coagulation, sedimentation, filtration, chlorination		Coagulant 10-12 ppm		Polymer, carbon, KMnO4
MWD	Lime softening, filtration, carbon adsorption	170 ppm as softener	Coagulant 20 ppm	4 ppm	Polymer activated carbon
MQD	Sedimentation, mixed media filtration, carbon adsorption, chlorination (NaOCl)		Coagulant		Polymer, KMnO4, GAC
HWD	Ozone contactor, flotation/skimmer, media filtration, disinfection		5 ppm		Cationic polymer
NCD	Presettling, coagulation, sedimentation, filtration, chloridation	Coagulant		20 ppm	PAC
RWA	Oxidation, flocculation, sedimentation, filtration, chlorination			7.2 ppm	
FLDM	Activated carbon addition, flocculation (alum, lime and polymer), sedimentation, postmixing (chlorine, ammonia and lime), mixed media filtration and chlorination		75 ppm		
SLD	Softening, sedimentation, dual medial filtration, disinfection	94 ppm		12.8 ppm (ferric sulfate)	
SLDF	Same as above				

(To be continued)

Table 2 Information Summary of Water Treatment Facilities and Residual Samples

Sample	Dewatering Process (Solids Content)	Conditioning Agent Added	Aging period for Sample Tested	Properties of Sample Tested		
				pH	Solids Content	Water Content
JCD	Thickener (1.5-2%), filter press (30-40%)	Lime (59%)		12.0	23.3%	329.2%
PVD	Thickener, Filter press (27-30%)	Lime (15%), (polyelectrolyte-occasionally)		12.0	26.2%	281.7%
WQD	Thickener, belt filter press (14%) (being installed). Lagoon (0.5-1.5%), drying bed			6.5	5.4%	549.4%
MWD	Gravity thicker (1-2%), centrifuge (55-60%)			11.0	69.2%	44.5%
MQD	Lagoon, drying bed (30%)		Twelve months	7.8	32.6%	206.7%
HWD	Lagoon, drying bed			6.8	59.7%	67.5%
NCD	Lagoon, drying bed			6.2	39.9%	150.6%
RWA	Lagoon, drying bed		3.5 months	5.3	18.1%	452.5%
FLDM	Lagoon, drying bed			6.4	57.1%	75.1%
SLD	Lagoon		Twelve months	9.1	72.2%	38.5%
SLDF	Lagoon			9.5	38.2%	161.8%

(To be continued)

Table 2 Information Summary of Water Treatment Facilities and Residual Samples

Sample	Location of Sample Collection	Description of Residual Sample Used for Geotechnical Testing	Sample Collection and Delivery
JCD	Outlet of dewatering machine	Cake form (about 2cm thick), composed of one inner black layer and two outer yellow layers, foul odor	Collected by NJIT research team
PVD	Outlet of dewatering machine	Cake form (about 5cm thick), grey color, with strong foul odor	Collected by NJIT research team
WQD	Drying bed	Paste form, brown and black color, foul odor	Collected by NJIT research team
MWD	Outlet of dewatering machine	Paste form, gray color	Sent by the facility, standing water was observed on top of the container when sample was received
MQD	Drying pile (six month aged)	Lump form, brown, yellow and black color, hard and brittle	Collected by NJIT research team
HWD	Drying bed	Lump form, dark grey color	Collected by NJIT research team
NCD	Drying bed	Lump form, black, brown, and grey color, soft	Sent by the facility
RWA	Drying bed	Paste form, black color, with foul odor	Sent by the facility, standing water was observed on top of the container when sample was received
FLDM	Drying bed prior to landfill	In pieces, coal black color, dry, hard and brittle. Residual material is dark because of high organic content in the raw water.	Sent by the facility
SLD	Landfill (one year aged)	Paste form, greenish grey color	Sent by the facility
SLDF	Lagoon (fresh)	Mud form, greenish grey color	Sent by the facility, standing water was observed on top of the container when sample was received

(Table 2 concluded)

Table 3 Physical/Chemical Characteristics of Water Treatment Plant Residuals

Sample	Iron (%)	Aluminum (%)	Calcium (%)	Sodium (%)	Manganese (%)	Volatile Solids (%)	Fixed Solids (%)	CEC (meq/100g)
JCD	0.06	3.92	12.86	0.14	0.19	34.45	65.55	134.8
PVD	0.04	1.26	17.97	0.15	0.13	9.47	90.53	53.1
WQD	0.60	0.26	0.03	0.12	0.09	39.24	60.76	106.0
MWD	0.042	0.004	0.550	0.024	0.001	15.02	84.98	72.32
MQD	0.051	0.893	0.026	0.106	0.007	3.55	96.45	21.96
HWD	0.006	0.826	0.101	0.006	0.148	14.33	85.67	59.35
NCD	1.172	0.001	2.280	0.174	0.177	17.37	82.63	105.99
RWA	2.125	0.097	1.887	0.263	0.094	38.24	61.76	74.91
FLD	0.162	3.027	0.127	0.043	0.009	61.44	38.56	133.75
FLDM	0.038	0.747	0.125	0.021	0.064	63.41	36.59	50.86
SLD	0.048	0.000	0.509	0.020	0.001	3.62	96.38	55.40

Table 4 Specific Gravity of Solids of Water Treatment Plant Residuals

Sample	Specific Gravity of Solids	Volatile Solids Content	Iron content
FLDM	1.87	63.41%	0.038%
WQD	2.27	39.24%	0.600%
JCD	2.38	34.45%	0.060%
HWD	2.63	14.33%	0.006%
NCD	2.65	17.37%	1.172%
MWD	2.67	15.02%	0.042%
MQD	2.61	3.55%	0.051%
SLD	2.65	3.62%	0.048%
PVD	2.67	9.47%	0.040%
RWA	2.71	38.24%	2.125%
Average:	2.51	23.87%	0.418%

Table 5 Liquid and Plastic Limits of Water Treatment Plant Residuals

Sample	Natural Water Content	Liquid Limit	Plastic Limit	Plasticity Index
WQD	549.4 % (15.4%)*	617.4% (13.9%)	387.4% (20.5%)	230.0
RWA	452.5% (18.1%)	429.2% (18.9%)	107.1% (48.3%)	322.1
JCD	329.2% (23.3%)	329.5% (23.3%)	200.1% (33.3%)	129.4
PVD	281.7% (26.2%)	207.2% (32.6%)	133.2% (42.9%)	74.0
MQD	206.7% (32.6%)	High sand content	High sand content	--
SLDF	161.8% (38.2%)	60.1% (62.5%)	44.2% (63.9%)	15.9
NCD	150.6% (39.9%)	138.1% (42.0%)	84.8% (54.1%)	53.3
FLDM	75.1% (57.1%)	Nonplastic	Nonplastic	--
HWD	67.5% (59.7%)	93.0% (51.8%)	High sand content	--
MWD	44.5% (69.2%)	35.5% (73.8%)	31.5% (76.0%)	4.0
SLD	38.5% (72.2%)	39.4% (71.7%)	31.4% (76.1%)	8.0

* Values in brackets are corresponding solids contents

Table 6 Weight Loss Observation Test Results of Water Treatment Plant Residuals

Sample	Initial Water Content	Weight Loss under Room Condition**	Weight Loss in Oven (35-45°C)	Weight Loss in Oven (105°C)
WQD	549.4 % (15.4%)*	83.0%	84.2%	86.4%
RWA	452.5% (18.1%)	72.5%	77.7%	81.7%
JCD	329.2% (23.3%)	76.5%	73.6%	70.0%
PVD	281.7% (26.2%)	70.2%	72.0%	74.2%
MQD	206.7% (32.6%)	59.0%	63.2%	68.2%
SLDF	161.8% (38.2%)	56.9%	58.2%	58.1%
NCD	150.6% (39.9%)	44.1%	48.1%	51.2%
FLDM***	75.1% (57.1%)	--	--	--
HWD	67.5% (59.7%)	38.2%	39.5%	42.1%
MWD	44.5% (69.2%)	28.2%	28.7%	28.9%
SLD	38.5% (72.2%)	28.1%	29.1%	29.7%

* Values in brackets are corresponding solids contents

** Room condition: 24±2 °C

*** Sample was in a dry condition at initial water content and could be broken to powder form, so this test was considered unnecessary

Table 7 Compaction Test Results from Wet Side of Water Treatment Plant Residuals

Sample	Compaction Curve Form	Optimum Solids Content	Optimum Dry Density (KN/m^3)
JCD	Increasing curve	--	--
WQD	Increasing curve	--	--
MQD	Increasing curve	--	--
RWA	Increasing curve	--	--
PVD	One hump	57.1%	5.82
MWD	One hump	82.0%	13.82
HWD	One hump	64.7%	9.35
NCD	One hump	53.9%	8.88
SLD	One hump	83.0%	14.29
SLDF	One hump	75.2%	12.69
FLDM*	--	--	--

* Sample was in a condition too dry to conduct compaction test

Table 8 Compaction Test Results from Dry Side of Water Treatment Plant Residuals

Sample	Compaction Curve Form	Optimum Solids Content	Optimum Dry Density (KN/m^3)
JCD	One hump	64.5%	9.05
WQD*	--	--	--
MQD	One hump	50.1%	5.40
RWA	One hump	68.8%	10.26
PVD	One hump	50.0%	6.37
MWD	One hump	80.0%	14.34
HWD	One hump	62.5%	9.69
NCD	One hump	55.6%	9.80
SLD	One hump	80.0%	14.64
SLDF	One hump	72.1%	13.24
FLDM	One hump	50.9%	5.99

* It was impossible to be break the sample into fine powder form after being oven dried (105°C) to conduct compaction test

Table 9 Freeze/Thaw Test Results of Water Treatment Plant Residuals

Sample	Initial Water Content		Weight Loss after Twelve Cycles**	Volume Loss after Twelve Cycles	Observation Descriptions
MQD	549.4 %	(15.4%)*	70%	20%	<Samples became light very quickly among all the residual samples, and experienced the highest weight loss. Finally samples became loose and crispy. The color turned from black brown to rusty brown.
WQD	457.4%	(17.9%)	60%	80%	<Samples shrunk and became light. Ice was observed on the surfaces during the first and second two cycles in freezer. Finally samples became crispy,and could bearly remain intact. The color turned from black to dark brown
JCD	320.0%	(23.8%)	63%	36%	<Samples shrunk, became light, and the color turned from black to brown during the process. Scale-like cracks formed on the surfaces and the surface material became very loose, crispy and could easily be peeled off.
PVD	281.9%	(26.2%)	60%	40%	<Samples shrunk and became light during the process. Vein-like fine cracks formed on the surface with few of them developing deep into the surface. The color turned from dark grey to light grey.
RWA	243.6%	(29.1%)	--	--	<Samples became dry, light and loose during the process. Ice was observed on the surface during initial two cycles in freezer. Finally samples collapsed into a dry, sandy, crispy material, and the color turned from black to dark brown.
NCD	123.0%	(44.8%)	51%	25%	<Samples shrunk and became light during the process. Cracks formed on the surfaces. The material on the surface became loose and crispy and scaled off. The color turned from black to brown.
FLDM	120.3%	(45.4%)	43%	11%	<Samples experienced weight loss, relatively little volume shrinkage, and became brittle. No cracks were observed on the surface. The color remained black.
HWD	67.5%	(59.7%)	40%	20%	<Samples shrunk and became light during the process. Cracks formed on the surface, and finally the material became very loose and crispy. The color of samples turned from black to rusty brown.
SLDF	63.1%	(61.3%)	37%	12%	<Samples shrunk and became light during the process. Vein-like fine cracks formed on the surface. Finally the color turned from greenish grey to light yellow, and the samples became brittle and remained intact.
MWD	34.3%	(74.5%)	29%	12%	<Samples underwent a reduction in volume and weight. Cracks formed on the surfaces. The loose material scaled off, and finally samples became brittle. The color turned from grey to white grey.
SLD	36.6%	(73.2%)	28%	10%	<Samples experienced the least weight loss and volume shrinkage. Vein-like fine cracks formed on the surface. Finally, the color turned from greenish grey to light yellow, and the samples became brittle and remained intact.

* Values in brackets are corresponding solids contents

** One cycle indicates a 48 hour period with the first 24 hours in freezer (-5±0.5°C) and the second 24 hours under room conditions (24±2°C)

Table 10 Wet/Dry Test Results of Water Treatment Plant Residuals

Sample	Initial Water Content	Weight Loss after Twelve Cycles**	Volume Loss after Twelve Cycles	Observation Descriptions
MQD	549.4 % (15.4%)*	65%	26%	<Samples experienced weight and volume losses. Cracks formed on the surfaces. Finally the samples became loose and crispy. The color turued from black brown to rusty brown.
WQD	457.4% (17.9%)	82%	85%	<Samples had high weight and volume losses after the process. Cracks formed on the surfaces. Finally samples became crispy, and could bearly remain intact. The color was dark brown.
JCD	320.0% (23.8%)	70%	64%	<Samples shrunk, became light, and the color turned from black to brown during the process. Fractures formed through the samples. Finally samples broke into several chunks.
PVD	281.9% (26.2%)	65%	39%	<Samples shrunk and became light during the process. No cracks formed on the surfaces and samples remained intact. The color turned from dark grey to light yellow.
RWA	243.6% (29.1%)	63%	52%	<Samples became dry, light and small during the process, and finally became dry, crispy and could easily be broken. The color turned from black to dark brown.
NCD	123.0% (44.8%)	55%	25%	<Samples shrunk and became light during the process. Cracks formed on the surfaces. The material became hard and brittle. Sample remained intact, and the color turned from black to brown.
FLDM	120.3% (45.4%)	--	--	<Samples experienced weight loss, volume shrinkage, and finally collapsed into a loose and crispy powder material. The color remained black.
HWD	67.5% (59.7%)	40%	20%	<Samples shrunk and became light during the process. Cracks formed on the surface. Finally the samples became very crispy and could bearly remain intact. The color of samples turned from black to rusty brown.
SLDF	63.1% (61.3%)	38%	21%	<Samples shrunk and became light during the process. No cracks formed on the surfaces. Finally the color turned from greenish grey to light yellow, and the samples became brittle, hard and remained intact.
MWD	34.3% (74.5%)	29%	15%	<Samples underwent a reduction in volume and weight, and finally became hard, brittle and remained intact. The color turned from grey to white grey.
SLD	36.6% (73.2%)	29%	19%	<Samples experienced weight loss and volume shrinkage. No cracks formed on the surface. The color turned from greenish grey to light yellow, and the samples became hard, brittle and remained intact.

* Values in brackets are corresponding solids contents

** One cycle indicates a 48 hour period with the first 24 hours in oven (60±2°C) and the second 24 hours in moisture chamber (28±2°C)

Table 11 Direct Shear Test Results of Water Treatment Plant Residuals

Sample	Liquid Limit	Water Content	Cohesion (KPa)	Friction Angle
WQD	617.4% (13.9%)*	549.4% (15.4%)	4.2	3°
RWA	429.2% (18.9%)	405.1% (19.8%)	2.4	7°
PVD	207.2% (32.6%)	157.1% (38.9%)	3.4	20°
NCD	138.1% (42.0%)	150.6% (39.9%)	9.0	25°
MQD	High sand content	189.0% (34.6%)	11.4	9°
HWD	93.0% (51.8%)	67.5% (59.7%)	15.5	26°
SLDF	60.1% (62.5%)	56.0% (64.1%)	3.1	20°
SLD	39.4% (71.7%)	38.7% (72.1%)	17.7	16°
FLDM	Nonplastic	90.8% (52.9%)	20.7	45°
MWD	35.5% (73.8%)	34.8% (74.2%)	45.1	24°
JCD	329.5% (23.3%)	327.4% (23.4%)	106.8	18°

* Values in brackets are corresponding solids contents

Table 12 Unconfined Compression Test Resules of Water Treatment Plant Residuals and Correlation with Some Geotechnical Properties

Sample	Form of Strength vs. Solids Content Curve	Optimum Solids Content	Maximum Compressive Strength (KPa)	Plasticity Index
SLD	Increasing curve	--	--	8.0
NCD	Increasing curve	--	--	53.3
SLDF	Increasing curve	--	--	15.9
FLDM	Increasing curve	--	--	Nonplastic
JCD	One hump	41.8%	316.9	129.4
MWD	One hump	88.6%	298.8	4.0
PVD	One hump	63.5%	280.5	74.0
HWD	Increasing curve	--	--	High sand content
MQD	One hump	38.9%	188.4	High sand content
WQD	One hump	23.8%	140.0	230.0
RWA	One hump	42.5%	70.0	322.1

(To be continued)

Table 12 Unconfined Compression Test Results of Water Treatment Plant Residuals and Correlation with Some Geotechnical Properties

Sample	Maximum Strength Developed	Weight Loss after Freeze/Thaw and Wet/Dry Tests	Volume Loss after Freeze/Thaw and Wet/Dry Tests	Phenomenon Observed During F/T and W/D Tests*
SLD	Very high (1000 KPa)	Low (28%, 29%)**	Low (10%, 19%)	Sample became hard and remained intact. No cracks were observed on the surface after W/D.
NCD	Very high (1000 KPa)	Medium (51%, 55%)	Low (25%, 25%)	Sample became hard and remained intact after W/D.
SLDF	High (500 KPa)	Medium (37%, 38%)	Low (12%, 21%)	Sample became hard and remained intact after W/D.
FLDM	High (500 KPa)	Medium (43%, --)***	Low (11%, --)***	Sample collapsed after W/D, but remained intact after F/T.
JCD	Medium (300 KPa)	High (63%, 70%)	Medium (36%, 64%)	Sample became hard and brittle after W/D, and broke into big chunks.
MWD	Medium (300 KPa)	Low (29%, 29%)	Low (12%, 15%)	Sample became loose and crispy. Sample had a high content of sand.
PVD	Medium (300 KPa)	Medium (40%, 65%)	High (60%, 39%)	Sample became brittle and remained intact after W/D.
HWD	Low (200 KPa)	Medium (40%, 40%)	Low (20%, 20%)	Sample became loose and crispy, and could bearly remain intect
MQD	Low (200 KPa)	High (70%, 65%)	Low (20%, 26%)	Sample became loose and crispy, and could bearly remain intect
WQD	Low (150 KPa)	High (60%, 80%)	Very high (80%, 85%)	Ice was found on sample surface during F/T. Sample became very loose, crispy, and could bearly remain intact.
RWA	Very low (70 KPa)	High (--, 63%)***	High (--, 52%)***	Ice was found on sample surface during F/T. Sample became very loose, crispy, and collapsed after F/T.

(Table 12 concluded)

* Detailed descriptions are presented in Tables 9, and 10

** The first value in bracket is for freeze/thaw (F/T) test, and the second value for wet/dry (W/D) test

*** Samples collapsed

Table 13 Consolidation Test Results of Water Treatment Plant Residuals

Sample	Initial Water Content	Initial Void Ratio	Coefficient of Permeability Kv, (cm/sec)	Preconsolidation Pressure Pc, (KPa)	Compression Index Cc	Swell Index Cs
WQD	552.4% (15.3%)*	17.20	9.71×10^{-6}	88	4.48	0.199
RWA	454.4% (18.0%)	5.52	1.28×10^{-7}	93	2.00	0.085
JCD	241.5% (29.3%)	5.40	5.53×10^{-7}	150	1.95	0.059
PVD	281.9% (26.2%)	3.95	6.47×10^{-6}	136	1.47	0.090
NCD	150.7% (39.9%)	1.60	5.56×10^{-6}	100	0.51	0.049
FLDM	114.2% (46.7%)	2.02	7.33×10^{-8}	105	0.36	0.030
HWD	67.7% (59.6%)	1.56	3.03×10^{-6}	120	0.47	0.024
SLDF	56.5% (63.9%)	1.44	2.60×10^{-6}	75	0.29	0.064
SLD	36.5% (73.3%)	1.35	2.94×10^{-7}	80	0.26	0.062
MWD	35.91% (73.6%)	1.04	3.28×10^{-6}	112	0.80	0.056
MQD	201.3% (32.5%)	0.63	5.49×10^{-6}	104	0.10	0.014

* Values in brackets are the corresponding solids contents

(to be continued)

Table 13 Consolidation Test Results of Water Treatment Plant Residuals

Sample	Initial Water Content		Initial Void Ratio	Secondary Compression Index C_α	C_α/C_c	Compression Index Cc	Swell Index Cs
WQD	552.4%	(15.3%)*	17.20	0.1120	0.0250	4.48	0.199
RWA	454.4%	(18.0%)	5.52	0.0380	0.0190	2.00	0.085
JCD	241.5%	(29.3%)	5.40	0.0101	0.0051	1.95	0.059
PVD	281.9%	(26.2%)	3.95	0.0080	0.0054	1.47	0.090
NCD	150.7%	(39.9%)	1.60	0.0072	0.0140	0.51	0.049
FLDM	114.2%	(46.7%)	2.02	0.0006	0.0017	0.36	0.030
HWD	67.7%	(59.6%)	1.56	0.0008	0.0017	0.47	0.024
SLDF	56.5%	(63.9%)	1.44	0.0064	0.0220	0.29	0.064
SLD	36.5%	(73.3%)	1.35	0.0064	0.0240	0.26	0.062
MWD	35.91%	(73.6%)	1.04	0.0581	0.0721	0.80	0.056
MQD	201.3%	(32.5%)	0.63	0.0003	0.0030	0.10	0.014

(Table 13 concluded)

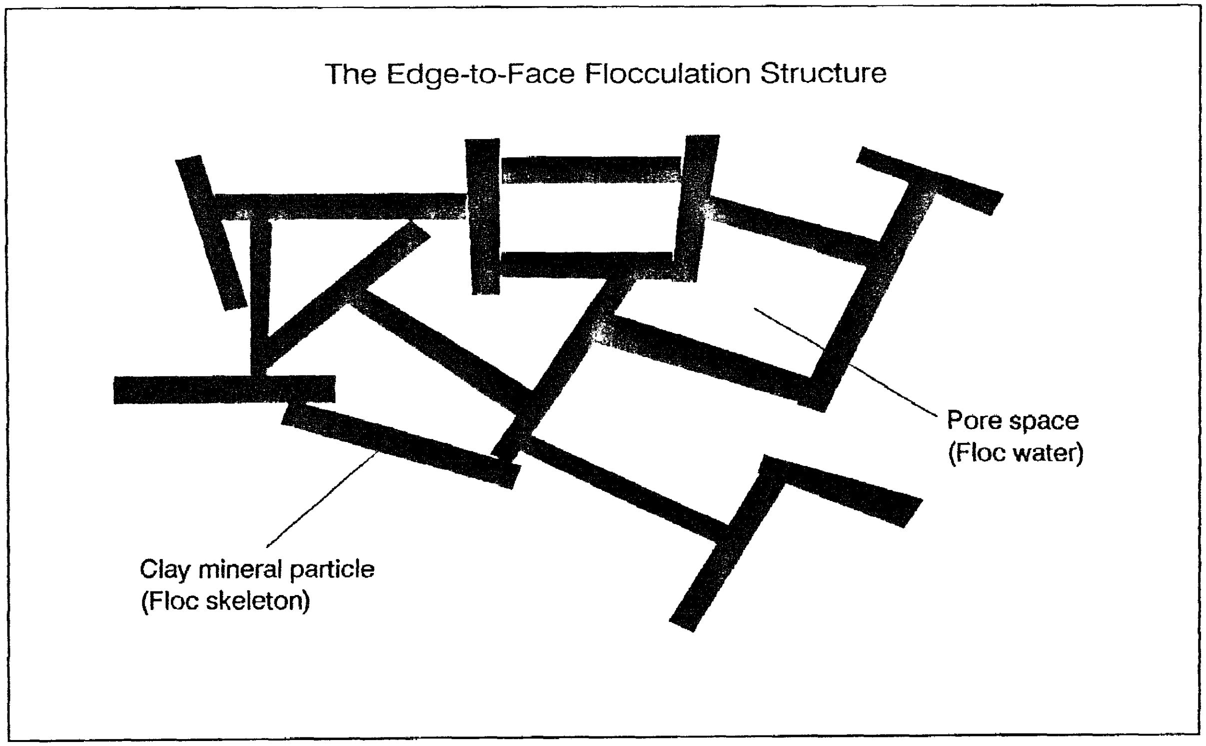

Figure 1 An Illustration of Flocculated Structure of Water Treatment Plant Residuals

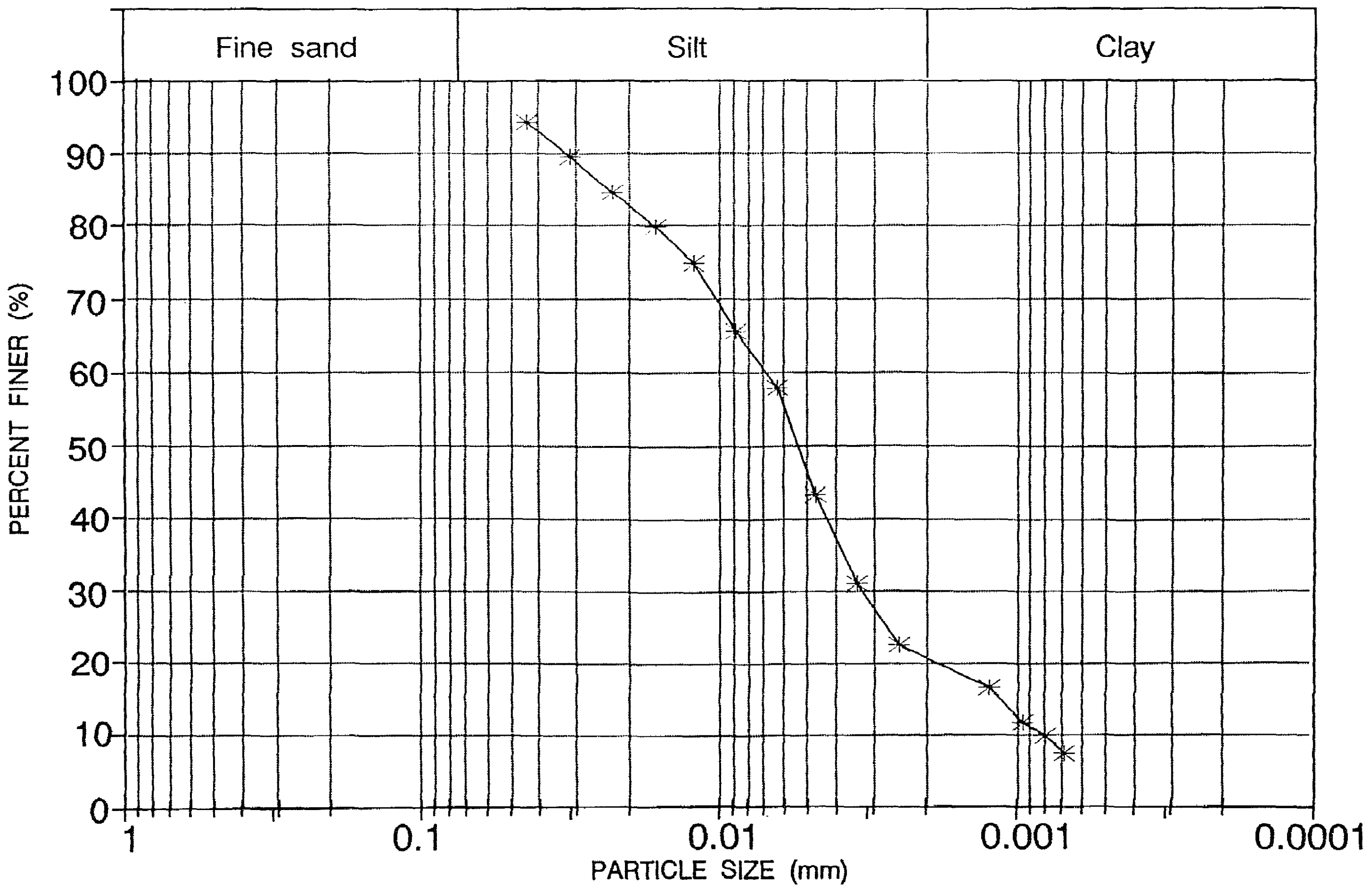

Figure 2 Particle Size Distribution Curve Obtained from Hydrometer Test for Sample JCD

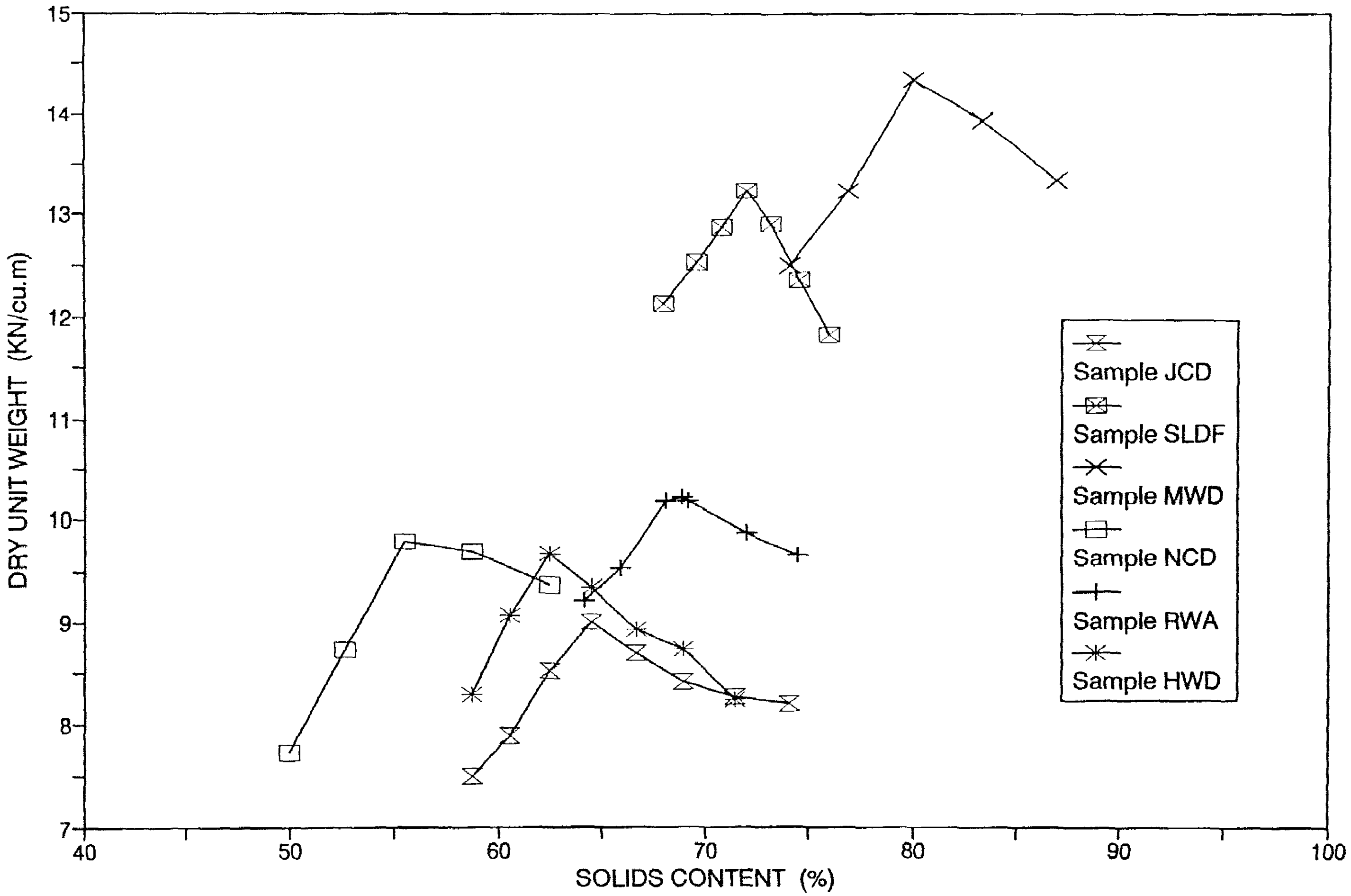

Figure 3 Compaction Curves of WTP Residual Samples from Dry Side (I)
(to be continued in Figure 4)

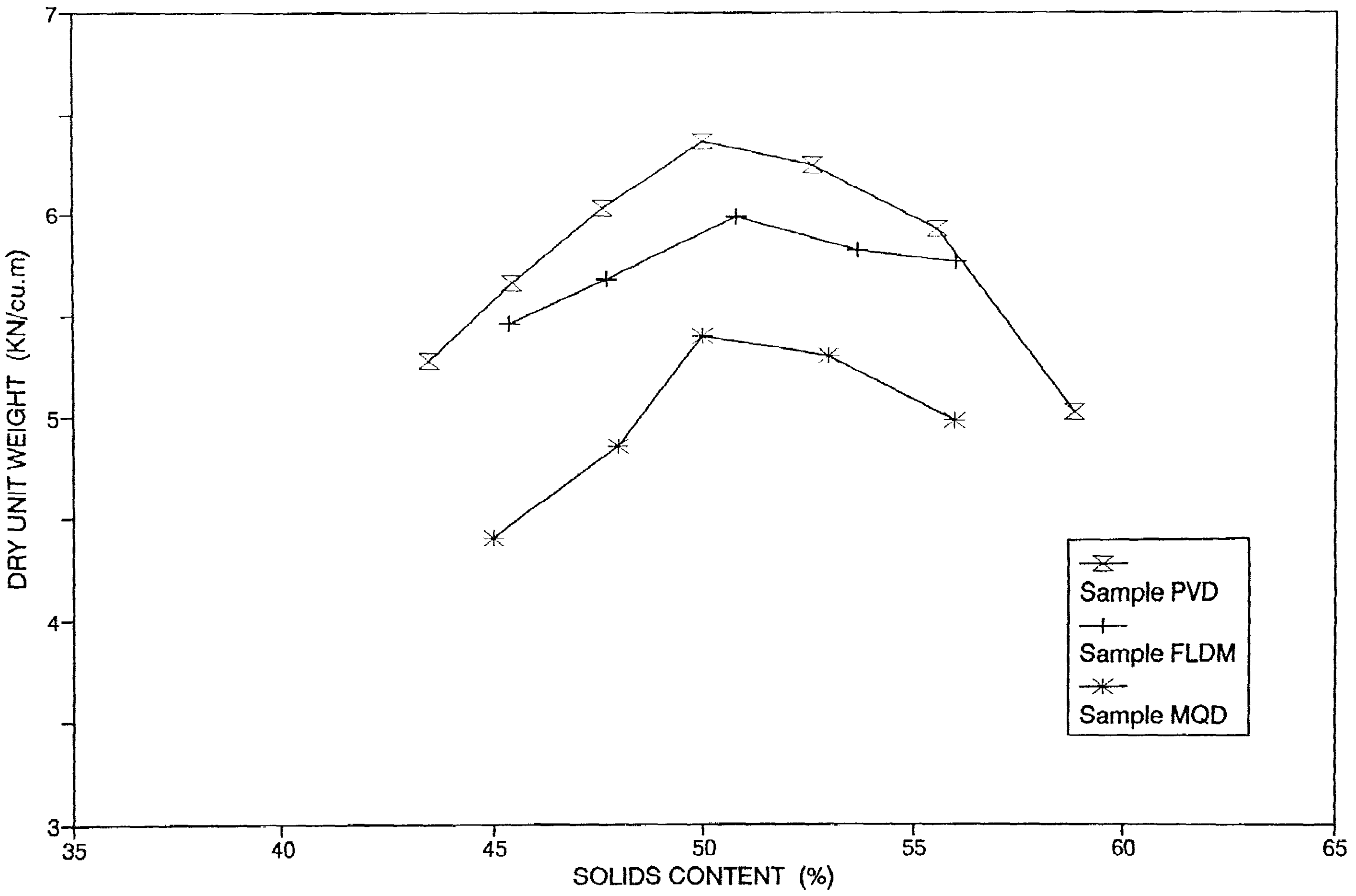

Figure 4 Compaction Curves of WTP Residual Samples from Dry Side (II) (continued from Figure 3)

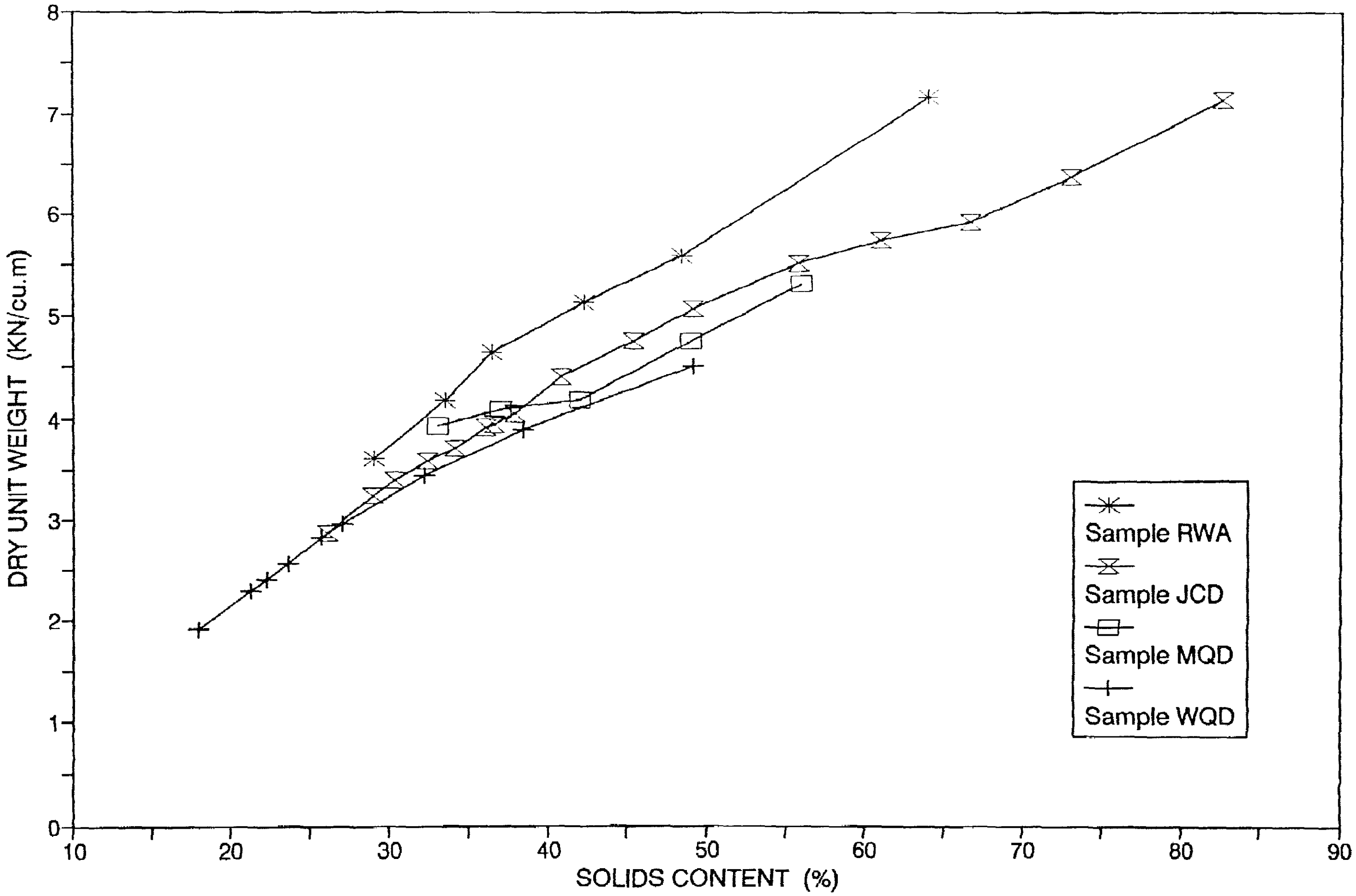

Figure 5 Compaction Curves of WTP Residual Samples from Wet Side with Increasing Pattern

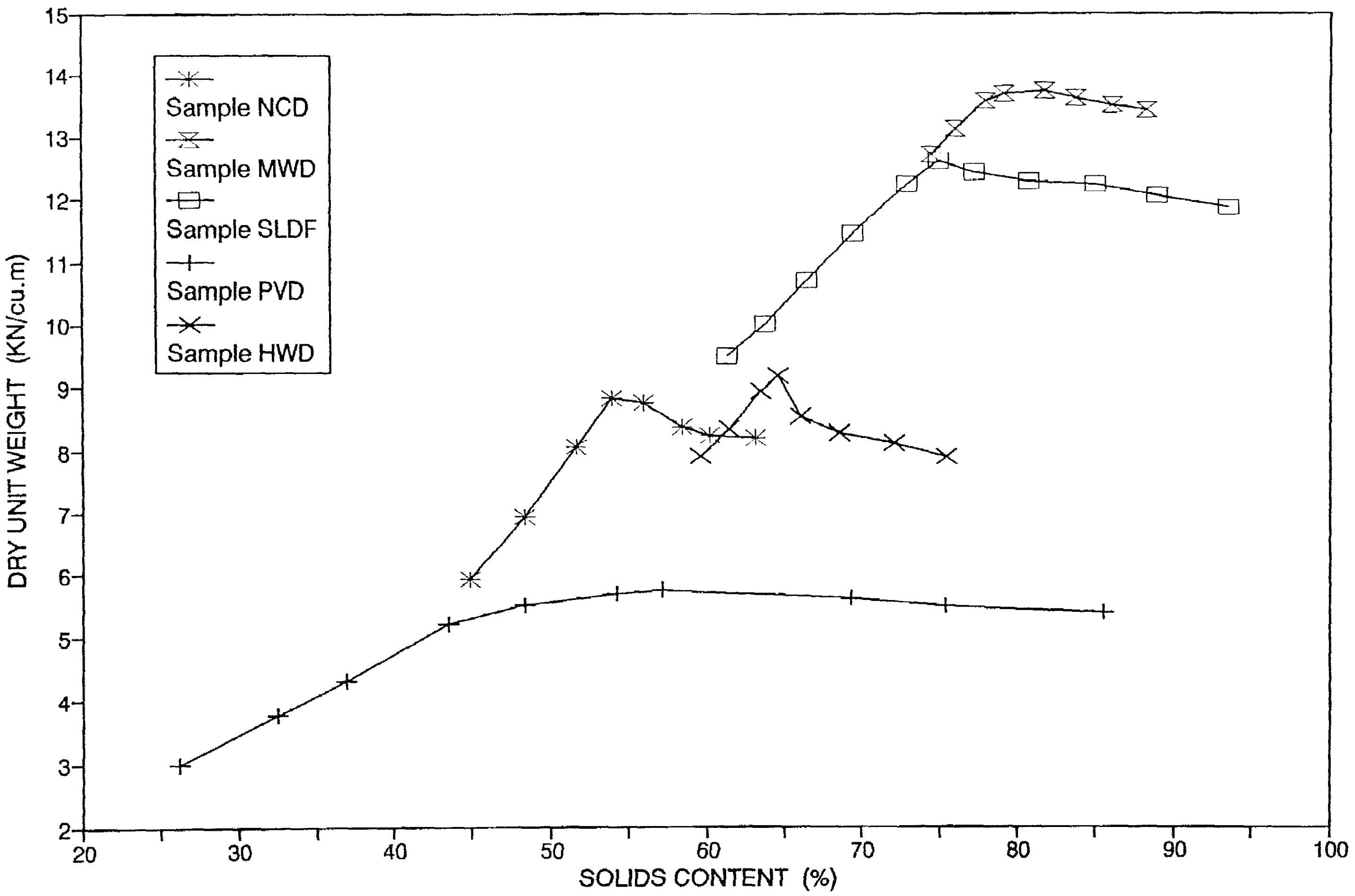

Figure 6 Compaction Curves of WTP Residual Samples from Wet Side with One Hump Pattern

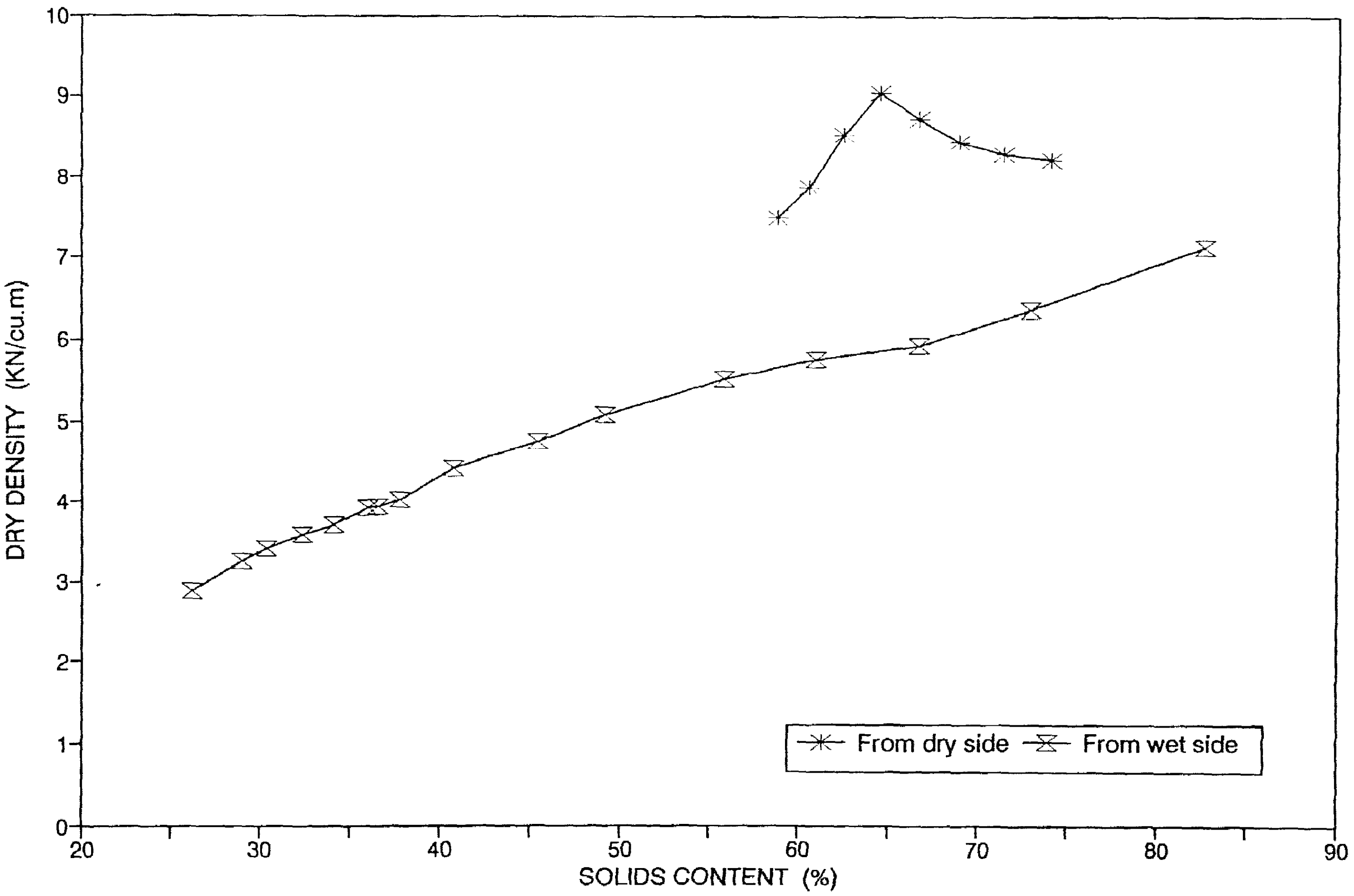

Figure 7 A Comparison of Compaction Curves from Dry and Wet Sides for Sample JCD

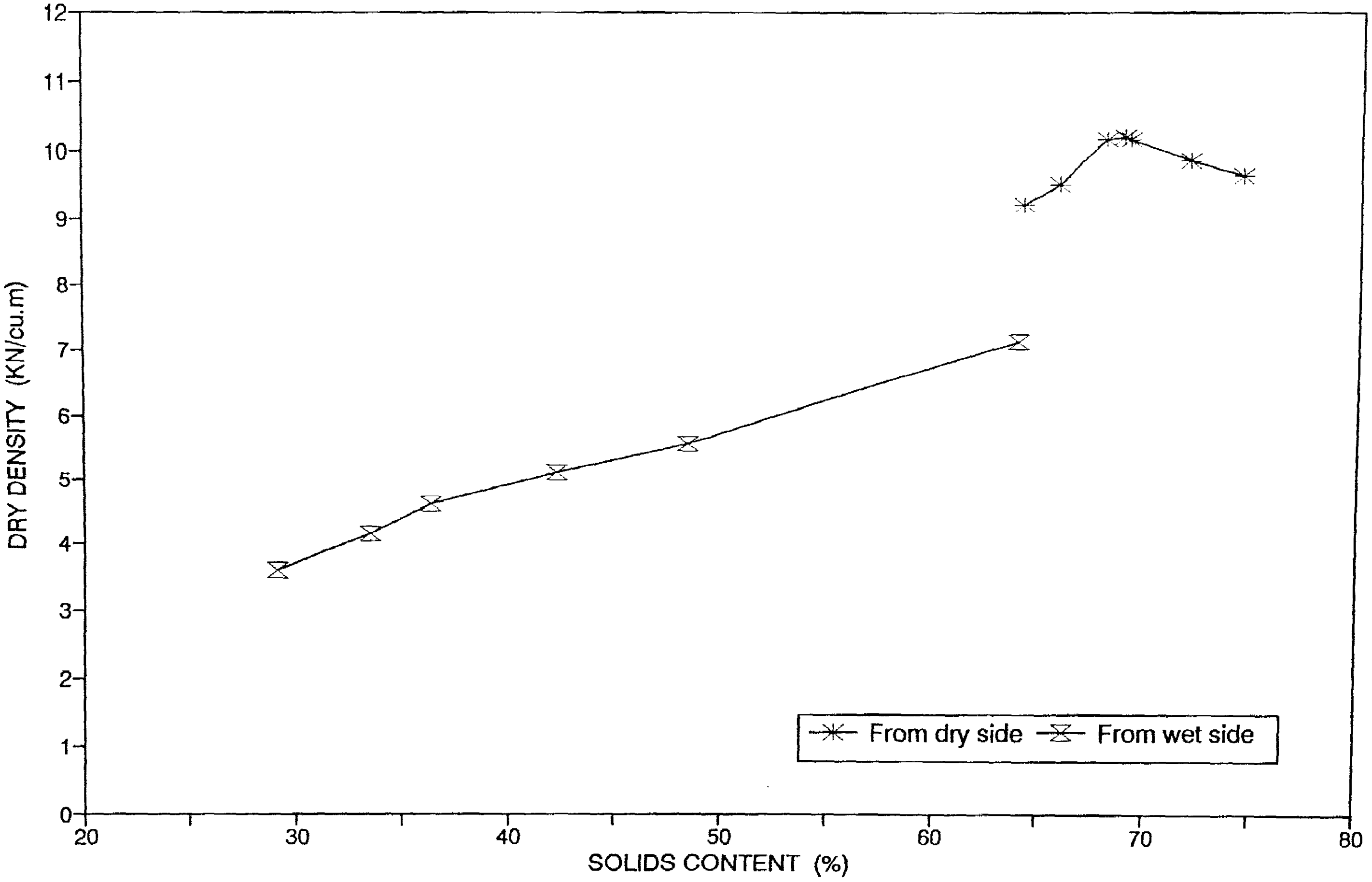

Figure 8 A Comparison of Compaction Curves from Dry and Wet Sides for Sample RWA

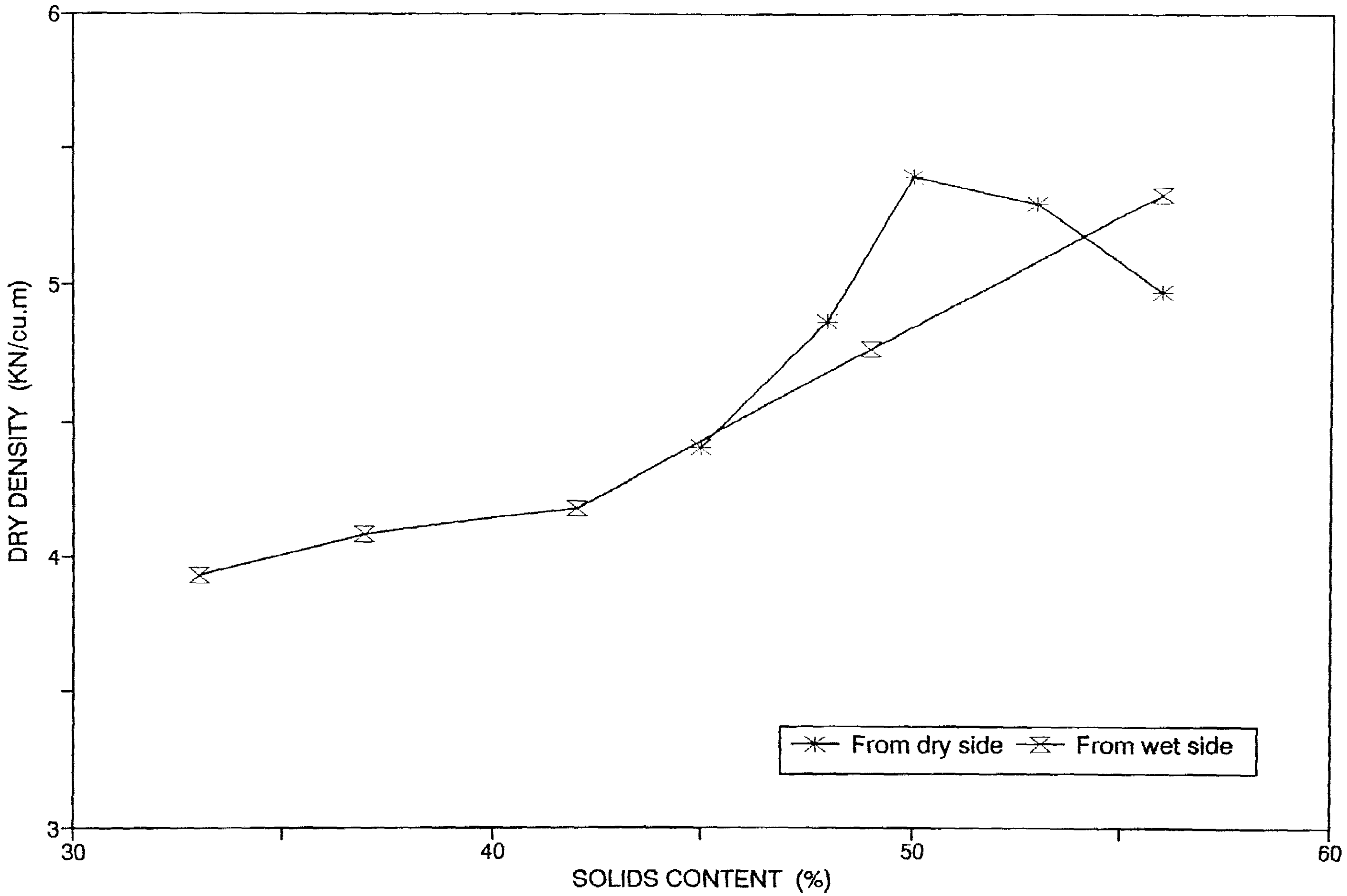

Figure 9 A Comparison of Compaction Curves from Dry and Wet Sides for Sample MQD

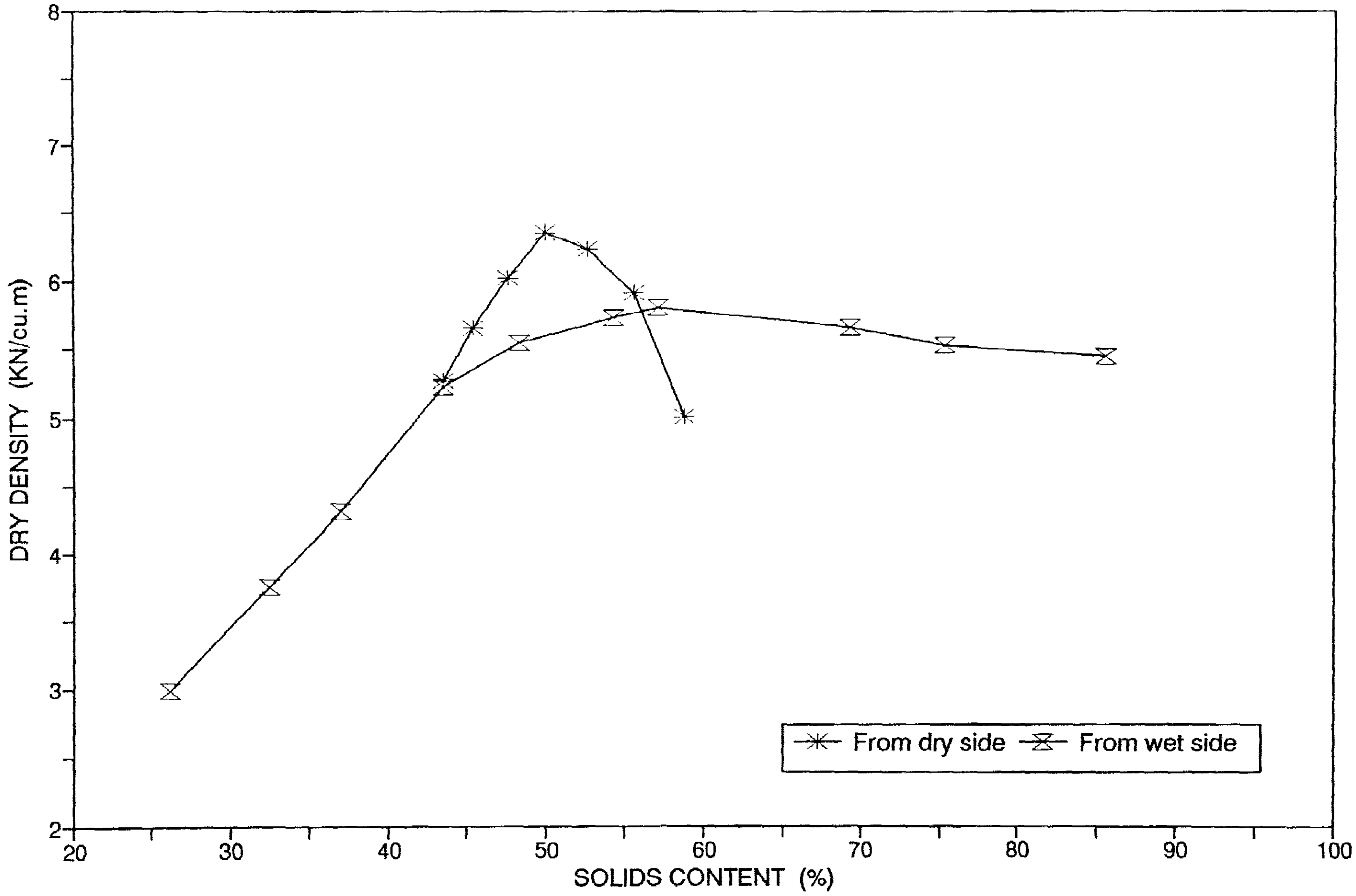

Figure 10 A Comparison of Compaction Curves from Dry and Wet Sides for Sample PVD

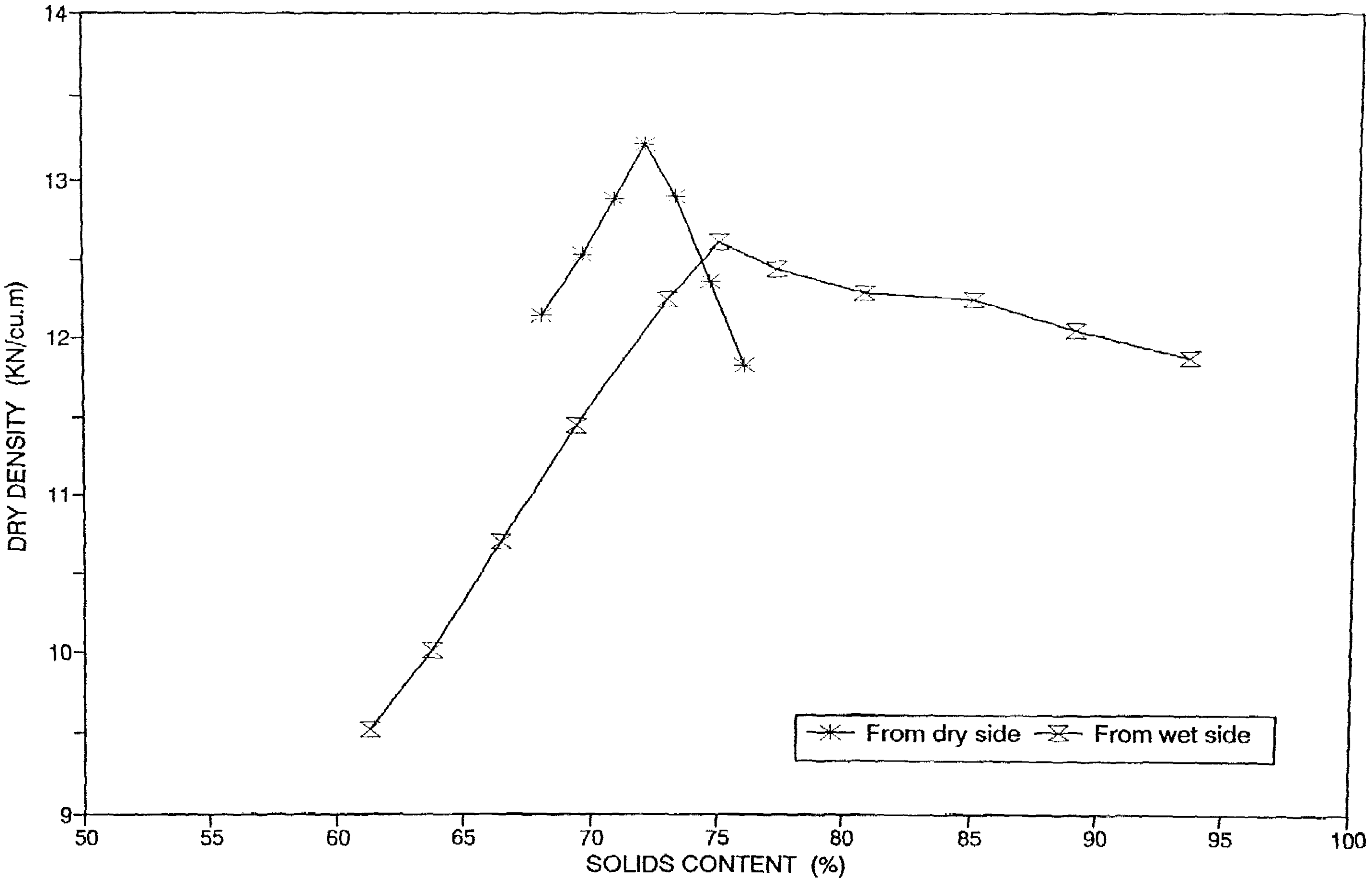

Figure 11 A Comparison of Compaction Curves from Dry and Wet Sides for Sample SLDF

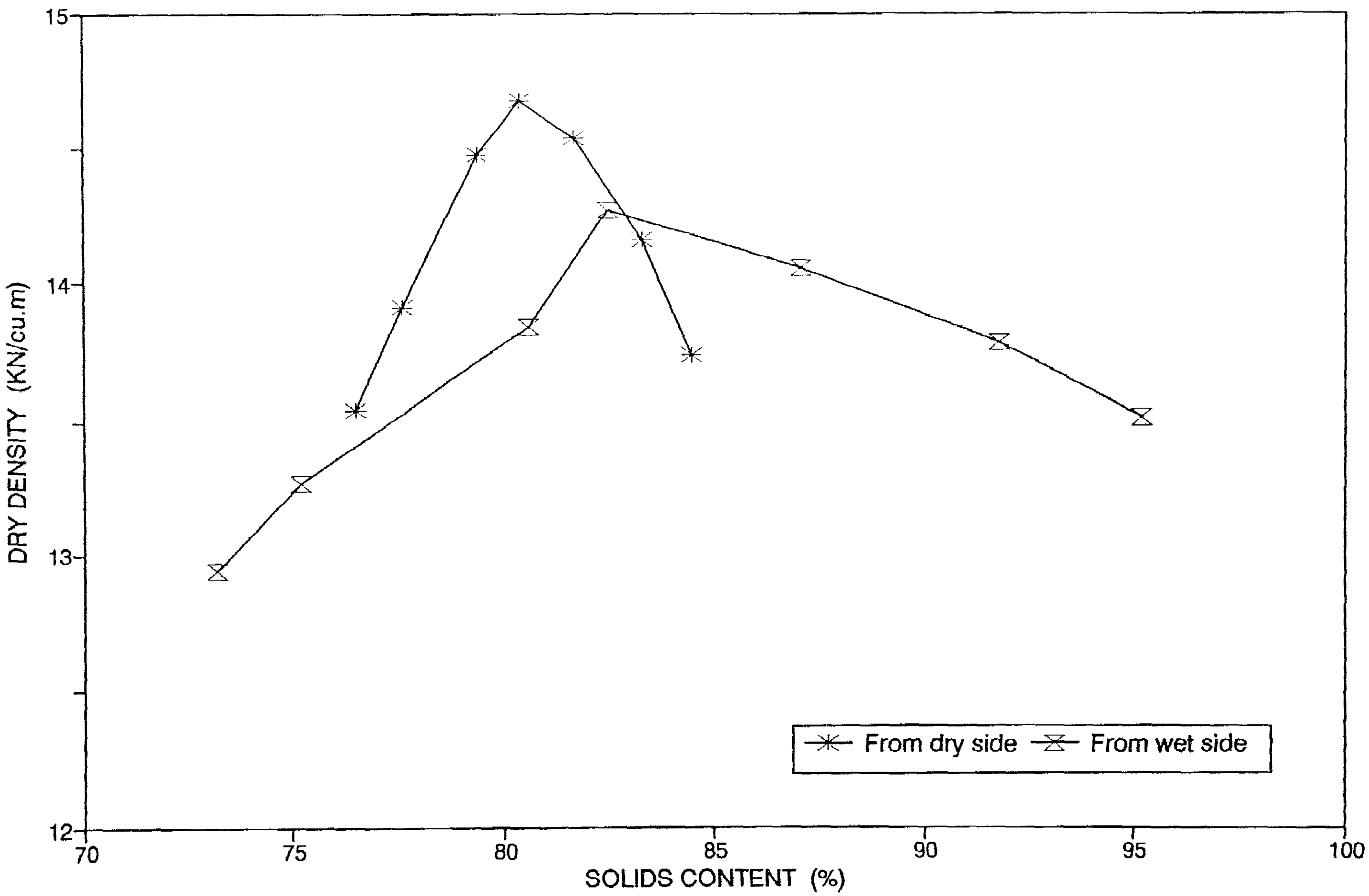

Figure 12 A Comparison of Compaction Curves from Dry and Wet Sides for Sample SLD

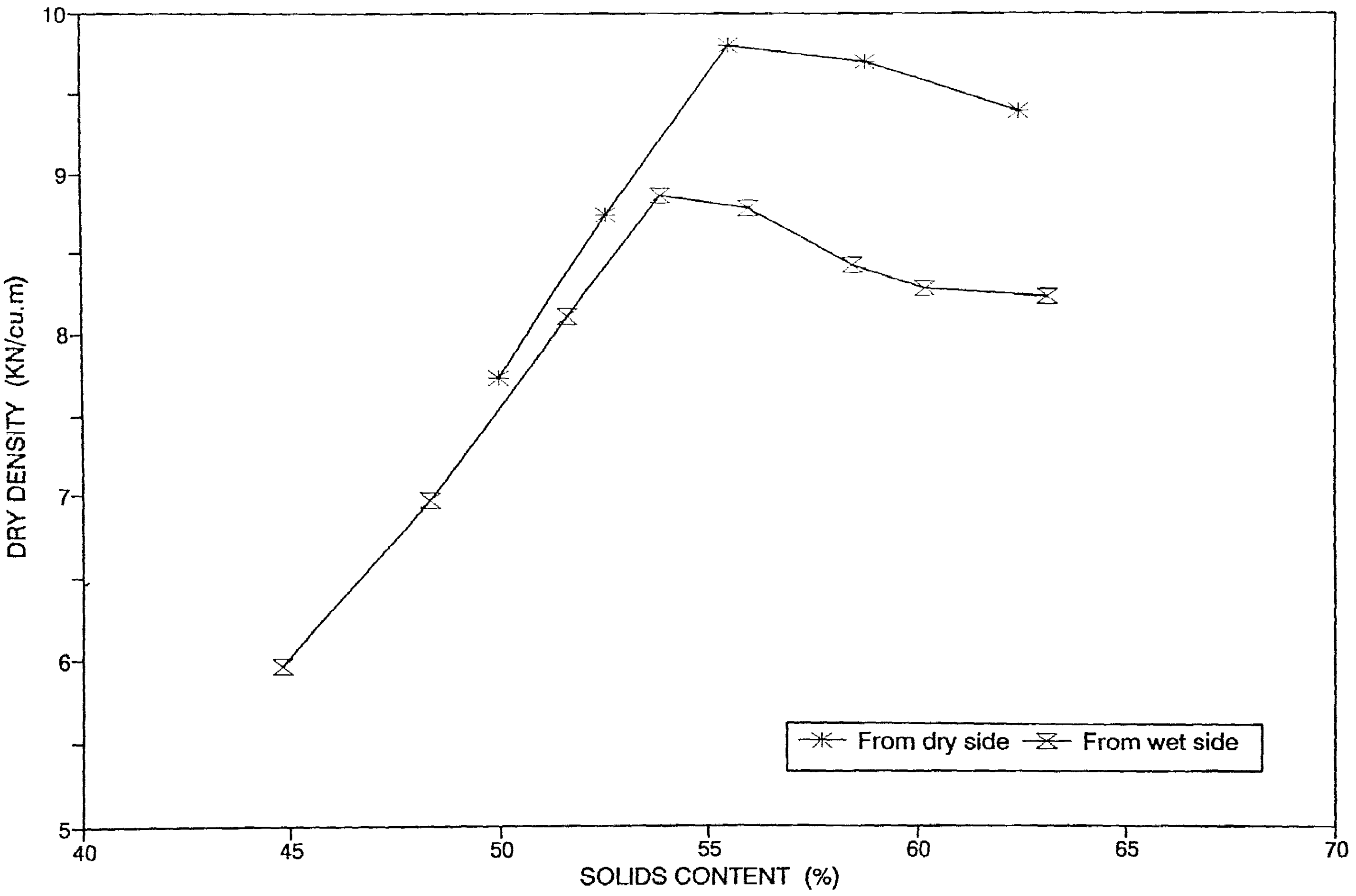

Figure 13 A Comparison of Compaction Curves from Dry and Wet Sides for Sample NCD

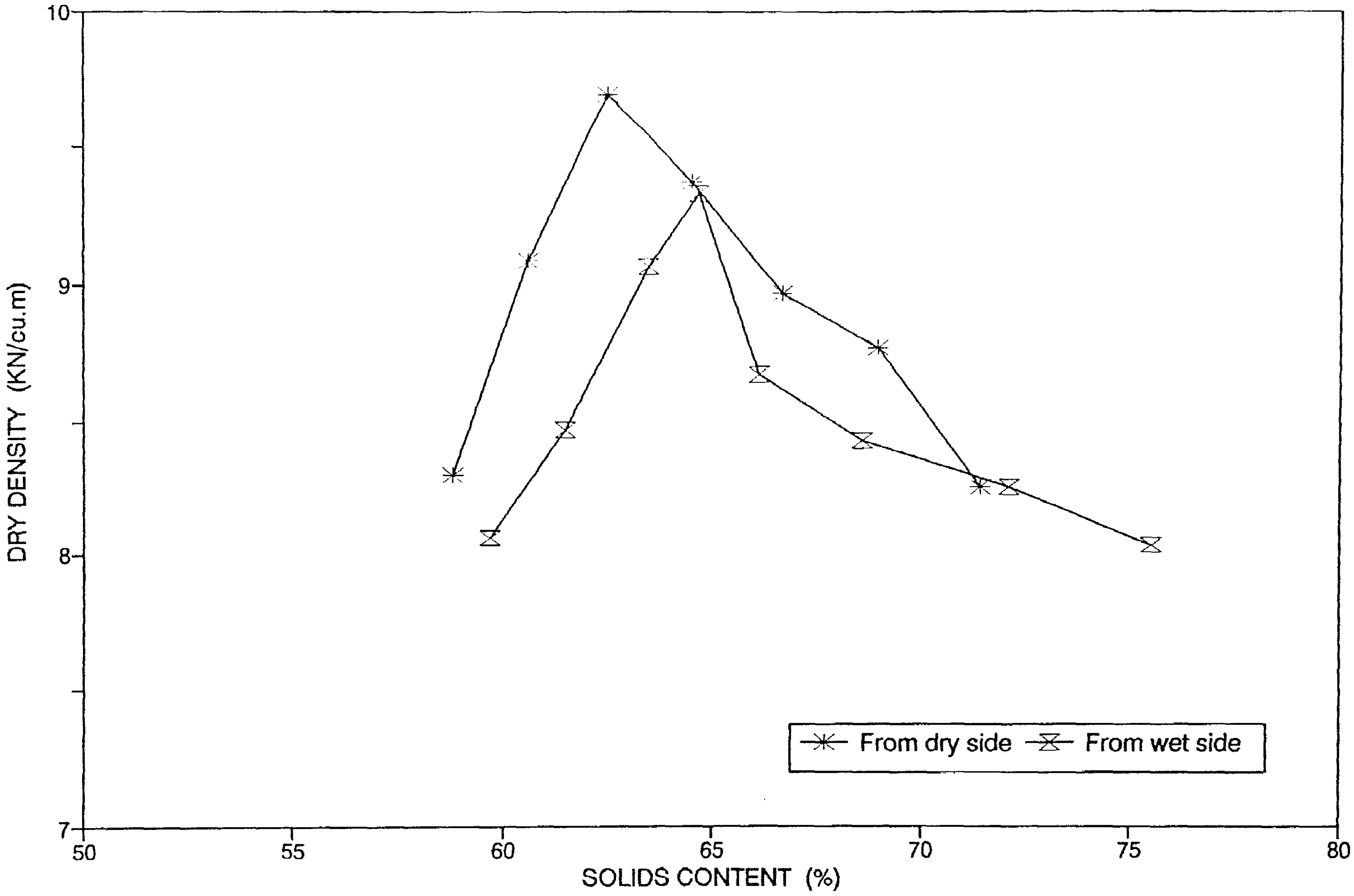

Figure 14 A Comparison of Compaction Curves from Dry and Wet Sides for Sample HWD

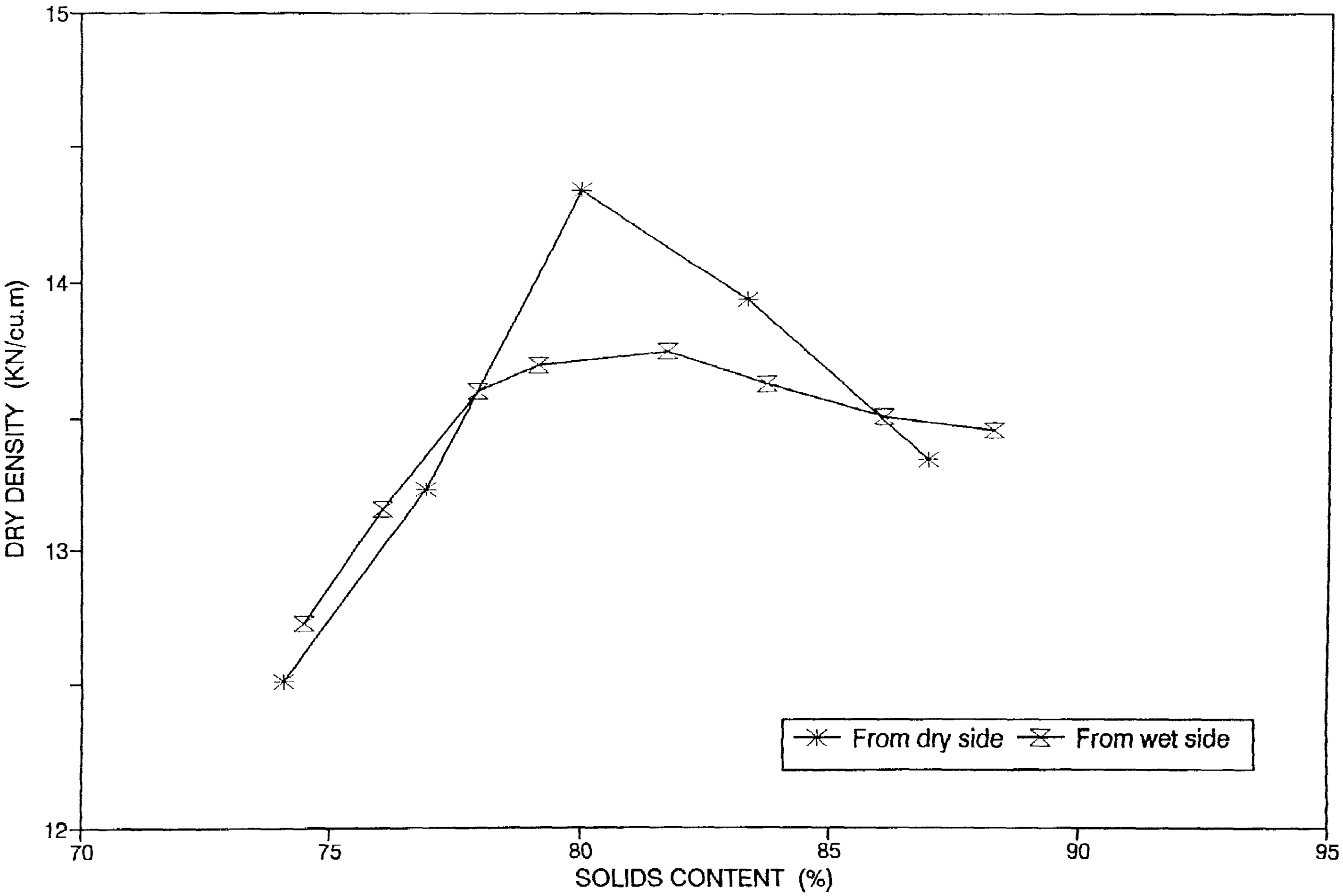

Figure 15 A Comparison of Compaction Curves from Dry and Wet Sides for Sample MWD

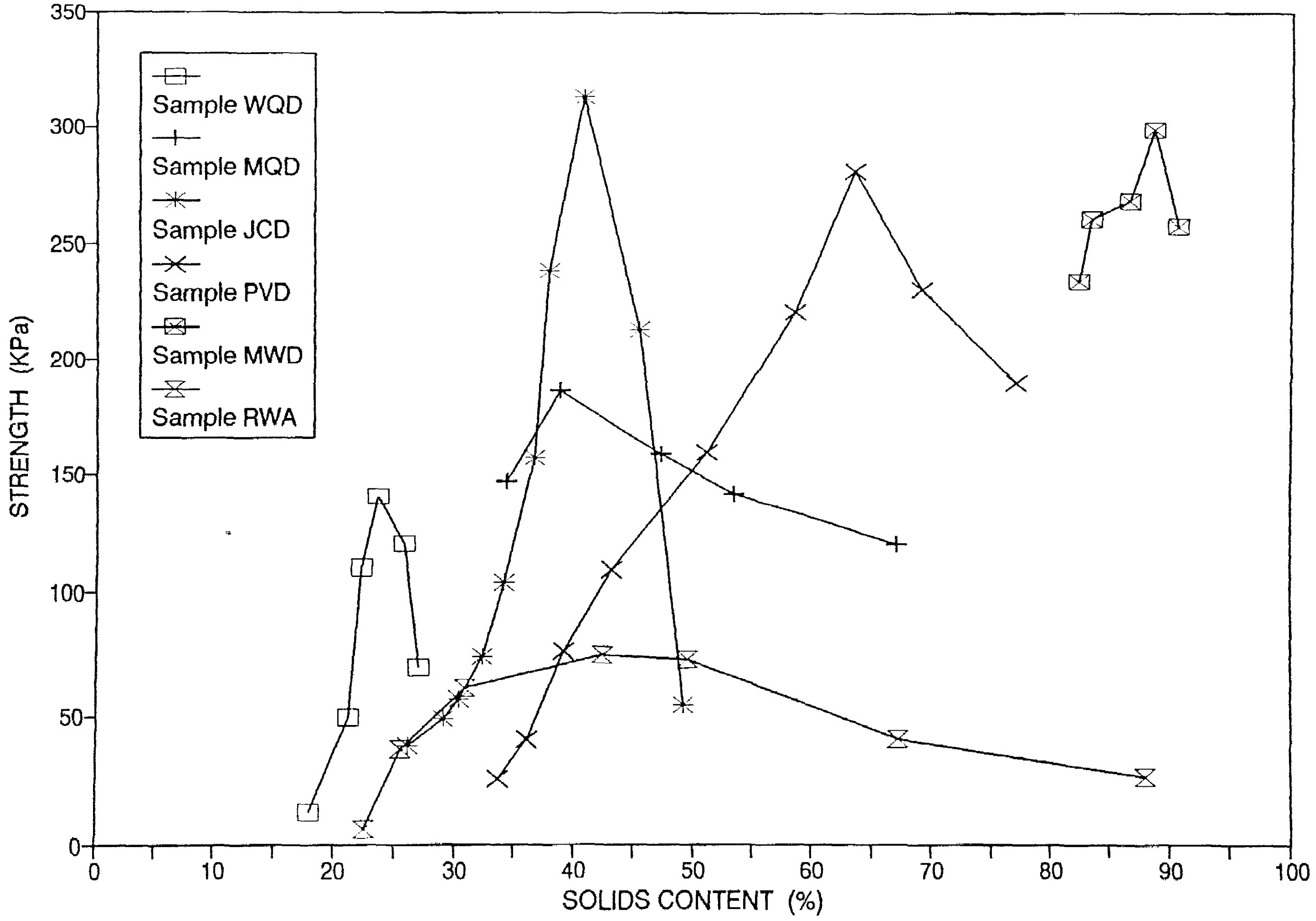

Figure 17 Strength vs. Solids Content Curves of Unconfined Compression Tests with One Hump Pattern of WTP Residual Samples

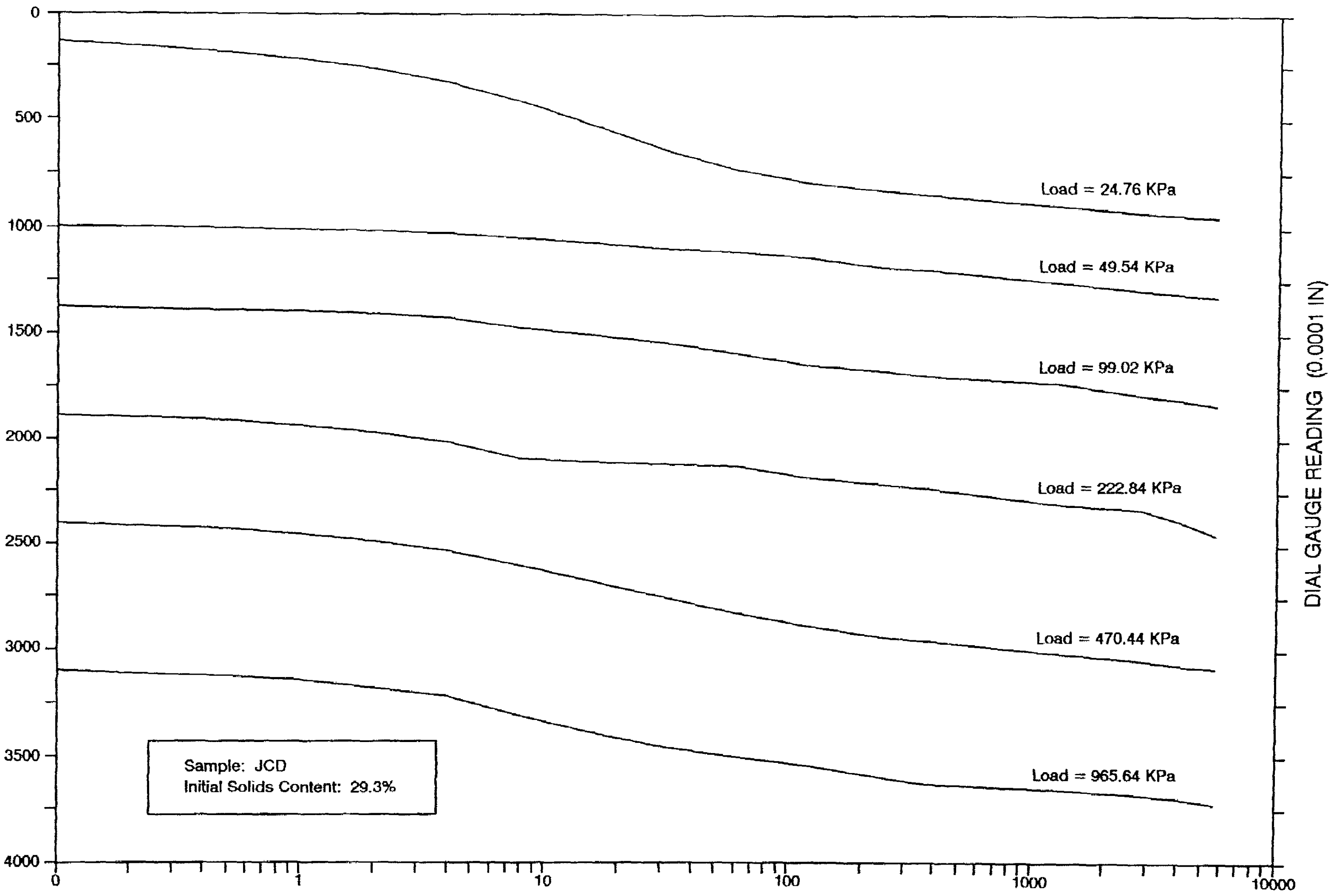

Figure 18 Dial Gauge Reading vs. Log Time Curves of Consolidation Test for Sample JCD

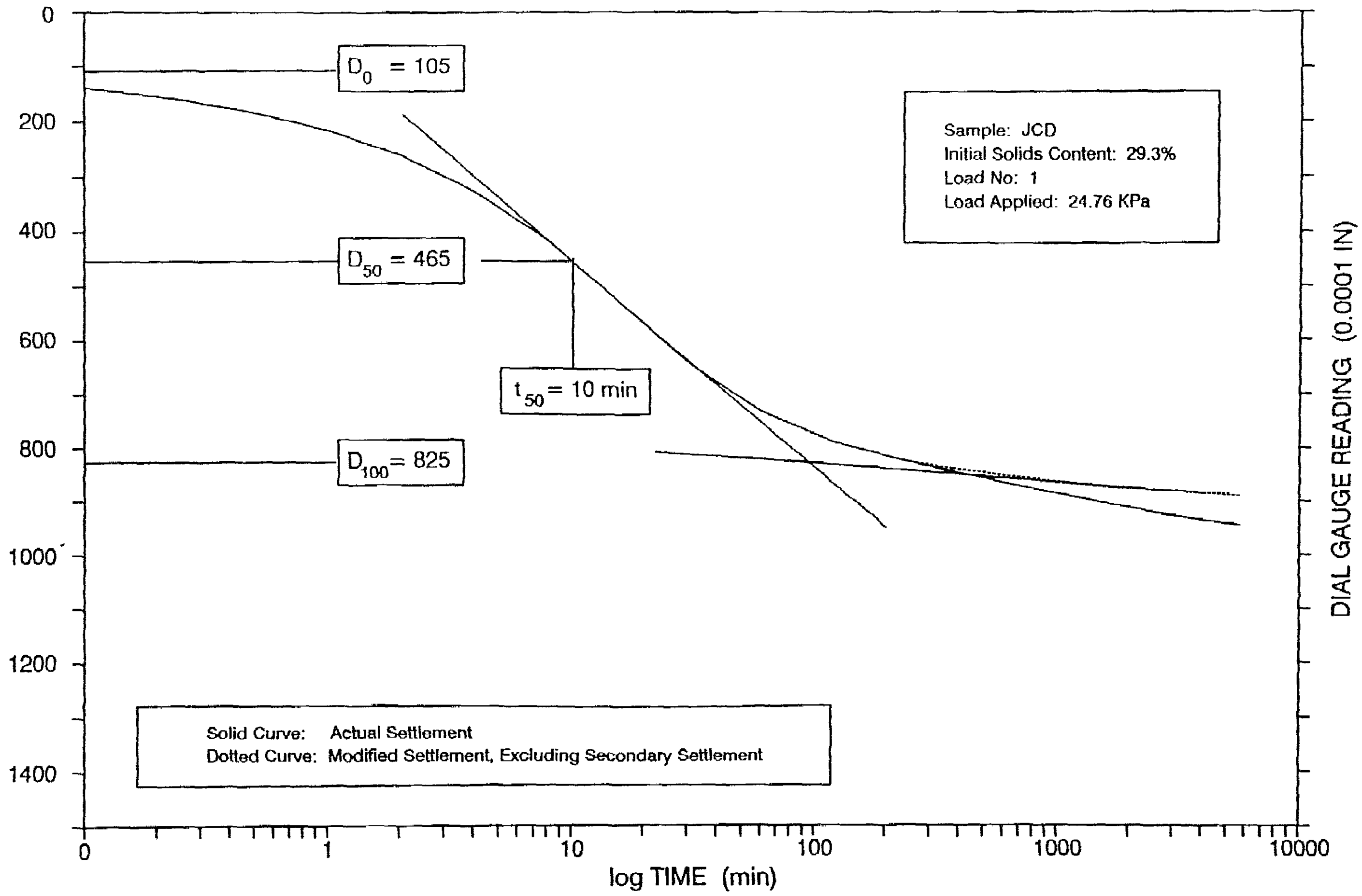

Figure 19 Determination of 50% Consolidation Time Under First Load for Sample JCD

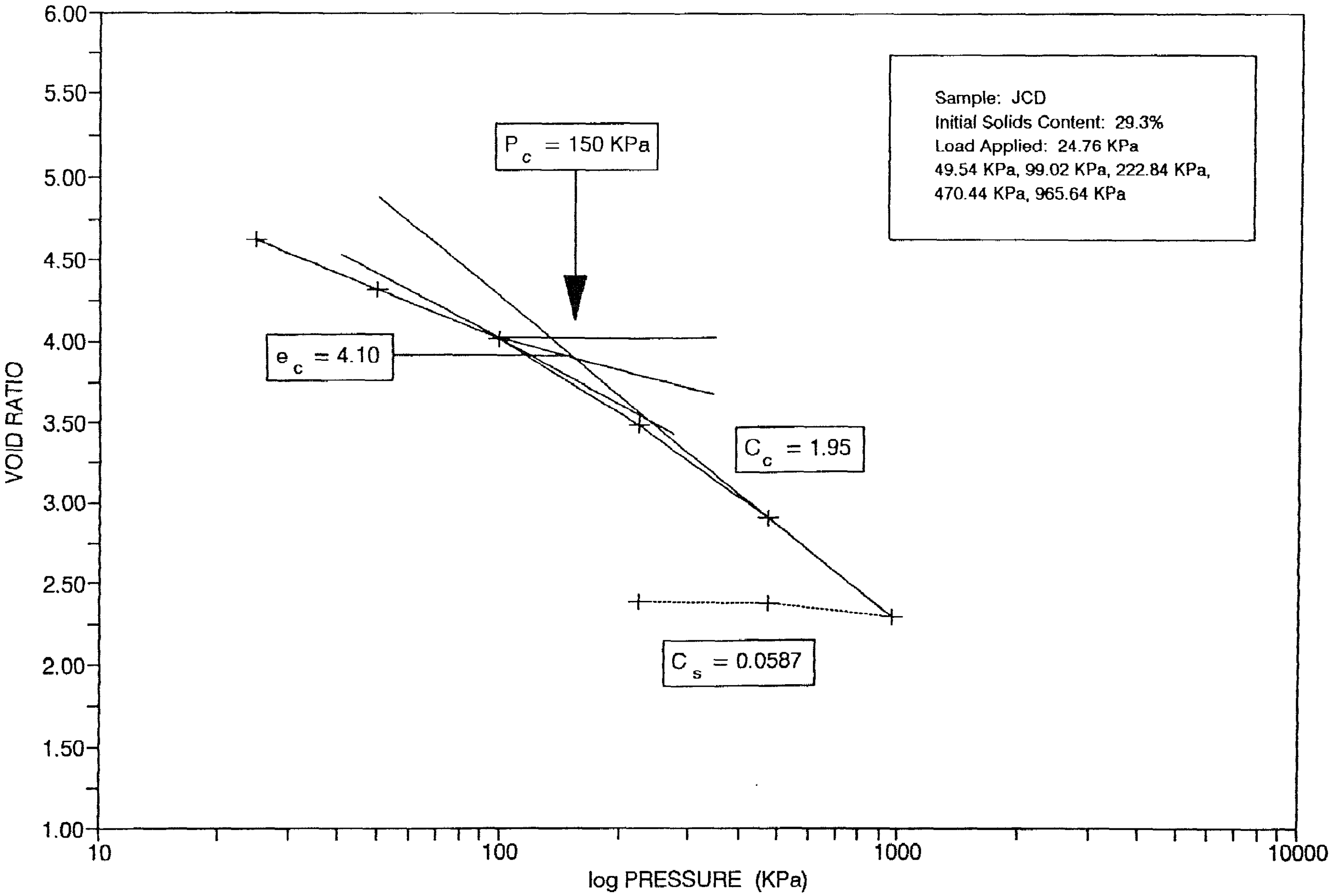

Figure 20 Determination of Preconsolidation Pressure, Compression Index and Swell Index for Sample JCD

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