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Full Length Research Paper

Permeability and swelling characteristics of bentonite

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Permeability and swelling characteristics of bentonite and bentonite-sand are the essential parameters for designing any type of waste disposal or in geo-environmental engineering applications. To design and construct these facilities accurate values of permeability for these bentonite-sand mixtures must be evaluated. For this purpose, a series of various laboratory tests were performed to investigate the coefficient of permeability using direct and indirect test methods derived from consolidation theory using liquid limit 1.5 of bentonite. Permeability tests were also carried out for dynamically compacted bentonite. Void ratio of bentonite is a key parameter of permeability for bentonite and bentonite-sand mixtures. The specimen manufacture method had no effect on permeability. A series of swelling pressure and deformation tests are performed using variable content (30 to 90%) of bentonite at initial dry density of 2 g/cm^3 to investigate the characteristics of buffer material for radioactive waste disposal. Content of bentonite in bentonite-sand mixture is the prime criteria of buffer material and must be taken into consideration in designing any types of waste disposal facilities. Content of bentonite and loading pressure on the specimens is noticeably influenced on maximum swelling rate.

Key words: Bentonite, permeability, swelling pressure, swelling deformation.

INTRODUCTION

As a buffer material bentonite and bentonite-sand mixture have no alternative for radioactive waste disposal. Most of the scientific and engineering development of underground disposal concepts has come from the nuclear industry although progress has been slow. Past practices in disposal of hazardous waste underground (e.g. liquid injects) have not always been appropriate. It is likely that the environmental requirements for all types of underground disposal will converge towards the approaches and standards being developed for long-lived radioactive waste disposal. Since the world’s first disposal of radioactive waste in Oak Ridge, Tennesse (1944), considerable experience has been acquired in the field. Similar approaches were adopted by other nuclear facilities and waste generators in the United States and other countries during the early phases of nuclear power development. Although some researches (Chapuis, 1990; Kashir and Yanful, 2001; Komine et al., 1991; Ogata and Komine, 1999; Pandian et al., 1995) have been carried out, few experiment on bentonite-sand mixture as a buffer material in relation to permeability are available. Coefficient of permeability of bentonite and bentonite-sand mixture by direct and indirect test methods should have to be evaluated.

World-wide there are many initiatives to store or dispose of highly toxic chemical and radioactive waste in deep underground facilities. IAEA (2003) reported that more than one hundred radioactive waste disposal facilities have been operating and more than 42 repositories are under some stage of development in different countries. Environmental requirements for all types of underground disposal will converge towards the approaches and standards being developed for long-lived radioactive waste disposal. Now-a-days compacted bentonite and bentonite-sand mixture is an essential material for waste disposal. To ensure the long term safety of geological disposal, a basic requirement on the buffer is to restrict radionuclide migration from breached waste packages to the surrounding host rock. The buffer material must restrict groundwater movement through it,

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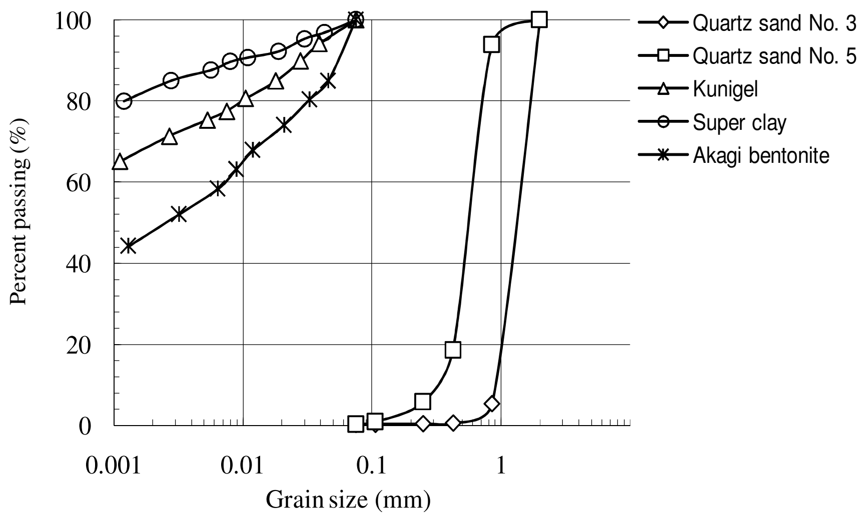

Figure 1. Grain size distribution of quartz sand and bentonite.

Table 1. Index properties of quartz sand and bentonite.

Properties		Akagi (Ca Type)	Kunigel (Na type)	Super clay (Na type)	Quartz sand No. 3	Quartz sand No. 5
Specific gravity G_s		2.744	2.797	2.857	2.622	2.623
Initial water content W_0 (%)		5.90	7.20	10.10	-	-
Liquid limit W_L (%)		295	497	690	-	-
Plastic limit W_P (%)		27	26	43	-	-
Plasticity index I_P		268	471	647	-	-
Grain size	0.075 - 2 mm	0	0	0	100	100
	0.005 - 0.75mm	44	25	13	0	0
	< 0.005 mm	56	75	87	0	0
Effective grain size D_{10} (mm)		-	-	-	0.31	0.47

sorbs dissolved nuclides and prevent migration of radionuclide bearing colloids. A material in which 70% bentonite and 30% sand mixed with a dry density of 1.6 g/cm^3 is selected as the base line for the buffer JNC (2000). This study describes a series of laboratory experiment that examined swelling characteristics and permeability of bentonite and bentonite-sand mixture from direct permeability test by falling head method and indirect test derived from consolidation theory.

MATERIALS AND METHODS

Test materials

Three different types of powdered bentonite i.e. Akagi (A), Kunigel (K) and Super clay (S) have been used in this experiment. Quartz sand No 3 (S_3) and 5 (S_5) is used in combination with bentonite as a mixture material. Grain size distribution of quartz sand and different types of bentonite are presented in Figure 1. Specific gravity, initial water content, liquid and plastic limit of bentonite and grain sizes are presented in Table 1.

Permeability

Bentonite powder was fully mixed with de-aired water to prepare slurry having initial water content of 1.50 times of liquid limit (W_L). The slurry was mixed with quartz sand number 3 and 5 to desired mixture ratio and poured directly into the consolidometer ring of model JIS A-1217. The inner diameter of the consolidometer ring was 60 mm and sample height about 20 mm. The applied pressure for slurry samples are 4.90, 9.81, 19.62, 39.24, 78.48, 156.96, 313.92, 627.84, 1255.68 kPa, respectively. A series of consolidation tests were run by incrementing the load at 24 h time interval.

The coefficient of permeability of the bentonite slurry was measured from consolidation tests. The permeability test by falling head method of the slurry samples was run at the end of each load increment. Direct permeability tests as well as a standard incremental loading consolidation test were run on the apparatus for the same specimen.

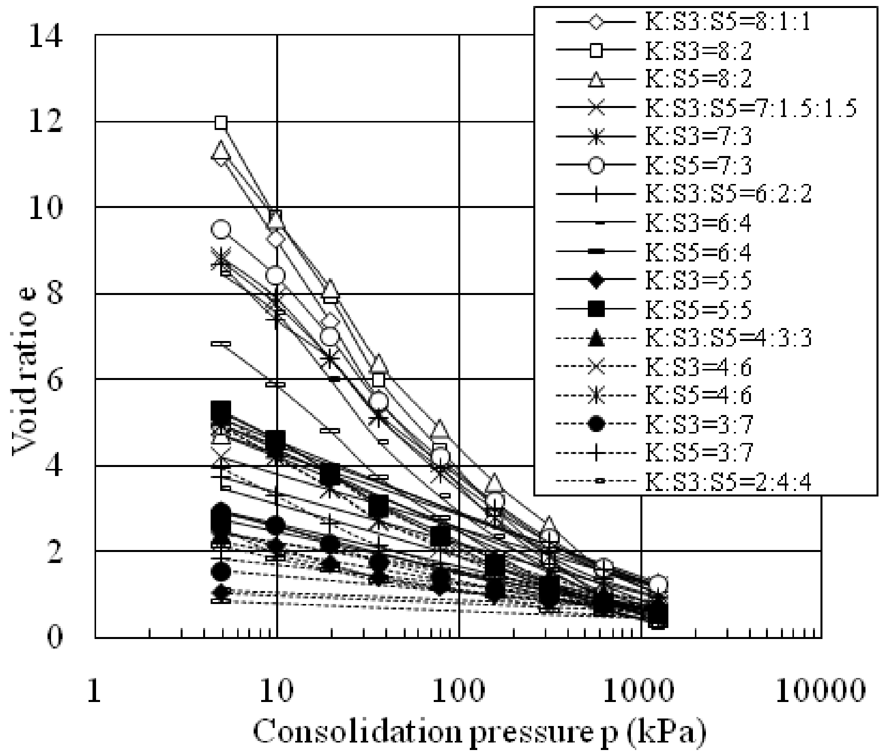

Figure 2. e-log p curve of Kunigel - sand slurry.

Swelling pressure

The vertical swelling pressure under constant volume conditions of the specimens was measured by a digital strain meter (TC-31K, Tokyo Sokki Kenkyuijo Co. Ltd., Japan). Distilled water was supplied from the bottom of the confined specimen. Petroleum jelly was added to the inner cell of the swelling pressure box to reduce the frictional force. During water uptake the volume change of the specimen was considered to be negligible due to stiffness of the pressure box which was sufficient to confine the specimen. The relationship between elapsed time and swelling pressure (MPa) was observed from the initiation of specimen wetting. Temperature was recorded after reaching the peak swelling pressure for each specimen to observe the relationship between temperature and swelling pressure. The water content of the specimen was measured at the end of the experiment and the degree of saturation of the specimens was at or close to 100%.

Swelling deformation

Swelling deformation under static load

The vertical swelling deformation of compacted specimens under static load of 0.16, 0.32, 0.64 and 1.28 MPa was measured by oedometer test apparatus. Distilled water was applied to the specimen simultaneously with the prescribed vertical pressure. Permeability tests were conducted at the completion of swelling. The swelling rate of the compacted specimen was calculated by $S_R = 100\Delta h / h_0$. Where S_R is the swelling rate, Δh is the swelling deformation and h_0 is the initial specimen height.

Swelling deformation without loading

Free swelling deformation tests were performed on the compacted specimens by adsorbing distilled water under approximately zero vertical pressure that is, loading plate only. The inner diameter and height of the free swelling deformation test apparatus was about 6 cm. Petroleum jelly was applied to the inner wall of the swelling deformation cell to reduce frictional force. The relation between elapsed time and axial swelling deformation was measured after the initiation of specimen wetting. The swelling rate was calculated in the same manner as for the swelling tests under loading condition.

RESULTS AND DISCUSSION

Permeability

The relationships of void ratio and logarithm of consolidation pressure are presented in Figure 2. It is depicted that higher percentage of bentonite have steeper slope compared to those for low percent bentonite content. The bentonite particles, due to their very large specific surface, form a coating around the coarser sand particles, thus preventing direct contact between grains. Substantially, the coarser particle floats in a matrix provided by the bentonite clay particles. Earlier, many researchers Pandian and Nagaraj (1990), Pandian et al. (1988) and Murthy et al. (1987) observed

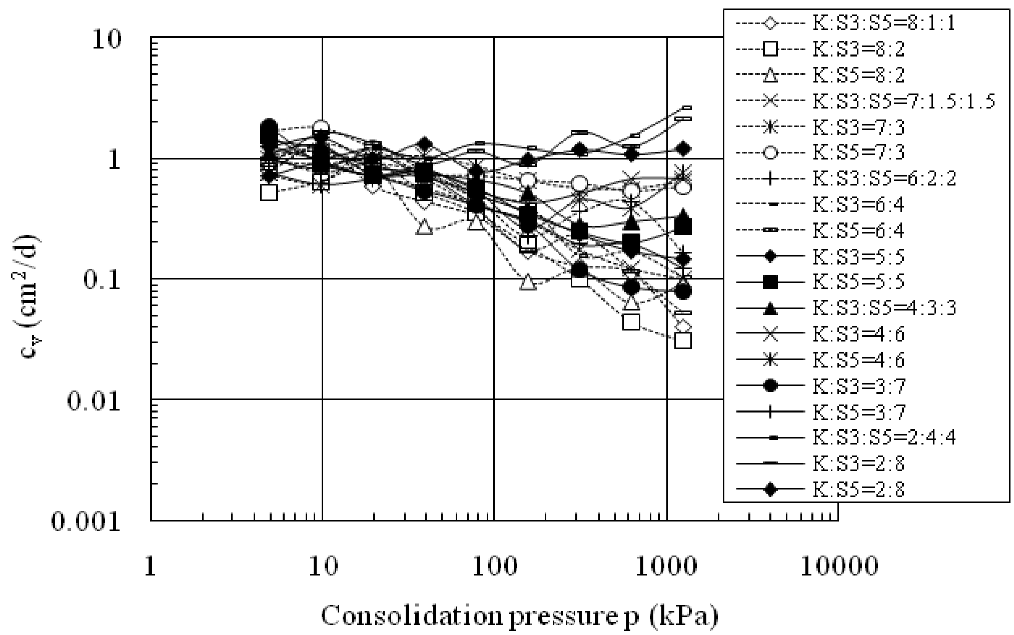

Figure 3. Log c_v - log p curve of Kunigel - sand slurry.

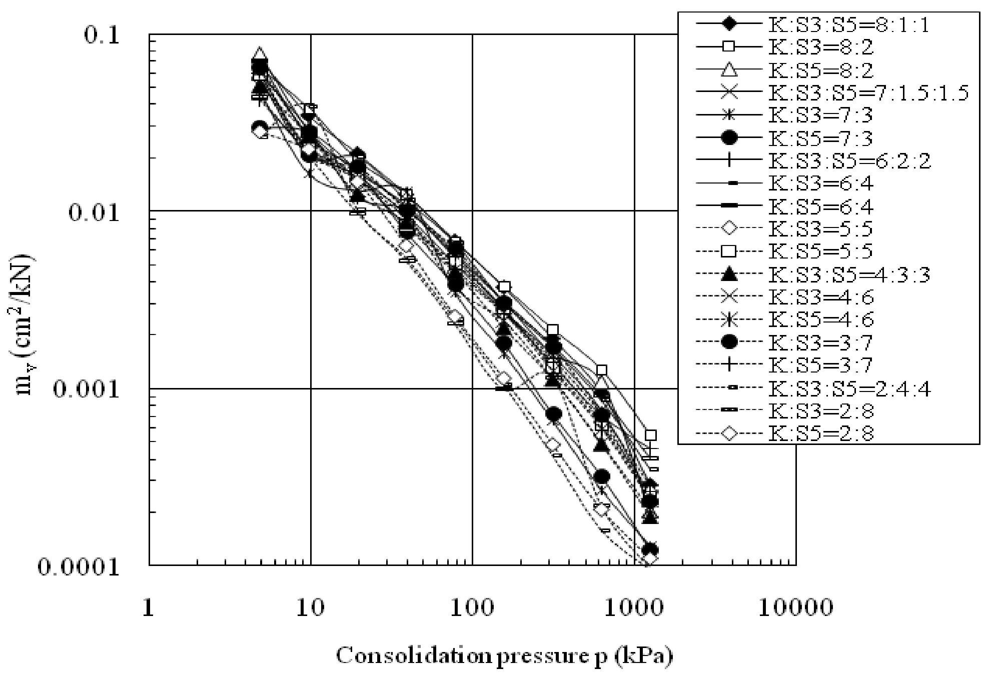

Figure 4. Log m_v - log p curve of Kunigel - sand slurry.

that coarser particles only dilute that physico-chemical potential of a soil proportionately. A soil possesses physico-chemical potential by dint of inherent interparticle forces as well as the associated clay fabric. Figures 3 and 4 shows the coefficient of consolidation (c_v) and coefficient of volume compressibility (m_v) of bentonite-sand slurry with respect to consolidation pressure, respectively. The c_v and m_v values were varied at the same consolidation pressure might be due to content of bentonite in bentonite-sand mixture.

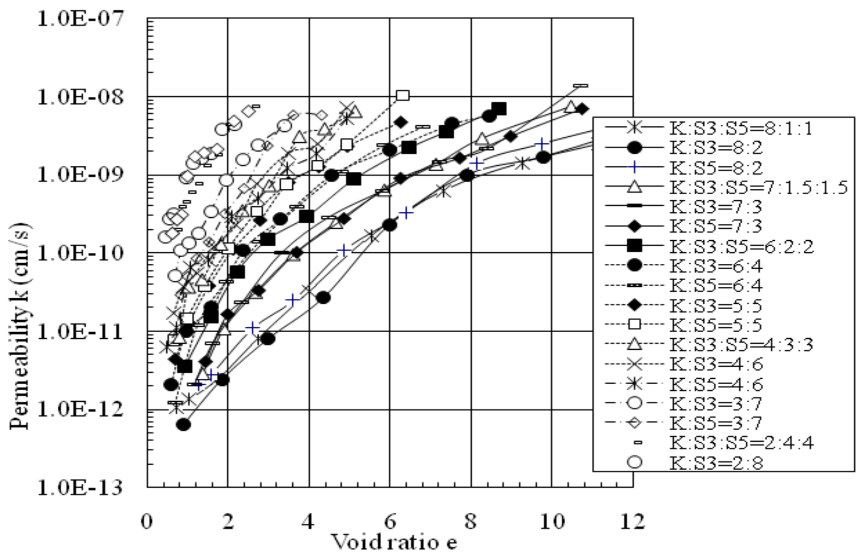

Figure 5. Permeability of Kunigel-sand slurry.

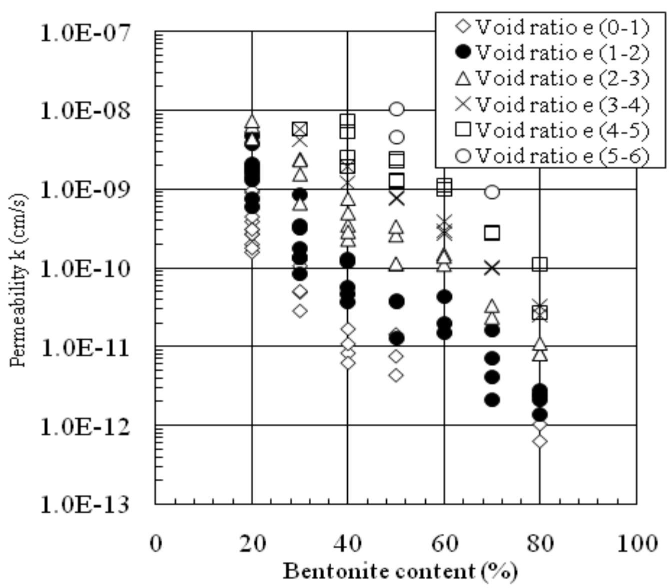

Figure 6. Relationship between permeability and bentonite content.

The coefficient of permeability of Kunigel-sand mixtures with void ratio is presented in Figure 5. Permeability varied in the range of 10^{-8} to 10^{-12} cm/s with the increasing sand content of 20 to 80%. Coefficient of permeability due to 30 % of S_3, S_5 and both in bentonite-sand mixture varied from 1.55×10^{-8} to 2×10^{-12} cm/s, but no significant difference among them. Permeability varied from 1×10^{-8} to 4×10^{-12} cm/s by 50% sand containing in bentonite-sand slurry and had clear distinct from 30% sand in respect of same void ratio. The coefficient of permeability distinctly varied between 70% of S_3 and S_5 in bentonite-sand slurry at the same void ratio. It ranged from 6×10^{-9} to 2×10^{-11} cm/s. It might be due to grain size distribution of S_3 and S_5. In mixture material permeability generally increased when grain size of sand in increased. Sivapullaiah et al. (2000) reported that permeability increases with the increase of coarse fraction, but in the case of higher content of clay permeability controlled by clay minerals only. The relationships between the permeability and content of

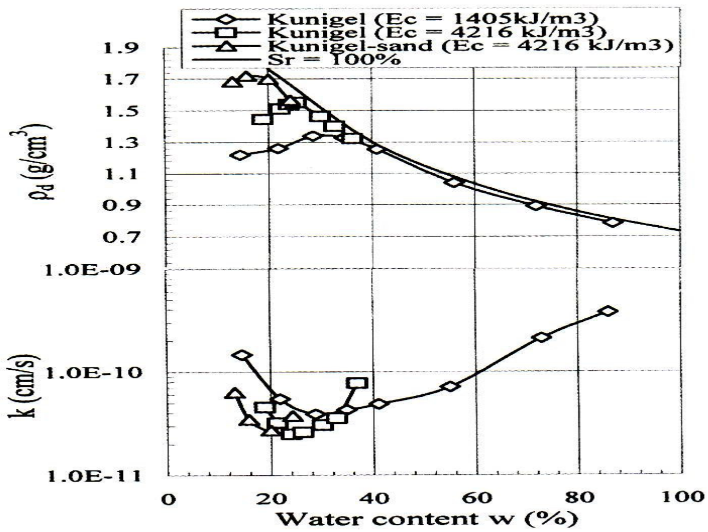

Figure 7. Relationship of permeability, dry density and water content.

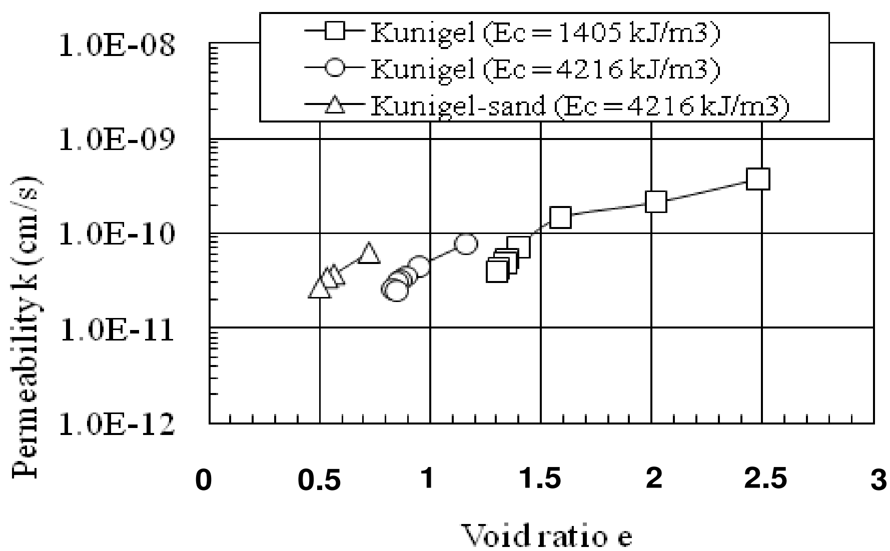

Figure 8. Relationship between permeability and void ratio of compacted specimen.

bentonite in bentonite-sand slurry are presented in Figure 6. Permeability remarkably decreased by the increasing of bentonite. The results showed that the coefficient of permeability varied at the same bentonite content in bentonite-sand mixture due to the void ratio. Relationships of compacted specimen among permeability, dry density and water content are presented in Figure 7. The amount of compaction energy greatly affected the maximum dry density and optimum water content. The effect of increasing the compaction energy resulted in an increase in the maximum dry density and decreases the maximum water content Maximum dry density is observed about 1.72, 1.54 and 1.35 g/cm^3 while water content about 20, 24 and 28%, respectively. In general, the water content which gives raise to the maximum density hardly agrees with the water content that gives rise to the minimum permeability. Increasing the molding water content resulted in a decrease in permeability on the dry side of optimum water content and a slight increase in permeability on the wet side of optimum. This behavior was also seen in other types of clay. Coefficient of permeability in relation to void ratio of dynamic compacted specimen for bentonite and bentonite-sand mixtures is presented in Figure 8. Permeability varied

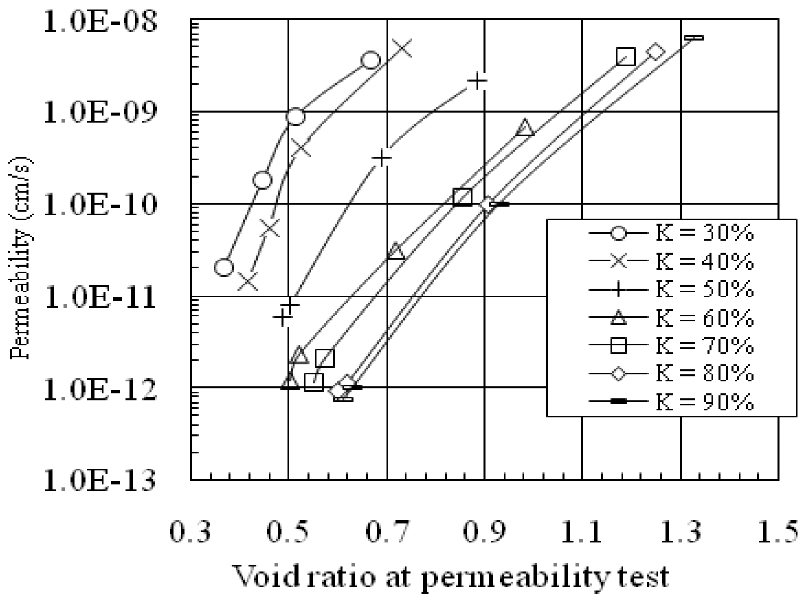

Figure 9. Permeability of compacted bentonite-sand mixture under static load.

remarkably by the application of different compaction energy. For solely bentonite, due to 1405 and 4216 kJ/m^3, coefficient of permeability varied from about 4 × 10^{-11} to 5 × 10^{-10} and 2.5 × 10^{-11} to 7.5 × 10^{-11} cm/s, respectively while k varied between 3.5 × 10^{-11} to 7.6 × 10^{-11} cm/s by 4216 kJ/m^3 in bentonite-sand mixtures. It might be due to the structural rearrangement of the particles. The effect of structural disturbance on permeability is much pronounced in fine-grained soils. Yoshinaka and Kazama (1973) observed that soil particles are gradually oriented due to increasing rate of compaction energy. Stratified soil masses have marked variations in their permeability in the direction parallel and perpendicular to stratification, the permeability parallel to the stratification being always greater.

Permeability of compacted bentonite-sand mixture is presented in Figure 9. It illustrated that permeability decreased due to increase of bentonite at the same void ratio. The coefficient of permeability has marked variation containing 30 to 50% bentonite content compared to 60 to 90% bentonite.

The coefficient of permeability of slurry and compacted bentonite determined from direct permeability test and derived from consolidation theory has distinct variation at the same void ratio (Figure 10). It is depicted from the figure that coefficient of permeability varied about 10 times among the direct and indirect test methods. Changes in permeability of bentonite slurry and bentonite-sand mixture may be accounted for in terms of changes in the state of flocculation of the clay minerals. In the flocculated sate they tend to adopt an open type of structural arrangement with a relatively high permeability. When dispersed the clay minerals may be transported and deposited in narrow pore openings where they have a clogging effect. Changes in the state of flocculation can be affected by compaction of the samples. For the same soil at the same void ratio, the permeability may vary with different method of placement or compaction of grains resulting in different geometric arrangement and shape of voids. Not only is the permeability of a soil dependent on its void ratio, but for any void ratio it would also be a function of the geometrical arrangement of the particles in the soil, that is of soil fabric. The permeability of a soil with a particular fabric and for a particular permeant is a function of effective stress. Effective stress increases, void ratio decreases and therefore permeability decreases. Important factors affecting the permeability values are the types of permeameter, effective stress, hydraulic gradient, size of the specimen, type and chemistry of the permeant and termination criteria. These findings were summarized by Benson et al. (1994), Daniel (1994) and Shakelford (1994).

Swelling pressure

Swelling pressure fluctuation pattern of different types of bentonite-sand mixtures are presented in Figure 11. Content of bentonite in the bentonite-sand mixtures is the main component for maximum swelling pressure. The initial dry density for all of the specimens was about 2 g/cm^3. Swelling pressure rapidly increased and reaching its peak within 30 to 50 h with respect to elapsed time and after that continued with little fluctuation. Maximum swelling pressure fluctuated with elapsed time might be due to temperature. Maximum swelling pressure distinctly

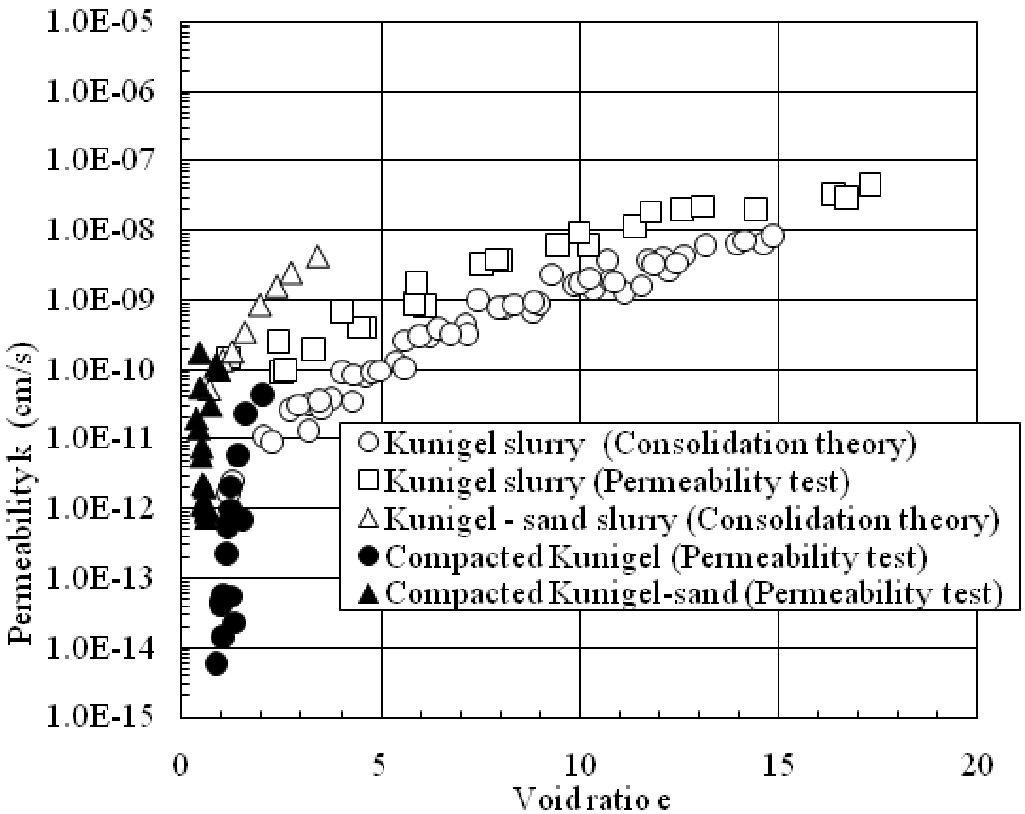

Figure 10. Relationship between coefficient of permeability and void ratio using different methods.

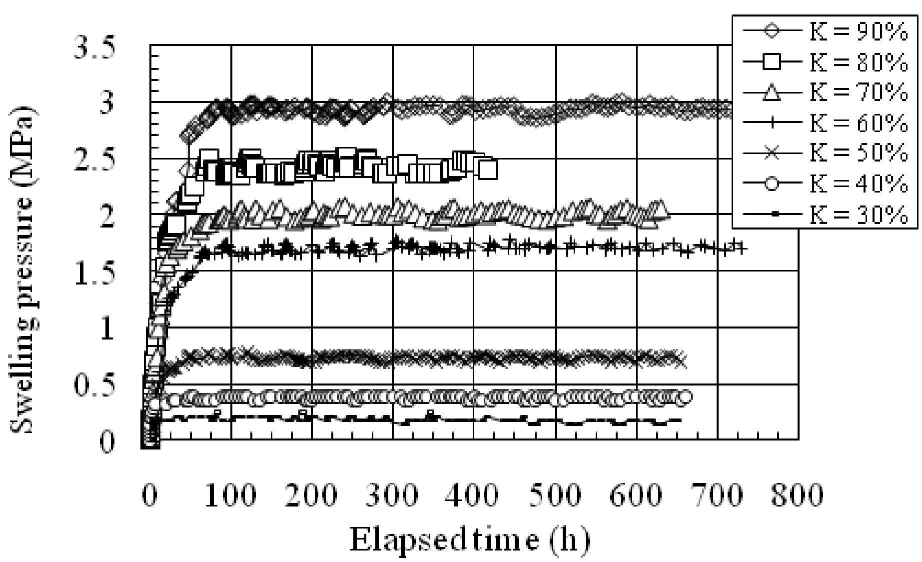

Figure 11. Swelling pressure fluctuation pattern of Kunigel-sand mixture.

increased with the increasing rate of bentonite. Relationships between maximum swelling pressure and temperature of Kunigel-sand mixtures are shown in Figure 12. This figure exhibited that swelling pressure increased due to temperature. General tendency was that swelling pressure increased at higher temperature. Swelling

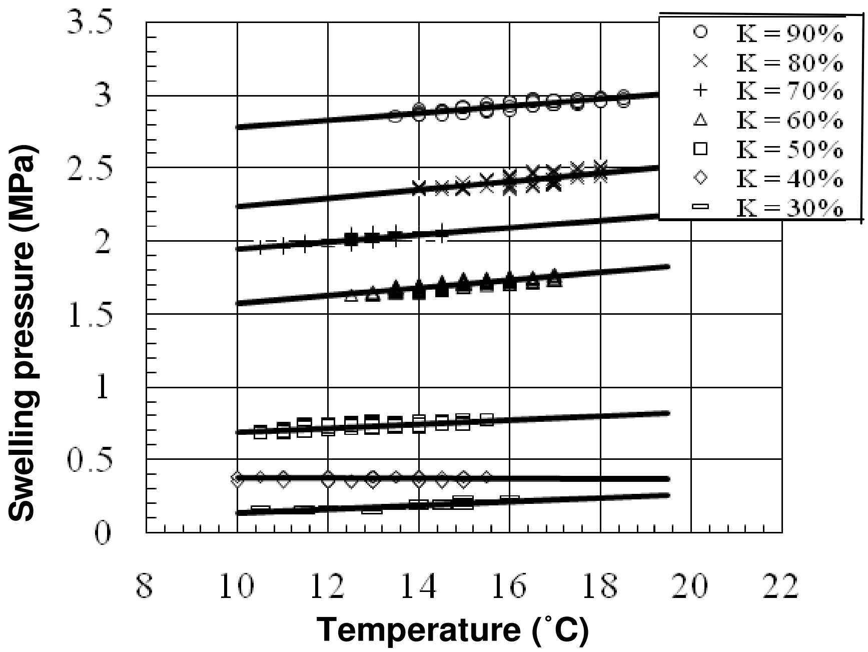

Figure 12. Relationship between Swelling pressure and temperature of Kunigel-sand.

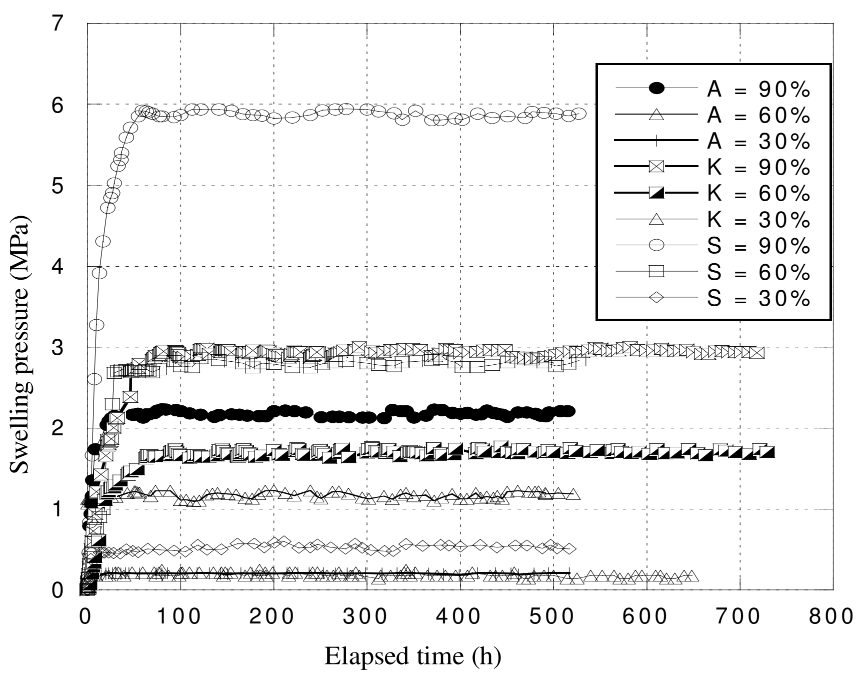

Figure 13. Swelling pressure of different types of compacted bentonite-sand.

pressure noticeably increased due different types of bentonite in bentonite-sand mixture (Figure 13). At the same percentage of bentonite content swelling pressure was significantly different due to montmorillonite mineral. Superclay specimen (90%) was exhibited distinctly higher due to content of montmorillonite. Superclay containing 85% montmorillonite mineral while the Kunigel and Akagi was 64 and 60%, respectively. Akagi bentonite showed

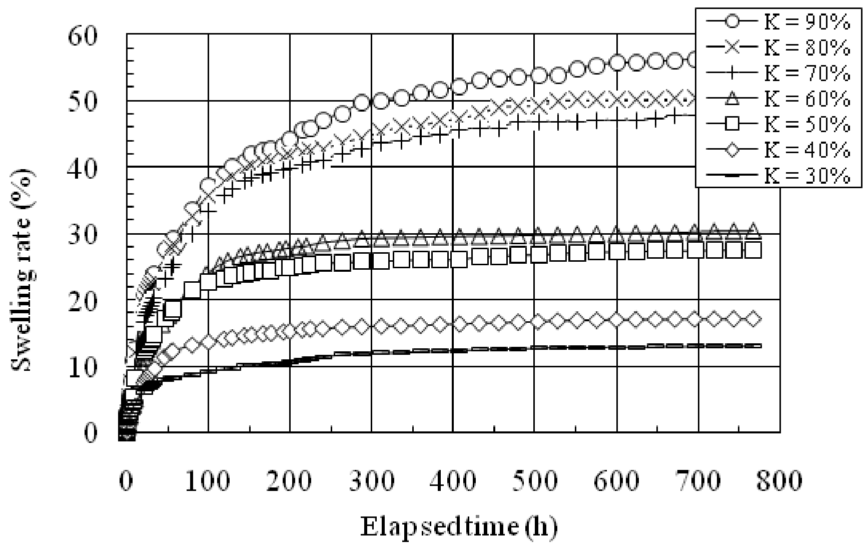

Figure 14. Swelling rate of Kunigel-sand at 0.16 MPa.

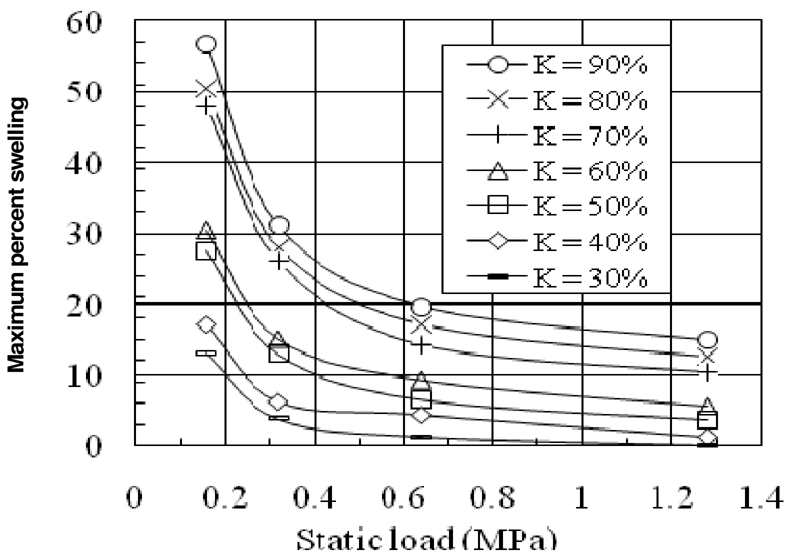

Figure 15. Loading effect on swelling rate of Kunigel-sand.

lower swelling pressure compared to Kunigel due to calcium type of bentonite. Superclay and Kunigel are sodium types of bentonite. Sodium types bentonite shows the higher swelling characteristics compared to calcium types bentonite containing same percentage of montmorillonite.

Swelling deformation

Relationship between swelling rate of Kunigel bentonite and elapsed time under 0.16 MPa loading condition is shown in Figure 14. It illustrated that content of bentonite is the key factor for influencing the swelling rate. Loading effects of compacted Kunigel on swelling rate are presented in Figure 15. Static load and content of bentonite are the important factor to control the swelling rate of compacted bentonite. Maximum percent swelling rapidly decreased using 0.16 ~ 0.64 MPa static load and after that swelling rate slowly decreased by static load up to 1.28 MPa. Low containing compacted Kunigel (30%) swelling rate was nearly zero that is, remained original height of the specimen under 1.28 MPa static load and swelling rate positively increased at 0.64 to 0.16 MPa. It

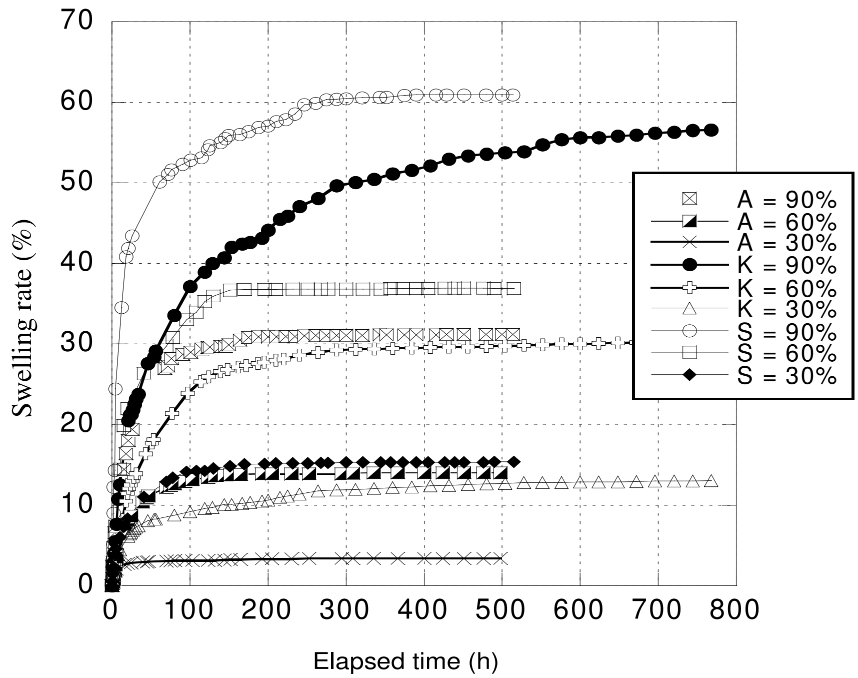

Figure 16. Swelling rate of different types of compacted bentonite-sand mixture at 1.6 MPa.

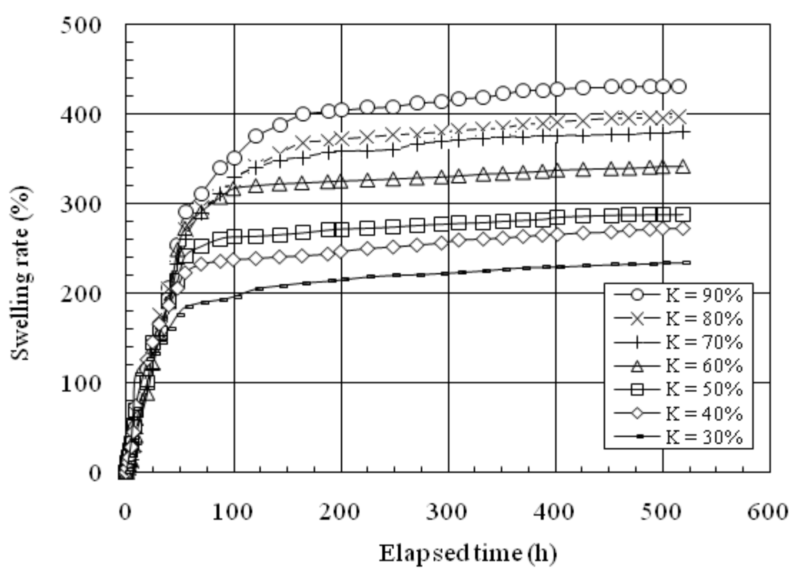

Figure 17. Free swelling rate of Kunigel-sand.

means to say that bentonite has self sealing ability for toxic or radioactive waste disposal. The swelling characteristics of bentonite serve as a measure of the self sealing capabilities of the backfill with respect to filling cracks or gaps between the compacted bentonite and host rock. Swelling rate of different types and content of bentonite at 0.16 MPa is shown in Figure 16. Swelling rate of superclay is higher compared to Kunigel and followed by Akagi due to montmorillonite mineral. Figure 17 shows the free swelling rate of Kunigel-sand compacted

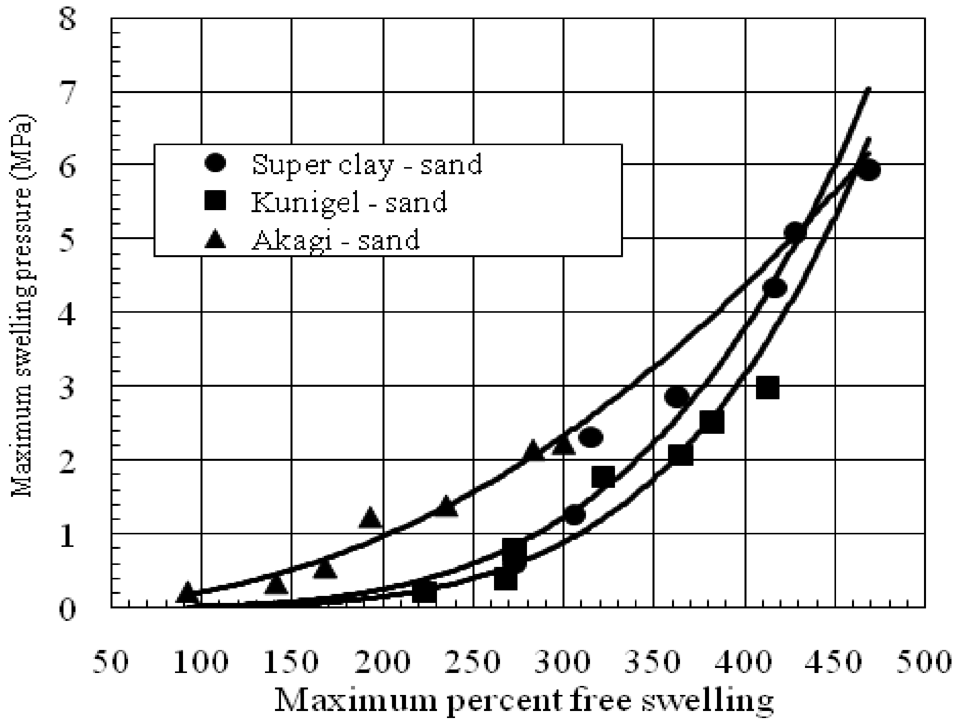

Figure 18. Relationship between maximum swelling pressure and maximum percent swelling of bentonite-sand mixture.

bentonite. It showed the effect of bentonite content in bentonite-sand mixture on swelling phenomenon. It has been clearly seen that content of bentonite in bentonite-sand mixture is the prime factor for swelling deformation. Minerals like montmorillonite from the smectite group have a structural gap in their mineral skeleton. This gap is the space where water molecules enter and stake one above other causing expansion of the whole mineral structure. Relationship of maximum swelling pressure and free swelling of compacted bentonite-sand mixture is shown in Figure 18. By these relationships it can be predict maximum swelling deformation rate by knowing the maximum swelling pressure of compacted bentonite. It is depicted that maximum swelling pressure increased exponentially to maximum swelling rate.

Conclusions

A compacted bentonite firstly adsorbed by groundwater and after that becomes it saturated condition and finally tends to slurry condition if any how static load by surrounding ground is reduced. Coefficient of permeability with void ratio exhibited similar trend by slurry and compacted specimens. Preparation methods had no effect on permeability. Permeability sharply decreased when values of void ratio was less than 2. Permeability noticeably decreased by the increasing rate of bentonite in bentonite-sand mixture. At the same mixture ratio due to types of bentonite permeability varied distinctly under loading or without loading conditions.

Swelling pressure of compacted bentonite-sand specimen is fluctuated with respect to temperature. Swelling pressure exhibited higher values due to higher temperature. Maximum swelling pressure is dependent on content of bentonite in bentonite-sand mixture. Relationships between maximum swelling pressure and maximum swelling rate followed exponential trend line. By this relationship can be predicted the maximum percent swelling of compacted bentonite-sand mixture by knowing the maximum swelling pressure.

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