ENGINEERING BEHAVIOUR OF SAND-BENTONITE MIXTURES AND THE INFLUENCE OF PARTICLE SIZE OF SAND

Thesis

submitted in partial fulfillment of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

by

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CERTIFICATE

This is to certify that the thesis entitled **"Engineering Behaviour of Sand-Bentonite Mixtures and The Influence of Particle Size of Sand"** submitted by **Srikanth Vadlamudi,** Roll No. 11610420, to the Indian Institute of Technology, Guwahati, for the award of the degree of Doctor of Philosophy in Civil Engineering is a record of bonafide research work carried out by him under my supervision and guidance. The thesis work, in my opinion, has reached the requisite standard fulfilling the requirement for the degree of Doctor of Philosophy.

The results contained in this thesis have not been submitted in part or full to any other University or Institute for award of any degree or diploma.

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STATEMENT

I do hereby declare that the matter embodied in this thesis is the result of investigations carried out by me in the Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam, India.

In keeping with the general practice of reporting scientific observations, due acknowledgements have been made wherever the work described is based on the findings of other investigators.

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Srikanth Vadlamudi

ABSTRACT

Waste disposal has always posed great challenges to mankind since times immemorial, novel ideas of dealing with the waste disposal were developed throughout the ages with the improvements in science and technology. Population explosion, rapid industrial growth, increased real estate value and consciousness about pollution in and around the human settlements etc. have created a necessity for a safe and engineered way of waste disposal scraping the old and traditional systems and so came into existence the concept of engineered disposal of both domestic and industrial wastes. Engineered disposal of waste involves isolating the waste from natural environment, be it domestic waste or otherwise, by putting in place a series of geotechnical barriers to prevent and minimize the interaction between both. Sand-bentonite mixtures are assuming greater importance as geotechnical barrier materials in waste disposal schemes around the world and like with any other geotechnical soil structure, a comprehensive understanding on the engineering behavior of various components used in the making of a geotechnical barrier becomes a necessity. A review of literature indicated a host of variables influencing the engineering behavior of a barrier to various degrees, including and not limited to mixing water content, compaction effort, mineralogy of the soil, size and shape of particles, interactions among the soil particles, interactions with water, interactions with any other pore fluid that may exist in the soil, pH, temperature, cation exchange capacity and concentration of cations in the soil pore fluid. Upon scrutiny, it has been observed that most of the studies conducted were primarily focusing on the role of bentonite in the sand-bentonite mixture. Studies highlighting the contributions of sand particle size, sand gradation etc. were very few though sand formed the major component in most of the sand-bentonite mixtures being employed around the world. This study sheds some light on the influence of sand particle size and sand composition on the engineering characteristics of sand-bentonite mixtures with varying bentonite proportions.

In the current study, locally available sand has been washed thoroughly and sieved for different particles sizes (fine sand and medium sand). Two commercially available bentonites with different swelling capabilities were procured. Fine sand-bentonite (FS-B), medium sand-bentonite (MS-B) and fines sand-medium sand-bentonite (FS-MS-B) mixtures were made with bentonite proportion varying from 10 to 50 percent by dry weight in the mix. These mixes were tested for Atterberg limits, standard compaction characteristics, consolidation characteristics, hydraulic characteristics, unconfined compressive strength behavior and shrinkage characteristics.

Liquid limit results indicated, for a given bentonite content, FS-B, MS-B and FS-MS-B mixes exhibited different liquid limits. Moreover, between FS-B and MS-B mixes, FS-B mixes exhibited relatively higher liquid limit and the difference is pronounced in mixes with higher bentonite contents. From the results of FS-MS-B mixes, it has been seen that sand gradation/composition has little influence on the liquid limits. Compared to liquid limit, shrinkage limit results indicated a higher sensitivity towards particle size distribution of the soil mixture. Standard compaction characteristics revealed that medium sand-bentonite mixtures exhibited higher dry density while fine sand-bentonite mixtures exhibited higher optimum moisture content, for the same bentonite content. Moreover, sand-bentonite mixtures exhibited highest dry density with 70-80% sand content in the mixtures.

Consolidation data indicated that, for a bentonite content, a wide range of swelling potential and swelling pressure can be observed by changing the sand composition in the mixtures. It has also been observed that apart from the magnitude of swelling pressure/potential, sand particle size and composition plays a major role in time taken for initial, primary and secondary swelling of a soil.

Fine sand-bentonite mixes exhibited lower hydraulic conductivities compared to medium sand-bentonite mixtures. While sand composition has some influence on the hydraulic behavior of sand-bentonite mixtures, the influence is seen to be more pronounced in the mixtures with bentonite content less than 30 percent. As the swelling nature of bentonite in the mixture is improved, benefits obtained by varying sand composition were seen to diminish.

Apart from being dependent on bentonite content, bentonite quality and initial compaction state, shrinkage behavior of sand-bentonite mixtures is seen to be particularly sensitive to sand composition. Bentonite content being constant, a variability to the tune of 75-100 kPa has been observed in the UCS behavior by varying the sand composition.

Sand composition has a definitive role to play on the geotechnical behavior of sand-bentonite mixtures, as has been seen in this study.

KEYWORDS: Atterberg limits, sand-bentonite mixtures, sand gradation, bentonite content, compaction, hydraulic conductivity, shrinkage, UCS.

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ABBREVIATIONS

MSW	Municipal Solid Waste
DDL	Diffuse Double Layer
SSA	Specific Surface Area
CEC	Cation Exchange Capacity
ESP	Exchangeable Sodium Percentage
GCL	Geosynthetic Clay Liner
OMC	Optimum Moisture Content
MDD	Maximum Dry Density
ASTM	American Society for Testing and Materials
EGME	Ethylene glycol mono-ethyl ether
XRD	X-ray diffraction
SAR	Sodium Absorption Ratio
DI water	De-ionized water
FS	Fine sand
MS	Medium sand
B1	Bentonite-1
B2	Bentonite-2

Symbols Used

k	Hydraulic conductivity
γ_d	Dry density
m_v	Coefficient of volume change
c_v	Coefficient of consolidation
t_{90}	Time for 90% of consolidation
c_c	Compression index
ΔP	Change in pressure
Δe	Change in void ratio
T_v	Time factor
γ_w	Unit weight of the pore fluid
G	Specific gravity of soil solid particles

Chapter 1

INTRODUCTION

1.1 GENERAL

Waste disposal has always posed great challenges to mankind since times immemorial, novel ideas of dealing with the waste disposal were developed throughout the ages with the improvements in science and technology. Population explosion, rapid industrial growth, increased real estate value and consciousness about pollution in and around the human settlements etc. have created a necessity for a safe and engineered way of waste disposal scraping the old and traditional systems and so came into existence the concept of engineered disposal of both domestic and industrial wastes. Engineered disposal of waste involves isolating the waste from natural environment, be it domestic waste or otherwise, by putting in place a series of geotechnical barriers to prevent and minimize the interaction between both. As with any other engineering domain, project economics plays a major role in deciding the material to be used in the waste disposal scheme design, thereby, creating a need to explore new materials. From the available literature it was observed that the possibility of attaining lower hydraulic conductivity (< 10^{-9} m/s) was considered the most important criterion while selecting a geotechnical barrier material (USEPA, 1988, Daniel and Benson, 1990). Apart from successfully fulfilling the low hydraulic conductivity criterion, a barrier is also expected to have sufficient shear strength in order to prevent excessive uneven settlements caused by the overbearing loads (Hoeks and Agelink, 1982). As far as the shear strength is concerned, compacting the barrier material to a higher density using heavy compaction techniques was seen to be a solution in the laboratory, which by the way isn't always possible in the site. Volumetric shrinkage and desiccation susceptibility is another important aspect of constructing geotechnical barriers in the field (Tay et al., 2001). Compacted clays were seen to be capable of low hydraulic conductivities under confinement. However, high compressibility, high desiccation shrinkage, low shear strength and low achievable density etc. are some reasons of concern while using compacted clays, which undermine its candidature as barrier material. An improvement in the engineering characteristics like shear strength, desiccation susceptibility, maximum dry density, thermal conductivity etc. has been observed when locally available soils such as sand were mixed with clays. Sand-bentonite mixtures were found to be a viable option (Ogata and

Komine, 1993; Cowland and Leung, 1991; Abeele, 1986) considering their engineering properties and project economics as well, since, sand is generally a locally available material though bentonite clay which is a relatively costly material and needs to be sourced from elsewhere. Extensive studies were conducted (Hoeks et al., 1987; Katsumi et al., 2008; Francisca and Glatstein, 2010; Hoeks and Agelink, 1982; Komine, 2004; Dumbleton and West, 1966) to understand the behaviour of sand-bentonite mixtures in terms of their application as a landfill liner material, backfill material for nuclear waste disposal schemes. Most of the studies found in the literature were carried out to optimize the bentonite content in the mixture to achieve a low hydraulic conductivity. Researchers have proposed various proportions of bentonite which can fulfill the design criteria for various applications. However, a very few studies were reported on the influence sand has on the engineering characteristics of sand-bentonite mixtures. In spite of the fact that sand occupies a major proportion in a sand-bentonite mixture, no particular importance has been given to assess the influence of sand composition and particle size on the behaviour of sand-bentonite mixture. If sand gradation is an influencing parameter in the performance of a barrier and should be reckoned with, is still a matter of ambiguity. Current study sheds some light on the role of different particle sizes of sand and sand composition on the Atterberg limits, compaction, strength, shrinkage, compressibility and hydraulic characteristics of bentonite-sand mixtures.

1.2 MOTIVATION FOR THE STUDY

From the available literature it is observed that

1) Hydro-mechanical behaviour of a material is of primary importance if the material is to be used in barrier applications be it landfill liner, buffer and backfill material in nuclear waste disposal.

2) Geotechnical properties of a sand bentonite mix were found to be varying when it is subjected to solutions mimicking the leachate that is generated from the waste to be contained as compared to a mix in contact with pure water.

3) Studies so far have been concentrated on determining optimum percentage of bentonite in a mix, mixing water content, compaction effort needed and pollutant containment characteristics etc.

4) The conclusions observed in these studies are more likely to be site specific than universally applicable as the studies employed locally available sands and other waste products and no emphasis whatsoever has been laid on the role of the particle size distribution of sand in the behaviour of a sand bentonite mix, which decides the voids in the liner or backfill system.

The present study aims to understand the influence of particle size of sand on the hydro-mechanical behaviour of a sand-bentonite mixture.

1.3 ORGANIZATION OF THE THESIS

This thesis consists of 5 number of chapters. **Chapter 1** presents the introduction to the problem and the motivation for the study. **Chapter 2** deals with the comprehensive literature review on the engineering characteristics of sand-bentonite mixtures and their suitability when used as geotechnical barriers in waste disposal schemes, and presents the objective of the current study and significance of the outcomes. **Chapter 3** deals with the materials and experimental procedures used in the study. **Chapter 4** deals with the experimental investigations carried out on fine sand-bentonite, medium sand-bentonite and fine sand-medium sand-bentonite mixtures to assess the influence of sand particle size and sand composition on the Atterberg limits, compaction characteristics, hydraulic conductivity, swelling potential, swelling pressure, shrinkage behaviour and various consolidation parameters such as compression index (C_c), coefficient of volume change (m_v), coefficient of consolidation (c_v) and time to complete 90% of the consolidation (t_{90}) of sand-bentonite mixtures made with two different bentonites. The conclusions from the present study and scopes for the future work are presented in **Chapter 5**.

Chapter 2

LITERATURE REVIEW

2.1 GENERAL

Disposal of wastes, which are caused as a result of rapid increase in population and urbanization, has become one of the serious environmental problems in both developing and developed countries. When these wastes come in contact with water and ambient atmosphere, they disintegrate and produce leachates, which contain various chemicals whose concentrations can be far higher than the safe prescribed limit from health point of view and are toxic in nature. Generally, these wastes are disposed off in sanitary landfills. The main purpose of these landfills is to isolate the waste and prevent the leachate from migrating into and contaminating the ground water table. To achieve this, low permeable compacted clay liners are generally provided in a landfill site, which acts as barrier between the waste material and the ground water. The clay liner limits or eliminates the movement of leachate and landfill gases from the landfill site. Owing to its higher swelling and lower hydraulic conductivity nature when compacted, bentonite is used as a liner material at the waste disposal site. Interlayer swelling and a thick layer of bound water associated with montmorillonite, a mineral present in bentonite, cause the bentonite to swell and exhibit low hydraulic conductivity to passage of water (Mesri and Olson, 1971). However, bentonite exhibits a higher shrinkage and lower compacted density. In order to reduce the shrinkage and increase the compaction density, sand is generally added to bentonite.

Nuclear power plants use enriched radioactive minerals to generate electricity for human energy needs. The nuclear power plant generates waste in the form of spent nuclear fuel rods, which continue to emit harmful radiation for a very long time in the future. These spent fuel rods are disposed off in cavernous structures constructed deep underground in seismological safe zones. To isolate these wastes from the surroundings, geotechnical barriers in the form of buffer and backfill are employed in these facilities.

Barrier materials are selected mainly based on their capability for high swelling, low hydraulic conductivity, self-healing nature, and low shrinkage and contaminant retardation characteristics. Bentonite-sand mixtures are finding applications as geotechnical barriers in domestic waste disposal schemes, low level and high level radioactive waste disposal facilities. During their design life period, these materials will be subjected to a host of complex chemo-thermo-hydro-mechanical loadings and it becomes a necessity to understand the performance of the barrier materials under these anticipated conditions a priori in the laboratory (Wang et al., 2013). This chapter deals with a comprehensive literature review on buffers, backfill and landfill liner studies related to bentonite and sand-bentonite mixtures.

2.2 REVIEW ON BUFFER AND BACKFILL MATERIAL

Urbanization, improved living standards of the populace and industrialization of communities etc. are the primary reasons for growing electricity needs of our times. This increasing need for electricity is paving ways for developing more nuclear power generation plants. One of the major concerns associated with nuclear power plants is the disposal of low to high level nuclear wastes i.e. spent nuclear fuel rods and other alpha bearing waste, which is generated in the power production process. The wastes being generated emit high ionizing radiations, which can contaminate the surrounding atmosphere, ground water and adversely affect human health. Disposal of nuclear waste in deep underground geologic repositories is gaining acceptance as the preferred method of nuclear waste disposal around the world. The idea is to put in place, a series of natural and engineered barriers that can help create a zone of isolation where the radioactive nuclide emitting waste can be placed away from the natural environment, which might help in minimizing the migration of ionizing radiation outside and seeping water inside the repository. The repositories are essentially a series of tunnels dug at a depth of 500 to 1500 m underground in stable geologic formations and are further lined with high strength concrete to make them stronger and impervious to water and gas migration. The geologic formation itself acts as the natural barrier against the elements of nature.

Components forming the artificial/engineered barrier are detailed as follows. The nuclear waste is encased in molten glass for vitrification, which after solidification is encased in a stainless steel cylinder called the ‘canister’. These canisters are placed at the bottom of the tunnels and the space between the tunnel and canisters is filled with a highly compacted mixture of sand-bentonite. Compacted sand-bentonite mixture is being seen as an effective component of the artificial barrier system, because of their low hydraulic conductivity, self-healing nature and high swelling properties, in the disposal of both low-level and high-level radioactive waste. Sand-bentonite mixtures used in the barrier system are classified as buffer and backfill materials based upon the bentonite proportion in the mixture. Buffer materials are the mixtures that contain a higher proportion of bentonite, usually around 40 to 50% of the mix proportion, and are used to fill the disposal pit. Backfill materials are the mixtures that contain a relatively lower proportion of bentonite and are used to fill the access tunnels leading to the disposal pit. Buffer and backfill demand a very low hydraulic conductivity (less than 1×10^{-10} m/s) and hence the design and development of buffer and backfill materials, which fill up the disposal facility, are important for developing the technology of high-level nuclear wastes disposal. To design the specifications, such as dry density and bentonite content, of buffer and backfill materials, we must investigate the hydraulic properties by experiments and evaluate quantitatively the hydraulic conductivities of compacted sand-bentonite mixtures. Addressing all the various barriers used in the deep geological repositories is beyond the scope of the current study; hence, further discussions would be limited to understanding the backfill material.

2.3 DESIGN CRITERIA FOR BACKFILL MATERIAL

2.3.1 Introduction

Backfill forms an important component of the engineered barrier system in the disposal of high level radioactive wastes in deep geological repositories. Simply put, backfill is the material used to fill the access tunnels after the metal canisters are placed in the disposal pit and secured in place with buffer material. Basic functions expected of the backfill include supporting the buffer maintain its integrity, by sufficiently restricting its swelling, and restrict the flow of ground water into the disposal pit via access tunnel. Given the nature of waste being disposed and a very long design life of the facilities involved, a backfill is expected to be sufficiently durable and function accordingly all through the design period.

2.3.2 Design criteria

Keeping in view the functional requirements of a backfill, guidelines were suggested by SKB (2010) on the type of materials to be used for making a backfill, parameters to be investigated for, and minimum limiting values of investigated engineering characteristics. Apart from long term durability, hydraulic conductivity and swelling pressure are two important parameters to be considered while choosing materials for backfill. Lower hydraulic conductivity helps in restricting or minimizing flow of water through access tunnel and sufficiently high swelling pressure makes sure that buffer stays in its place. Minimum limiting values of engineering characteristics set forth by SKB (2010) are hydraulic conductivity to be lower than 1x10^{-10} m/s; and swelling

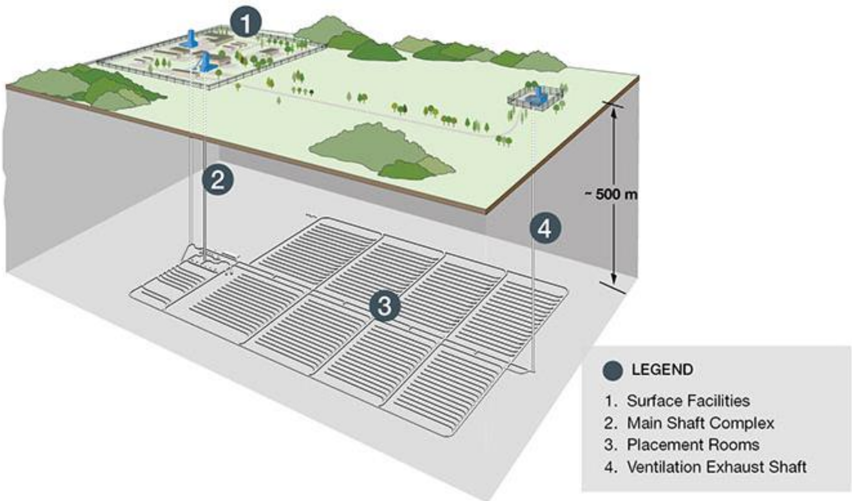


Figure 2.1 Conceptual layout of a radioactive wastes disposal facility (Deep Geological Repository, NWMO, 2016)

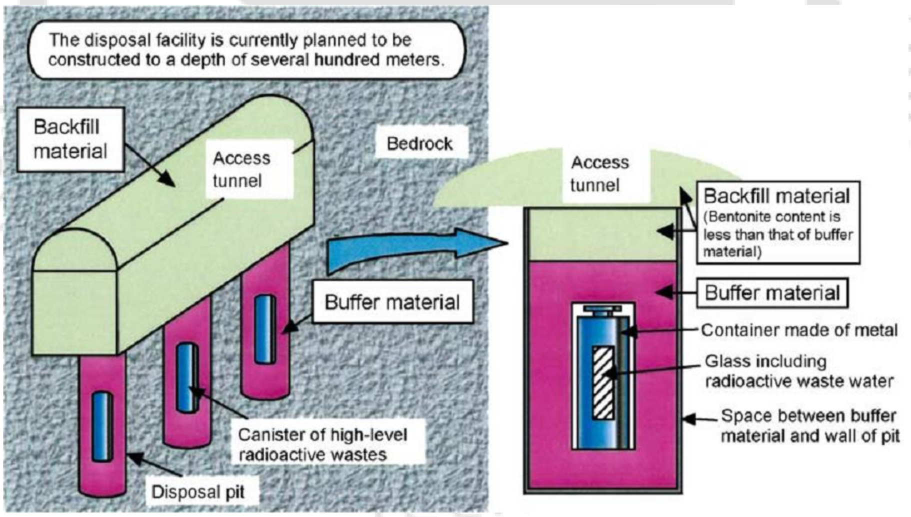


Figure 2.2 Barrier systems for radioactive wastes disposal facility (Komine 2004)

pressure higher than 0.1 MPa. An average installed dry density of 1240 kg/m^3 has been specified for backfill as the minimum desired value necessary to restrict the expansion of buffer and ensure the saturation density requirements of the buffer (1950 kg/m^3) are met. While Japan Nuclear Cycle Development Institute (1999) required the hydraulic conductivity of backfill materials to be between 1x10^{-11} m/s and 1x10^{-12} m/s. Since, long term performance of backfill is critical to the success of the repository, smectite-rich clays, bentonite clays and mixtures of bentonite and local soils etc. were the suggested materials for backfill because of their capability for low hydraulic conductivity and high swelling pressures. The design parameters of interest while designing backfill are dry density, water content, montmorillonite content in the soil.

2.4 BENTONITE

2.4.1 Introduction

Bentonite is widely used as a backfill material during the construction of slurry trench walls, as a soil admixture for the construction of seepage barriers, as a grout material, as a sealant for piezometer installations and for various other civil engineering construction techniques. Bentonite is an absorbent aluminium phyllosilicate, essentially impure clay, formed as a deposit of volcanic ashes at shallow wet sites in various location of the world (Grim & Guven, 1978). These deposits are variable, depending on the nature of the volcanic ashes and the salinity of the water into which they were deposited. Since the bentonite is a natural material, its mineral composition, chemical state, and grain size distribution varies considerably from one source to another. Different parameters such as mineralogical composition (i.e. amount and type of montmorillonite), type of exchangeable cations, surface area and the surface charge density affect the behaviour of bentonite considerably.

Bentonite is primarily composed of the smectite group of minerals, most common among which is montmorillonite $(Al_{1.7}Mg_{0.3})[Si_4O_{10}(OH)_2]^{-0.3}(M)^{+0.3}$, where M represents the exchangeable cation (Mitchell and Soga, 2005). The behaviour of bentonite primarily is governed by montmorillonite which has characteristics like a large specific surface area (as high as 800 m^2/g), high charge deficiency (0.5-1.2 per unit cell), high cation exchange capacity (80-150 $cmol_c/kg$), and ability for interlayer swelling. These factors contribute to the high swelling, low hydraulic conductivity and contaminants adsorption ability of the bentonite.

2.4.2 Structure of Montmorillonite

Clays are the particles with an effective diameter smaller than 2μm and phyllosilicates as its main mineralogical components. These phyllosilicates are made of silica (SiO_2) tetrahedral sheets and Aluminium (Al^{3+}) or magnesium (Mg^{2+}) oxides octahedral sheets.

Montmorillonite has a prototype structure similar to that of pyrophyllite consisting of an octahedral sheet sandwiched between two tetrahedral sheets (2:1 mineral) and diagrammatically in three dimensions (Fig. 2.3). The silica and gibbsite sheets are combined in such a way that the tips of the tetrahedron of each silica sheet and one of hydroxyl layers of octahedral sheet form a common layer and all the tips of the tetrahedral point toward the center of the unit cell. The oxygen forming the tips of the tetrahedral is shared with the octahedral sheet as well. The anions in the octahedral sheet that fall directly above and below the hexagonal holes formed by the bases of the silica tetrahedral are hydroxyls. Bonding between successive layers is by van der Waal's forces and by cations that balance charge deficiencies in the structure. These bonds are weak and water or other polar liquids can easily enter between the layers, causing them to expand significantly. It has a lateral dimension of 1000 to 5000 A^0 and thickness 10 to 50 A^0.

The layers formed in this way are continuous in 'a' and 'b' directions and stacked one above the other in the 'c' direction. Bonding between successive layers is by van der Waal's forces and by cations that balance the charge deficiencies in the structure. These bonds are weak and easily separated by cleavage or adsorption of water or other polar liquids. The basal spacing in the c direction, $d_{(001)}$, is variable, ranging from about 0.96 nm (1 nm = 10^{-6} mm) to complete separation.

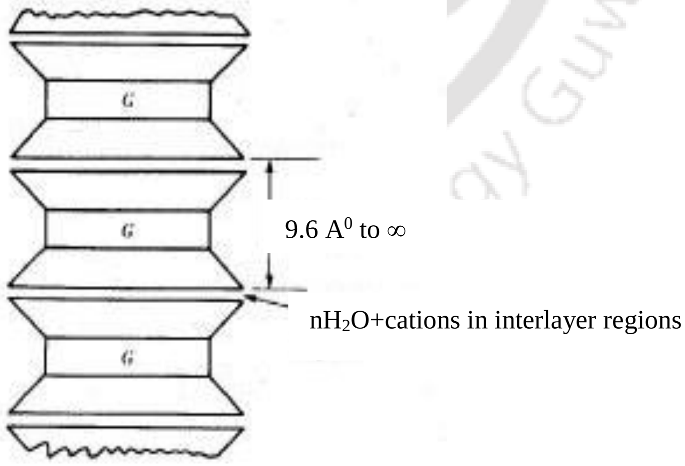


Figure 2.3 Structure of montmorillonite (Mitchell and Soga, 2005)

The montmorillonite is the primary mineral of bentonite. In the dry state a particle of montmorillonite resembles a closed book composed of many thin crystalline sheets held together by weak van der Waal's forces and by cations. Each sheet has charge deficiencies within its crystal structure, and is neutralized by the presence of cations held loosely to the surface of the sheets. When the dry bentonite and water are mixed, water is drawn into the montmorillonite particles to hydrate the surface of the elemental sheets and the cations. For the combination of sodium montmorillonite and freshwater, the fluid that enters the particles forms thick, viscous diffuse ionic layers around the layer, causing the montmorillonite particles to swell, possibly to the extent of complete separation of the sheets. The fabric of freshwater, low salt, sodium bentonite resembles a pile of crumbled paper. For the combination of dry sodium bentonite and a saline solution, less fluid is required to neutralize the negatively charged sheets, and if the ion concentration is large or the valence of the cations are large, the separation distance between sheets will remain small and the montmorillonite particles will remain in the form of closed books. The fabric of bentonite in this case will consist of swollen but intact montmorillonite particles surrounded by thin, viscous diffuse ionic layers, in an arrangement resembling a pile of fallen books. A third case is that of calcium bentonite, an example of bentonite in which dominant exchangeable cations is polyvalent. The calcium cation is very effective in holding together the montmorillonite sheets, and therefore calcium bentonite has small potential to swell, even when mixed with freshwater. Calcium bentonite behaves similarly to sodium bentonite in a high salt state, and its permeability properties are about same.

2.4.3 Swelling behaviour of Bentonite

The swelling of bentonite takes place in two stages, inner-crystalline swelling and osmotic swelling (Norrish and Quirk, 1954).

2.4.3.1 Inner-crystalline swelling

In inner-crystalline swelling, water molecules enter the interlayer region of the montmorillonite to hydrate the exchangeable cations located there. The cations upon contact with water order themselves on a plane halfway between the clay layers which lead to a widening of the spacing between the layers. The volume of montmorillonite can double in the process of inner-crystalline swelling. Polarity of the water molecule is an important factor in the inner-crystalline swelling of clay. When cations hydrate, the water molecules orient their negative dipoles towards the cation and thus weaken the electrostatic interaction between the negatively charged layers and the interlayer cations.

Inner-crystalline swelling, which has also been referred to as Type I swelling, is a process whereby expandable 2:1 phyllosilicates sequentially intercalate one, two, three or four discrete layers of H_2O molecules between the mineral interlayers (Norrish, 1954). In this process the swelling occurs prior to osmotic (Type II) swelling which is associated with longer range electrical diffuse double layer effects. Figure 2.4.a and 2.4.b shows inner-crystalline swelling of sodium montmorillonite.

In inner-crystalline swelling, there is a balance between attractive and repulsive forces operating between adjacent interlayer surfaces (Norrish, 1954; van Olphen, 1965; Kittrick, 1969). Electrostatic attraction between the exchange cations and the basal surfaces of the clay dominates the net potential energy of interaction (Laird, 1996 and 2006). The positive charged cations provide links or are like charge bridges between adjacent negatively charged clay layers. On the other hand, the hydration energy of the exchange cations dominates the net potential energy of repulsion. Net forces of attraction are dominant for unsaturated conditions or saturated conditions with high electrolyte concentrations, while net forces of repulsion are dominant in case of fully saturated conditions of low electrolyte concentration.

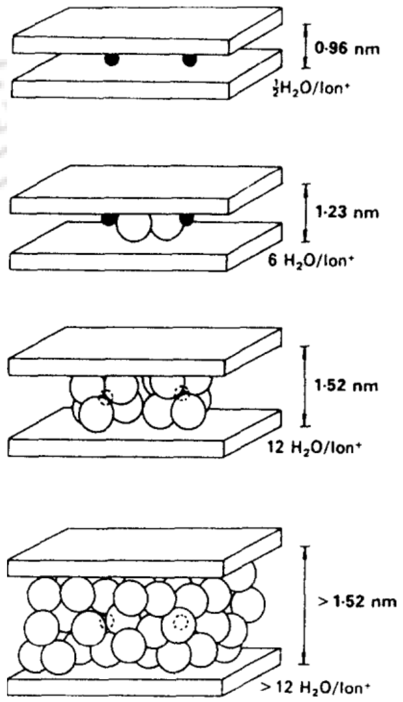


Figure 2.4.a Inner-crystalline swelling of sodium montmorillonite. Given are the layer distances and the maximum number of water molecules per sodium ion (Kraehenbuehl et al., 1987)

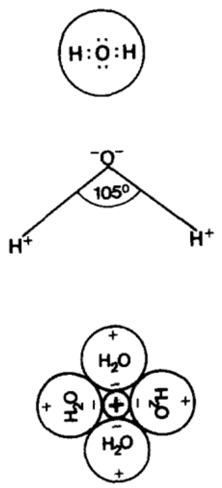


Figure 2.4.b The structure of water molecule

2.4.3.2 Osmotic swelling

The osmotic phase of swelling follows the hydration phase but occurs only when the exchange sites contain monovalent cations (Norrish and Quirk, 1954; Jellander et al., 1988; McBride, 1994; Prost et al., 1998). The interlayer region retains numerous layers of water molecules during the osmotic phase. The number of layers of water molecules at equilibrium is proportional to the cation concentration in the bulk water (Norrish, 1954; Zhang et al., 1995; Onikata et al., 1999). Accordingly, when the bulk water contains a low concentration of monovalent cations and monovalent cations occupy the exchange sites, a larger fraction of the total water is bound and less mobile water is available for flow resulting in a lower value of hydraulic conductivity. This condition is commonly observed when sodium-montmorillonite are hydrated and/or permeated with DI water (Lutz and Kemper, 1958; Alther et al., 1985; Gleason et al., 1997; Petrov and Rowe, 1997; Ruhl and Daniel, 1997; Shackelford et al., 2000). When polyvalent cations occupy the exchange sites, only the hydration phase occurs. The interlayer expands until it contains four monolayers of water and then expands no further (Norrish and Quirk, 1954; Posner and Quirk, 1964; Jellander et al., 1988; McBride, 1994; Prost et al., 1998). There are several explanations for the lack of additional interlayer swelling when polyvalent cations occupy the exchange sites, but consensus does not exist regarding which explanation is correct (McBride, 1994). Nevertheless, absence of the osmotic phase is well documented experimentally in the literature (Norrish and Quirk, 1954; Posner and Quirk, 1964; McBride, 1994; Prost et al., 1998). Lack of an osmotic phase is evident in the free swelling of calcium-montmorillonite (i.e., bentonites where the exchange sites are occupied by Ca^{2+} cations), which typically is about 3 mL/2g even when DI water is the hydrating liquid. In contrast, the free swelling of sodium-montmorillonite typically exceeds 30 mL/2g in dilute monovalent solutions or DI water (Egloffstein, 1995; Lin and Benson, 2000).

In sodium-montmorillonite the swelling can result in the complete separation of the layers. The driving force for the osmotic swelling is the large difference in concentration between the ions electrostatically held close to the clay surface and the ions in the pore water of the rock (Fig. 2.5.a). Irregularities in the crystal lattice are manifested by an excess negative charge, which must be compensated by positive ions close to the surface of the clay. The concentration of positive ions close to the surface is thus extremely high, while that of negative ions is very small. The positive ion concentration decreases with increasing distance from the surface, whereas the concentration of negative ions increases. The negatively charged clay surface and the cloud of ions form the diffuse electric double layer (Fig. 2.5.b). A high negative potential exists directly at the surface of the clay layer. The value of this potential is reduced, with increasing distance from the surface and reaches zero in the pore water. When two such negative potential fields overlap, they repel each other, and cause the observed swelling in clay. The profile of the potential curves, and therefore the repulsion at a given distance vary with the valence and the radius of the counter-ions in the double layer and with the concentration of electrolytes in the pore water. A transformation of sodium montmorillonite into its calcium form or an increase in the electrolyte concentration in the pore water results in the decrease in the double layer thickness and a reduction in the swelling stress.

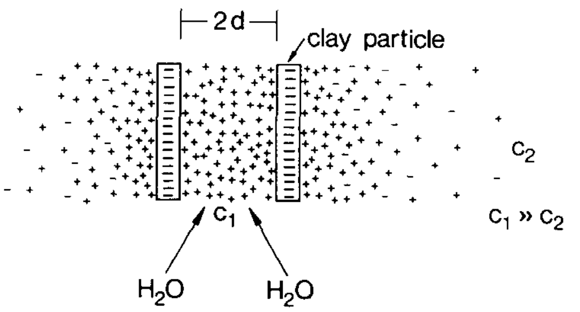


Figure 2.5.a

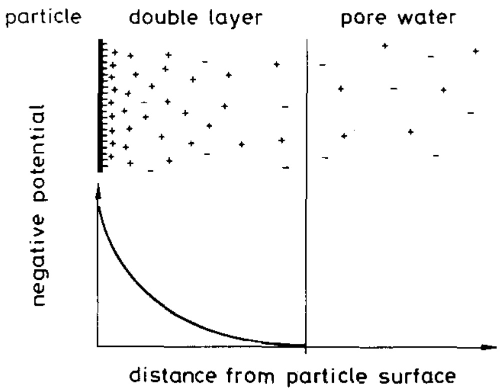


Figure 2.5.b

Figure 2.5.a Two negatively charged clay layers with ion cloud. The ion concentration C_1 between the layers is much higher than the ion concentration C_2 in the pore water. An equilibration of the concentration can only be reached through the penetration of water into the space between clay layers, since the interlayer cations are fixed electrostatically by the negative charge of the layers (osmotic swelling)

Figure 2.5.b Negatively charged clay surface, ions in the diffuse double layer and ions in the pore water. The distribution of the negative potential changes with the valence and the radius of the ions in the double layer and with the electrolyte concentration in the pore water

2.5 LITERATURE REVIEW ON BACKFILL MATERIAL

Kenney et al. (1992) studied the compaction, shrinkage and hydraulic conductivity behavior of sand-bentonite mixes by varying the bentonite content in the mixes from 0 to 32% by their dry weight. The standard proctor compaction test results indicated that with increasing the bentonite content the maximum dry density increased till optimum bentonite content is reached. The optimum bentonite content was as 20% of bentonite content and beyond this point a decrease in dry density was noted. From the compaction data, sand was identified as the primary load-carrying member in the mixtures at low bentonite proportions and as the bentonite content in the mixture increases the role was found to be increasingly shared with bentonite. Hydraulic conductivity of compacted mixtures was found to be dependent on the distribution of bentonite in the compacted soil mass and also on the initial mixing water content. Contribution of compaction density to hydraulic conductivity was found to be lower when compared to that of bentonite content of the mixture, mixing water content and effectiveness of mixing.

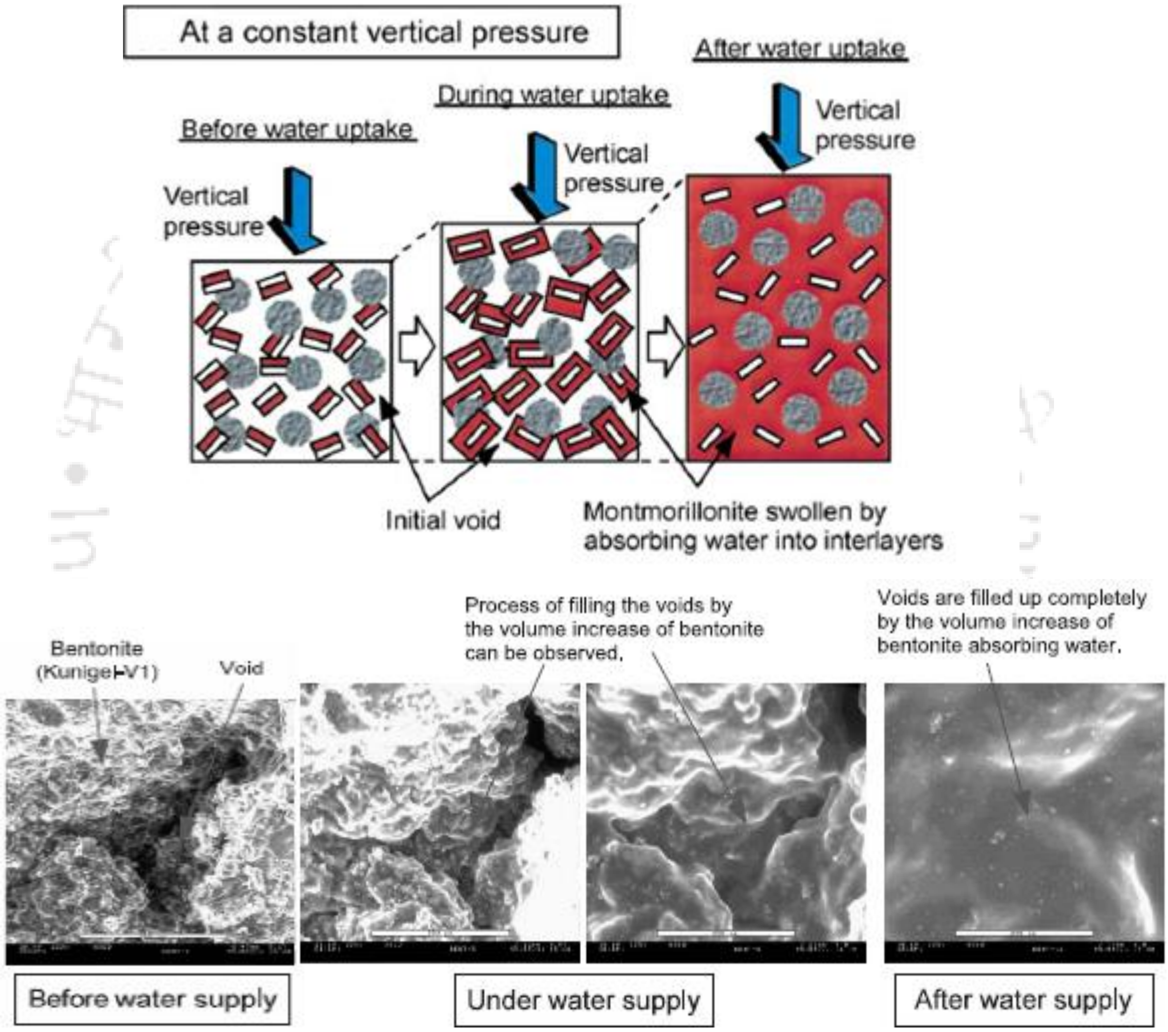


Figure 2.6 Bentonite swelling in sand-bentonite mixtures under constant vertical pressure (Komine, 2004)

Komine and Ogata (1999) studied swelling characteristics of sand-bentonite mixes as a part of backfill development studies for high level nuclear waste disposal in Japan. Studies were conducted on the mixtures with 5, 10, 20, 30 and 50% of bentonite content by their dry weight. Swelling pressure results showed that it is very much dependent on amount of bentonite present in the mixture and the initial dry density of the mix. It was also noted that the swelling pressure increased with increasing the dry density and bentonite content in the mix. Similar behavior was also reported regarding the swelling strain of the sand-bentonite mixes. Scanning Electron Microscope (SEM) studies were conducted on the sand-bentonite mixes to know the underlying process of swelling and associated swelling pressure. SEM studies revealed;

1) Upon access to water, bentonite particles present in the sand matrix start adsorbing water on to its surface and same is reflected as increase in volume. With the increase in bentonite volume the voids in the sand matrix are filled.

2) Under a constant vertical pressure, an increase in volume can be observed if the bentonite can fill all the voids in sand matrix and still keep on swelling. This behavior is very much dependent on the bentonite content in the mixture.

3) In mixes with higher dry densities void volume is relatively small and the available bentonite fills the voids more easily resulting in a relatively higher swelling pressure as compared to mixes with low dry densities, for any given bentonite content.

Komine (2004) performed experimental studies on sand-bentonite mixes to assess their suitability as backfill material in a nuclear waste disposal facility. Commercially available sodium bentonite (Kunigel VI) with a liquid limit of 474% was used for the study along with locally available Mikawa silicate sand. Studies were conducted on the mixtures with 5, 10, 20, 30 and 50% bentonite by dry weight. All the mixtures were tested using standard compaction test and the results obtained indicated that 30% bentonite mix provide the highest dry density of all the other mixes. Figure 2.6 shows stages of swelling when sand-bentonite mix was brought into contact with water under a constant vertical pressure. It was also observed that the mixes containing 5 to 30% bentonite content behaved more like a sandy soil than a clayey soil probably due to their relatively lower bentonite content; while, the mixture with 50% or higher bentonite content showed the characteristics of a clayey soil owing to its relatively high bentonite content. The mixes were tested for hydraulic conductivity and the observed that the hydraulic conductivity decreases as the dry density and bentonite content increases. The decrease in the hydraulic conductivity was particularly noticeable for bentonite contents of 5 to 20% where the hydraulic conductivity decreased from 2.66×10^{-10} m/s to 4.85×10^{-12} m/s; whereas, mixtures with bentonite content in the range of 30 to 50 % exhibited hydraulic conductivities in the range of 6.87×10^{-12} m/s to 1.21×10^{-12} m/s. The reduction in mixes with higher bentonite content was less as there were almost no voids left for the swollen bentonite to fill. Other notable observation was that for mixtures with bentonite content less than 20%, when in contact with water there was not enough bentonite to fill all the voids in those mixtures.

2.6 DESIGN CRITERIA FOR LANDFILL LINERS

Functionally, a landfill liner is expected to prevent, minimize, and provide a sufficiently long flow through time for the contaminants before they reach the natural environment. Hydraulic conductivity is considered an important criterion while choosing a landfill liner material. The other factors that play an important role in the selection of materials and design of a landfill liner are placement moisture content, maximum dry density, grain size distribution of materials, shear strength, desiccation susceptibility of the materials, optimum bentonite content in the soil mixture, thickness of liner etc. A hydraulic conductivity of 1×10^{-9} m/s or lower is a universally accepted design guideline for landfill liners.

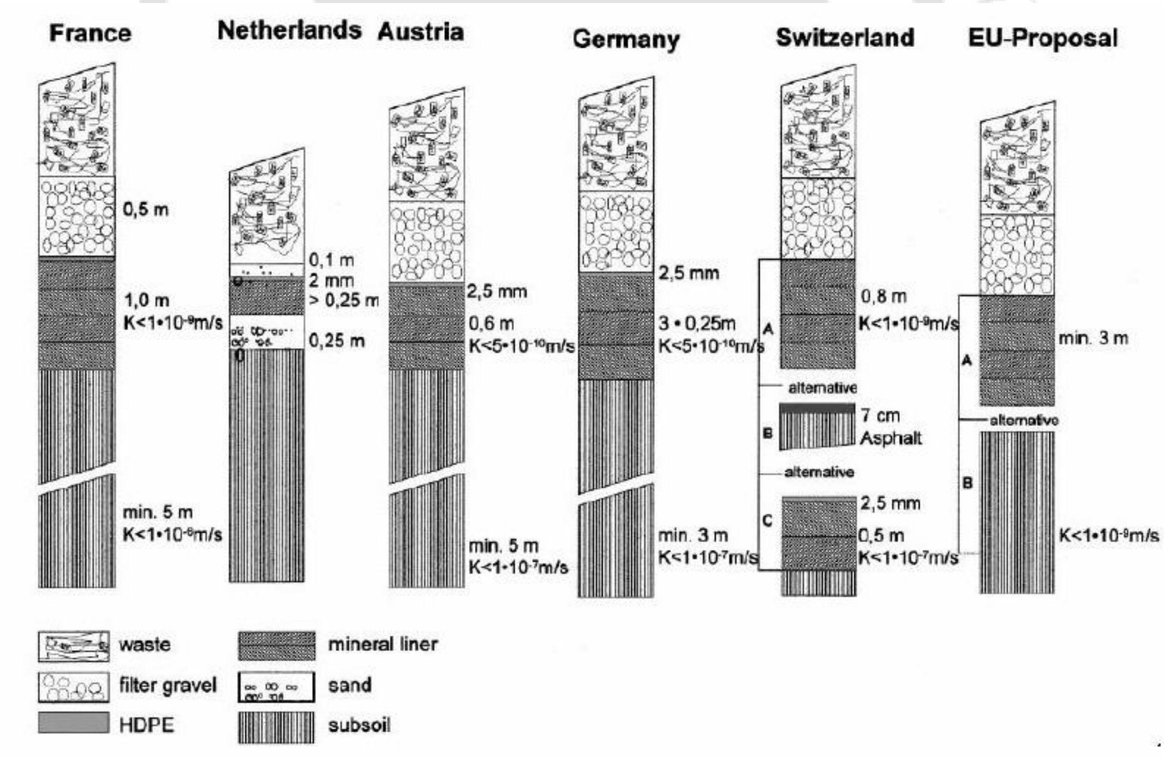


Figure 2.7 National regulations for landfill liners for different countries (Koch, 2002)

Type and thickness of liner a landfill needs is based on the type of waste being disposed in the landfill and severity of risk it poses to the surrounding environment. United States

Environmental Protection Agency (USEPA) suggests a minimum thickness of 0.9 m; while, Swedish Environmental Protection Agency (SEPA) has suggested a minimum thickness of 0.5 to 1 m depending upon the classification of landfill. Figure 2.7 shows a comparative view of typical sections for the base sealing of a landfill liner for domestic waste in France, Netherlands, Austria, Germany, Switzerland, and European Union (EU)-Proposal.

2.7 REVIEW ON LANDFILL LINERS

The liner is a critical element in a waste disposal facility. The primary purpose of the liner system is to isolate the landfill contents from the environment; bottoms of engineered landfills are lined to prevent the uncontrolled release of leachate into the ground water in the surrounding areas. A landfill liner or a composite landfill liner as it is sometimes called as, essentially is a compacted clay layer intended to behave as a relatively impermeable barrier. Until it deteriorates, the liner prevents and retards the migration of leachate, and its toxic constituents, into underlying aquifers. The sites where a liner cannot be provided due to practical limitations i.e. older landfills and surface dumps etc. surface capping can be done to prevent infiltration of rainfall and thereby reduce the production of leachate (Hoeks et al., 1987; Katsumi et al., 2008).

Landfill liners are designed and constructed to create a barrier between the waste and the ground water and to divert the leachate to collection and treatment facilities. Modern landfills generally require a layer of compacted clay with a minimum required thickness and a minimum allowable hydraulic conductivity, overlaid by a high-density polyethylene (HDPE) geo-membrane. The design criterions to be observed are generally provided as guidelines by the environmental protection agencies or the local public administration. Synthetic liners can be used as barriers in contaminant isolation as they provide better impermeability but when durability of the liner in the long run is considered natural materials are preferred over synthetic liners because of their physical and chemical resistance towards contaminants (Hoeks et al., 1987; Katsumi et al., 2008).

The most significant factor affecting a liners performance is its hydraulic conductivity (Daniel and Bowders, 1987; Daniel and Benson, 1990). Expansive soils undergo an increase in volume when subjected to contact with water, which helps in blocking the flow paths and thereby reduce the hydraulic conductivity (Hussain, 1999). Compacted clays or mixtures of local soils with clay are frequently used to achieve very low hydraulic conductivity (Francisca and Glatstein, 2010). If clayey soils are not available in the vicinity, locally available soils can be improved by mixing commercially available high-swelling clay like bentonite. Laboratory studies have indicated that this low hydraulic conductivity limit can be satisfied quite well with swelling clay materials like bentonite and saturated hydraulic conductivity as low as $5x10^{-12}$ m/s can be achieved under controlled conditions (Hoeks and Agelink, 1982). The most important property that makes bentonite, the most favored candidate while choosing a liner material is its high adsorption capacity and its high swelling potential. Adsorption capacity of a soil is directly related to its cation exchange capacity and specific surface area. Some authors have encouraged engineers to use gravelly soils for barriers as gravel strengthens the material, reduces shrink-swell potential, and may even reduce hydraulic conductivity if nearly impermeable gravel particles block flow paths (Shelley and Daniel, 1993).

The wastes which are generally dumped into a landfill are primarily divided into liquid and solid wastes; and secondarily into municipal, industrial, special wastes, and radioactive wastes. Municipal liquid waste is primarily domestic sewage, whereas, municipal solid waste (MSW) is that refuse from residential and commercial sources that is collected in garbage cans and trash bins. These solid wastes produce leachate which contain extracted, dissolved, or suspended inorganic and organic materials. The most common municipal landfill pollutants are total dissolved solids, chlorides, sulfates, hardness, methane, oils and greases, plastic and other organics, in addition to bacteria and algae. The main types of industrial wastes are pesticides, batteries, chemical manufacturing, electroplating, explosives, textile, pharmaceutical, mining and metallurgy, coal and petroleum wastes, etc. The hazardous substances from these wastes are chlorinated hydrocarbons, cyanides, organics such as PCB's, and heavy metals (Matrecon, 1980).

Leachate is the liquid that results from rain, snow, dew, and natural moisture that percolates through the waste in landfill, the volume of leachate generated depends on the water that infiltrates into the landfill. It consists of many different organic and inorganic compounds that may be either in dissolved or suspended state, while traversing through waste, the liquid dissolves salts, picks up organic constituents, and this may contain heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), Zinc (Zn), Nickel (Ni) etc**.** and composition varies due to a number of different factors such as the age and type of waste and operational practices at the site. The chemical composition of leachate depends on the chemical reactions taking place between the waste and water present inside the landfill, including dissolution, precipitation, ion exchange and biochemical processes (Francisca and Glatstein, 2010). The conditions within a landfill vary over time from aerobic to anaerobic thus allowing different chemical reactions to take place. Most of landfill leachates have high BOD, COD, ammonia, chloride, sodium, potassium, hardness and boron levels present in them.

2.8 LANDFILL COMPONENTS AND ITS FUNCTIONS

As shown in Fig. 2.8, a landfill primarily consists of the following these components;

- A 'liner system' at the base and sides of the landfill prevents the migration of leachate or gas to the surrounding soil.
- A 'leachate collection and control facility' which collects and extracts leachate from with in and from the base of landfill and the treats the leachate.
- A 'gas collection and control facility' (optional for small landfills) which collects and extracts gas from with in and from the top of the landfill and then treats it or uses it for energy recovery.
- A 'final cover system' at the top of the landfill which enhances surface drainage, prevent infiltrating water and supports surface vegetation.
- A 'surface water drainage system' which collects and removes all surface runoff from the landfill site.
- An 'environmental monitoring system' which periodically collects and analysis air, surface water, soil gas and ground water samples around the landfill site.
- A Leakage detection system (LDS) detects, collects, and remove leachate between the two liners
- A 'closer and post closersystem' which lists the top 6 components that must be taken to close and secure a landfill site once the filling operation completed and the activities for long term monitoring, operation and maintenance of the complete landfill.

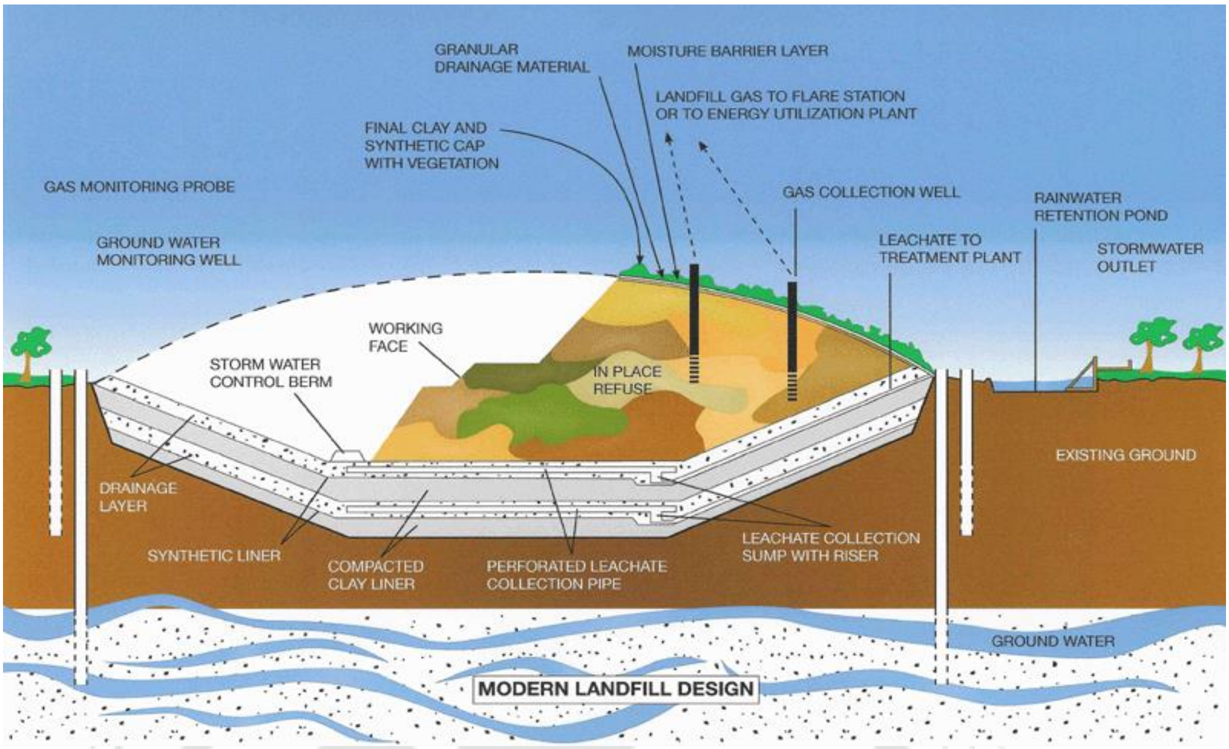


Figure 2.8 Cross section of landfill components

2.9 LINER COMPONENTS AND FUNCTIONS

Modern landfills are designed and built to handle various types of wastes, which necessitate the use of composite materials. This section deals with the materials used and their function in the landfill liner.

2.9.1 Bentonite

- It is a cohesive soil, has very fine particles and possesses the ability to swell and provide a very low hydraulic conductivity, an important parameter while choosing a liner material.
- The thickness of bentonite layer depends on characteristics of the underlying geology and liner type.
- The effectiveness of bentonite liners can be reduced by fractures induced by freeze-thaw cycles, desiccation, and the presence of some chemicals (from leachate).

2.9.2 Geomembrane

- These liners are made from various polymer materials, including polyvinyl chloride (PVC) and high-density polyethylene (HDPE), mostly HDPE is preferred.
- HDPE is strong, resistant to most chemicals, and is considered to be impermeable to water. Therefore, HDPE minimizes the transfer of leachate from the landfill to the environment.
- The thickness of geomembrane used in landfill liner construction is regulated by environmental regulatory agencies.

2.9.3 Geotextile

- It is used to prevent the movement of soil and refuse into the leachate collection system and to protect geomembrane from punctures. These materials facilitate the movement of leachate but trap particles to reduce clogging in the leachate collection system.

2.9.4 Geosynthetic clay liner (GCL)

- These liners consist of a thin bentonite layer (5 to 10 mm) sandwiched between two layers of a geotextile. These liners can be installed more quickly than traditional compacted clay liners, and the efficiency of these liners is impacted less by freeze-thaw cycles.

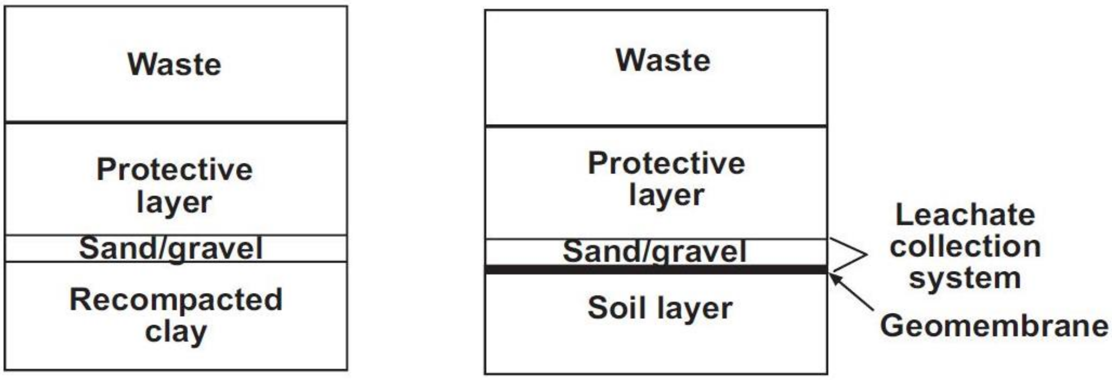
2.9.5 Geonet

- It is used in landfill liners in place of sand or gravel for the leachate collection layer as geonets convey leachate more rapidly than sand and gravel.
- Geonets are more susceptible to clogging by small particles. This clogging would impair the performance of the leachate collection system.

2.10 TYPES OF LANDFILL LINER SYSTEMS

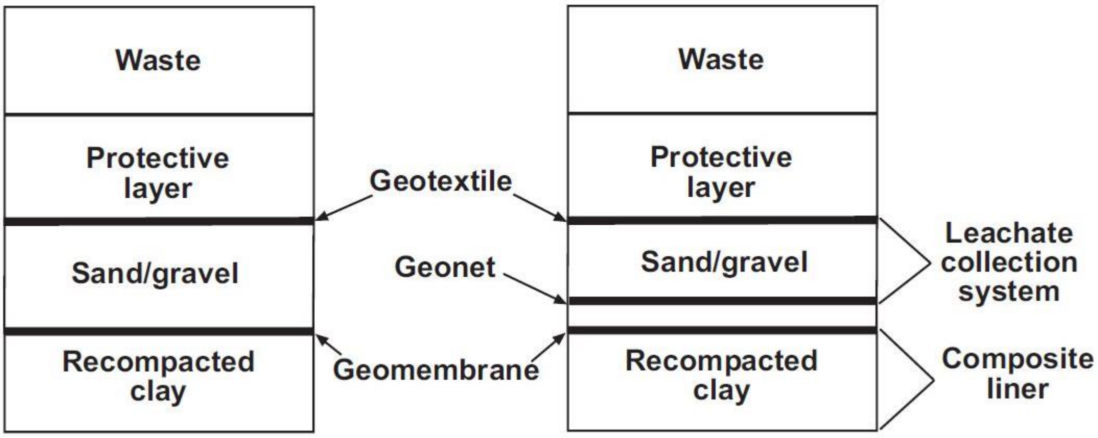
2.10.1 Single liner system

A single liner system includes only one liner material either natural impervious soil (clay) or a geosynthetic (geomembrane) material. Single liners are used in landfills designed to hold construction and demolition debris that include concrete, asphalt, shingles, wood, bricks, glass. These landfills are not designed to contain paint, asphalt, and municipal garbage. Figure 2.9 presents a typical view of a single liner system.



(a) (b)

Figure 2.9 Single liner system



(a) (b)

Figure 2.10 Composite liner system

2.10.2 Composite liner system

A Composite liner includes two or more different low-permeability material in direct contact with each other. Geotextile-bentonite is often used as a substitution for natural soil liner material (clay), for application along slopes. Composite liner systems are most effective in limiting municipal solid waste (MSW) leachate migration into the subsoil and are not suitable in hazardous waste disposal facilities. Figure 2.10 presents a typical view of a composite liner system.

2.10.3 Double liner system

A double liner system consists of either two single liners or two composite liners or single and a composite liner. The upper (primary) liner usually supports the leachate collection system (LCS) and lower (secondary) liner act as a leak detection system (LDS) and also back up to primary liner. Double liner systems are used in municipal solid and hazardous waste. Figure 2.11 presents a typical view of a double liner system.

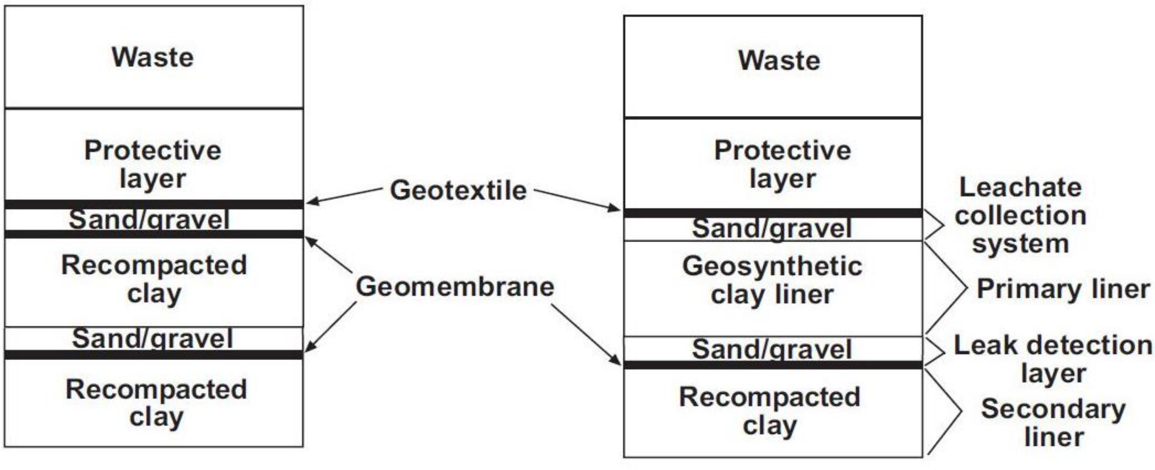


Figure 2.11 Double liner system

2.11 REVIEW ON DIFFERENT CRITERIA USED IN DESIGNING LINERS

Matthew and Jones (1999) observed that the important variables in the construction of soil liners are the compaction variables: soil water content, type of compaction, compactive effort, size of soil clods, and bonding between lifts. They observed that the lowest hydraulic conductivity of the compacted clay soil usually occurs when the soil is moulded at moisture content slightly higher than the optimum moisture content. They concluded that the acceptable zone of initial water content is in between the right side and optimum moisture content in the compaction curve and the zero air voids line. Figure 2.12 shows the influence of moulding water content on hydraulic conductivity of the soil. The lower half of the diagram is a compaction curve and shows the relationship between dry density and water content of the soil.

Daniel and Benson (1990) proposed a procedure for evaluating acceptable zone for compacted soil liner based on hydraulic conductivity and the recommended approach is;

- Soils to be compacted over a range of water content using three compactive efforts that represent the high, moderate, low effort expected in the field;

- Compaction specimens will then be permeated to determine hydraulic conductivity (*k*);

- Compaction data i.e. water content (*w*) and dry density (γ_d) are plotted for specimens with $k < 1 \times 10^{-9}$ m/s;

- An acceptable zone will be drawn to encompasses the test results meeting or exceeding the design criteria;

The acceptable zone will then be modified to account for other factors e.g., shear strength considerations, shrink /swell criteria, and local construction practices that may be relevant on any given project.

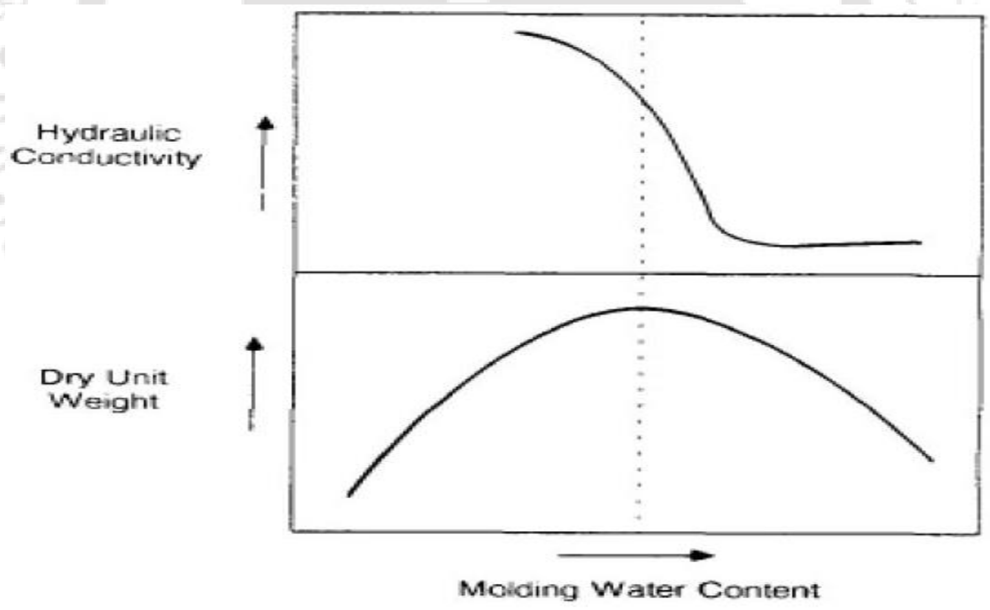


Figure 2.12 Variation of hydraulic conductivity, dry density and molding water content (US-EPA, 1980)

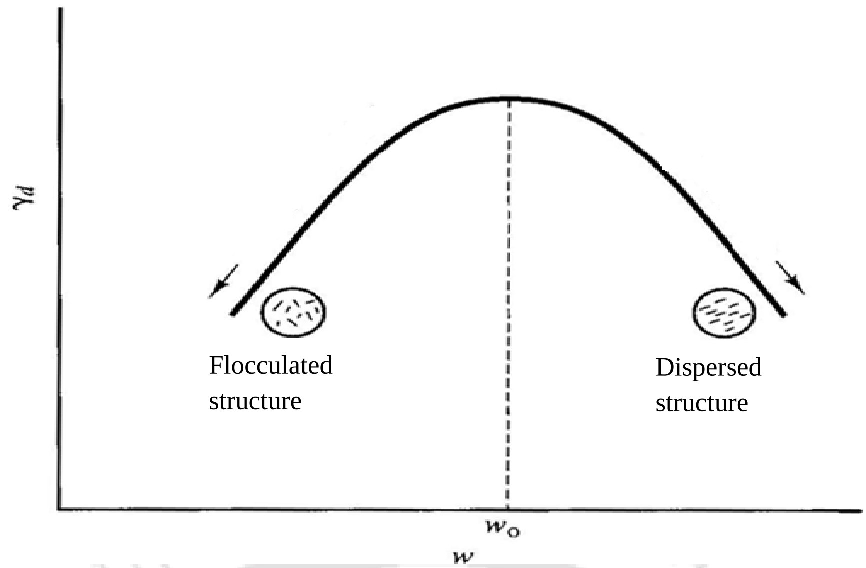


Figure 2.13 Variation of dry density (γ_d) and moulding water content (w) with soil structure (Lambe, 1958)

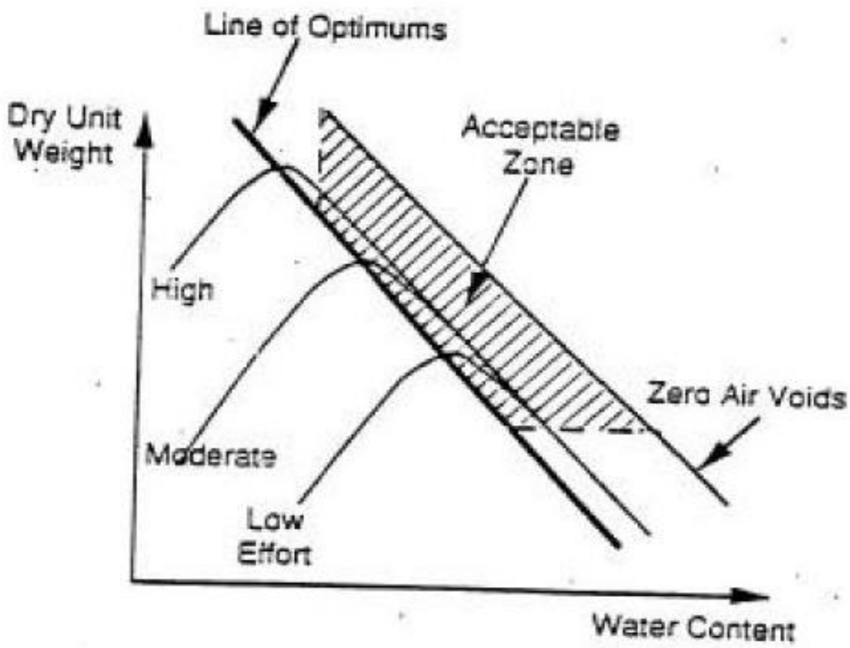


Figure 2.14 Acceptable zone of dry density and moisture content with compactive effort (Daniel and Benson, 1990)

2.12 REVIEW OF LITERATURES ON THE BEHAVIOUR OF SAND-BENTONITE MIXTURES

Dumbleton and West (1966) performed Atterberg limits tests on calcium montmorillonite, kaolinite clays and their mixtures with sand-silt mixes. Liquid limit results of clay-sand-silt mixes were found to diverge from their expected values i.e. a proportional liquid limit for the amount of clay in the mix assuming there is no effect of the sand-silt mix on the liquid limit, and the difference was found to be more in case of mixes with low clay content. In addition to the clay mineralogy and amount of clay in the soil sample, they noted that fine grained particles, not necessarily clay minerals, under 2-micron size range influenced the plasticity of clay-sand-silt mixture. Plasticity was found to reduce with the addition of sand-silt mix and upon further investigation; it was found that sand reduced the plasticity more than for the same amount of silt indicating a possible influence of particle size on plasticity. They suggested a minimum mixing period of 40 minutes before testing the soils to obtain repeatable results.

Polidori (2007) conducted liquid limit tests on bentonite- silica sand and bentonite-silica silt mixtures. Results indicated that for mixtures with high bentonite content the liquid limit is proportional to clay content in the mixture. When the non-clay particle comes in contact with each other the influence of non-clay fraction was seen to affect the mixes with low clay content. In a low clay content bentonite-soil mixture, as the particles are in contact with each other, resistance to deformation offered by the soil was relatively higher leading to a liquid limit higher than the value proportional to clay content in the mixture.

Abeele (1986) conducted a series of consolidation tests on bentonite-silty sand mixes for evaluating the influence of bentonite on the hydraulic conductivity of sandy silts. The major objective of his study was to select the appropriate bentonite-silt ratio for the use as a landfill liner material. He observed from his study that the coefficient of consolidation decreases inversely with the square of the bentonite/silty sand ratio. He also observed that the hydraulic conductivity decrease with increase in bentonite fraction in the mixture. Similarly, the compression index (C_c), swelling index (S_c), and the hydraulic conductivity change index (C_k) found to be increased with increasing the bentonite content in the mixture.

Hoeks et al. (1987) mixed 5% of Wyoming and activated European bentonite to the locally available sand and tested for hydraulic conductivity under a hydraulic gradient ranging from 5 to 55. The following observations were made from their investigation;

- In a bentonite clay liner flow does not occurs when the applied hydraulic gradient is low as the water molecules are tightly bound by bentonite, which restricts the easy movement of pore fluid and hence the inter-pore flow is non-laminar i.e. non-Darcian in nature.

- At higher hydraulic gradients (*i* = 50 to 100, where, *i* is the hydraulic gradient) the binding force, water molecules were seen to move more freely and the inter-pore flow is Darcian in nature.
- Hydraulic conductivity test results showed that 5% bentonite content serves the purpose; however, when leachate is considered, it was felt that an increase in bentonite content is necessary considering the ionic strength of cations present in the leachate.

Soil structure in a soil mass refers to the arrangement of soil particles, their electrochemical forces and the associated voids (Ranganatham, 1961), which has been further classified as micro structure and macro structure (Collins and McGown, 1974). A few instances where a better understanding of soil structure has been felt necessary in the analysis of engineering behaviour of soil are presented below.

From his study, Lambe (1964) observed a hydraulic conductivity ratio up to 60 for a given void ratio for the soil samples compacted on the dry of optimum moisture content (OMC) and wet side of OMC indicating the importance of soil structure (Lambe, 1954) on the hydraulic conductivity of soil. Lambe (1964) concluded that the hydraulic conductivity of a fine grained soil varies with some power of its "structure coefficient", where, the structure coefficient was a multiplication factor and assumed to account for the variations in hydraulic conductivity caused due to changes in soil structure.

From their scanning electron microscopy study of clays Matsuo and Kamon (1977) noticed that clay particles exist as aggregated entities called peds and so coined the terms "peds and pores". These peds and pores are the basic units constituting the structure of a soil and therefore have a defining role on the engineering behaviour of clay soil (Akagi, 1994). Brewer (1964) classified the pores associated with peds as intra-elemental, intra-assemblage, interassemblage and transassemblage pores (Collins and McGown, 1974). Intra-elemental pores are formed between individual particles, intra-assemblage pores are the ones formed between particle groups, interassemblage pores occur between individual particle assemblages of any level of complexity and transassemblage pores are pores without any specific relationship to other microfabric features (Collins and McGown, 1974).

Ranganatham (1961) conducted studies on the compressibility characteristics of clays and the influence of soil structure and observed that irrespective of the mixing fluid and initial platelet orientation, with increase in surcharge loading, clay particles assume a parallel array.

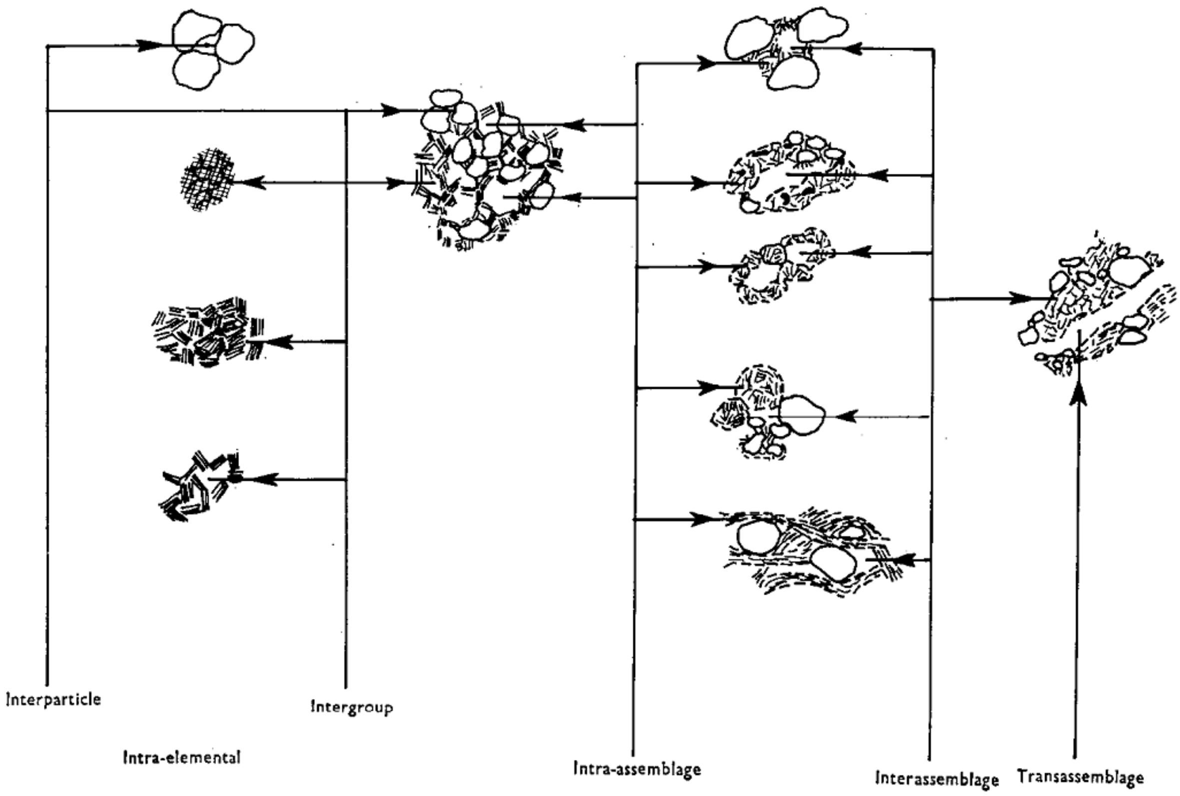


Figure 2.15 Schematic representations of pore space types (Collins and McGown, 1974)

Cowland and Leung (1991) carried out field and laboratory tests on the completely withered granite (CWG) mixed with 5, 7 and 10% of bentonite by dry weight and suggested a range of initial water content from OMC to 4% wet of OMC as compaction water content at the site, where OMC was the optimum moisture content obtained in the laboratory. It was also concluded from their study that hydraulic conductivity of the mixture decreases with the time and also with the increase in the bentonite content. Considering the test results and site conditions a bentonite content of 5 to 7% by dry weight was suggested for the use as a liner material.

Shelley and Daniel (1993) conducted experimental studies on gravel-clayey soils to understand their performance when used as liner material. Gravel was added to the clayey soil to obtain mixtures with 0, 20, 40, 60 and 80% of gravel by dry weight. Maximum dry density for the mixtures was observed to be peaking at 60 to 80% gravel content. Hydraulic conductivity tests carried out on the samples compacted at 2 to 4%

wet of optimum showed that at the gravel content of 60% or higher the hydraulic conductivity increased markedly. It was also observed that all the mixtures exhibited their lowest hydraulic conductivity when the molding water content was 4% wet of optimum.

Bolt (1956) indicated that volume change behaviour upon loading in a laterally confined coarse grained soil depend upon deformation and rotational displacement of soil particles, while the same in a clay rich fine grained soil depends upon nature of pore fluid present in the soil, elastic deformation of diffuse double layers of clay platelets along with rearrangement and rotational displacement associated with the clay particles (Ranganatham, 1961). Bolt (1956) observed that the compressibility of a clay-coarse soil mixture is a result of contributions by mechanical properties of coarse soil and complex physico-chemical interactions of clay particles.

Sivapullaiah et al. (1996) conducted consolidation tests to study the swelling characteristics of the different mixtures of swelling and non-swelling soils mixed in various proportions. Bentonite was added as a swelling soil to different non-swelling soils like silt, kaolinite, fine and coarse sand in a proportion of 10% to 100% by dry weight. The following observations were made from their investigation;

- Swelling occurs only after the voids of the non-swelling particles are filled up with swollen particles.
- Swelling within the voids is called as Inter void swelling, and it is large when the size and percentage of the non-swelling coarse particles is large and does not contribute to volume increase, after end of this swelling, primary swelling occurs and it contributes about 80% of the total swelling. Secondary swelling occurs when 90 % swelling is reached.
- Total swelling directly depends upon the percentage of bentonite present in the mixture.
- Primary and secondary swelling follows rectangular hyperbolic relationship on time vs swelling curves.

Howell et al. (1997) conducted compaction tests on sand - clay soils (granular bentonite (GB), powder bentonite (PB), attapuligite clay (AC)) to observe the effect of mixing procedure and curing time on the compaction properties of the mixes. Two mixing procedures were used for making the soil sample, first, water was added to sand before mixing with clay soils; second, sand and clay were mixed thoroughly before adding water. The mixes were made and left to cure for a period of one day and seven days respectively. From the experiments, they observed that for the sand-attapuligite clay mix the MDD decreases and OMC increases with the increase in the percentage of attapuligite clay in the mixture. Similarly, for sand–GB and sand–PB mix, the OMC decreased with increasing the percentage of GB and PB, respectively; while, MDD remained constant with increasing percentage of GB but increased with increasing the percentage of PB for both curing periods.

Chyi Sheu et al. (1998) investigated the feasibility of using mudstone as a natural liner material at the waste disposal site and observed that the factors which effect the hydraulic conductivity includes; soil composition, permeant characteristics, void ratio, soil structure, and degree of saturation during permeation. The hydraulic conductivity of the soil compacted at wet of optimum was observed to be lower than the hydraulic conductivity compacted at dry of optimum and this difference was attributed to the formation of flocculated particle structure compacted at dry side of optimum. Chyi Sheu et al. (1998) concluded that the lowest hydraulic conductivity of compacted clay occurs at water content 2 to 4% wet of optimum water content. At the macroscopic viewpoint, increasing water content generally results in an increased ability to break down clay and to eliminate interparticle pores. At the microscopic standpoint, increase in water content result in reorientation of clay particles and reduction in the size of interparticle pores. From the study it was opined that the construction of landfill liner using mudstone can be accepted provided the water content is carefully controlled.

Benson et al. (1999) conducted a series of large scale field hydraulic conductivity (k_F) on compacted clay liner for evaluating the performance of clay liner and observed that the hydraulic conductivity decreases with increase in initial saturation. It was observed that the hydraulic conductivity became $\leq 10^{-9}$ m/s when the initial degree of saturation was higher than 80%.

Studds et al. (1998) conducted studies on bentonite and sand-bentonite mixes (10% and 20% of bentonite by dry weight), to understand the swelling and hydraulic conductivity behaviour in the presence of distilled water and chloride solutions of Na, K, Ca, Mg, Cs and Al. From the study they observed that in the presence of distilled water, sand-bentonite mix behaves in terms of clay void-ratio as pure bentonite does in low effective stress condition (less than 200 kPa); however, with the increase in the effective stress the behaviour changes and this change was very much dependent on the percentage of bentonite in the mix. At higher effective stress apart from being dependent on pore fluid the swelling behaviour was also found to be dependent on sand pore volume also. Hydraulic conductivity was noted to be increasing with concentration for all the salt solutions probably due to the increase in the effective porosity.

Hussain (1999) investigated the swelling and compressibility characteristics of sand-bentonite mixes in the presence of distilled water, sodium nitrate and calcium nitrate, as cations of sodium and calcium are found in relatively higher concentration in municipal solid waste leachate. Two bentonites with liquid limit 505% and 316% were added to sand to make 20% bentonite and 80% sand mixes and permeated with solutions of concentration ranged from 0.1 to 4 N. Results showed that the swelling pressure of the mixes reduced with an increase in concentration of pore fluid and more notably a rapid reduction in swelling pressure was observed at concentrations higher than 0.1 N concentration.

Sivapullaiah et al. (2000) conducted studies on locally available bentonite, sands and silts to understand the role of coarse fraction in the bentonite-soil mixes. Coarser fractions i.e. sand and silt were mixed with different bentonite contents ranging from 5 to 100%. The results showed that the hydraulic conductivity decreases with an increase in the bentonite content in the mixes. The effect of coarse fraction was found to be notable in the lower percentages of bentonite due to the presence of large but fewer voids. At higher bentonite contents all the mixes seemed to have the possessed similar pore distribution and hence exhibit equal hydraulic conductivity. The study concluded that hydraulic conductivity increases with an increase in coarse content of the mix, even though the effect is small in higher bentonite contents.

Tay et al. (2001) conducted laboratory tests on bentonite enhanced sand (BES) mixtures to evaluate the effects of shrinkage and desiccation cracking on hydraulic conductivity. The study indicated that the volumetric shrinkage of compacted BES mixtures upon air-drying increases with increasing moulding moisture content. Mixtures containing 20% bentonite was found to be shrunk more than those containing 10% bentonite, but was insensitive to compactive effort. It was observed from the study that the compacted layers of BES containing 10 and 20% bentonite do not exhibit desiccation cracking if the volumetric shrinkage during drying is less than about 4%. A BES layer compacted at a moisture content that would not result in desiccation cracking upon drying may swell upon access to further water and may then crack on subsequent drying.

Won-jin cho et al. (2002) studied the effects of dry density and bentonite content on the hydraulic conductivity of soil-bentonite mixes with bentonite content ranging from 0 to 20%. Results for the compaction tests showed that OMC increases and MDD decreases with an increase in bentonite content. The reduction in hydraulic conductivity was not found to be significant for the mixes compacted to dry densities of 1400 and 1500 kg/m^3 even with the increasing bentonite content. With increasing bentonite content, a rapid decrease in hydraulic conductivity was observed when compacted to a dry density of 1600 kg/m^3.

Cokca and Yilmaz (2004) added rubber and bentonite to fly ash for evaluating the feasibility of utilizing fly ash, rubber and bentonite as a low hydraulic conductivity liner material. Unconfined compressive strength was found to decreases with a reduction in the bentonite content and with less curing period. Coefficient of volume change increased with bentonite content and curing time.

Chalermyanont and Arrykul (2005) investigated the use of sand-bentonite mix as a liner material and observed that the frictional angle and hydraulic conductivity decreases with increasing the bentonite content in the mix. They also observed that atleast 9% bentonite by dry weight of the mixture is sufficient to cover all the sand particles in the mix and concluded that the sand-bentonite mixtures with 3% bentonite content compacted at about 2% wet of optimum water content qualifies for use as liners in hydraulic containment applications with relatively high friction angle.

Ameta and Wayal (2008) conducted laboratory tests on bentonite-dune sand mixes for evaluating the influence of bentonite on the mix. Coefficient of consolidation (c_v) – pressure relationship demonstrated that c_v decreases rapidly with pressure for lower bentonite contents (2 - 6%), whereas, at higher bentonite contents (6 – 8%) the variation was marginal. Further it was noted that the coefficient of volume change decreases with the increase in the pressure for all bentonite contents. The tests results showed that the hydraulic conductivity of dune sand was greatly affected by addition of bentonite and it reduced from 10^{-6} m/s to 10^{-10} m/s with the addition of 10% bentonite to the sand when compacted at maximum dry density and optimum water content.

Crawford (1965) conducted consolidation studies on undisturbed sensitive Leda clay to understand the influence of loading strain rates on the pre-consolidation pressures and noticed that the pre-consolidation pressure decreases with decreasing strain rate for any given soil specimen. From the study they concluded that this time-dependent resistance to compression attributed to the soil structure, implying a deeper understanding on the role of soil structure is necessary in understanding the hydro-mechanical characteristics of a soil.

Gueddouda et al. (2008) conducted a series of laboratory tests to evaluate the feasibility of utilizing dune sand and bentonite as a liner material by adding 0 to 15% of bentonite to dune sand. The results showed that the frictional angle decreases and cohesion increases due to the addition of bentonite to the dune sand. It was noted from the study that the hydraulic conductivity of the dune sand-bentonite mixtures decreases with increasing bentonite content and the study concluded that the dune sand with 12% of bentonite and compacted at OMC-MDD exhibited a hydraulic conductivity value lower than 10^{-9} m/s and met the design hydraulic conductivity criteria for a landfill liner.

Roberts and Shimaoka (2008) investigated the effect of compaction on the bentonite coated gravel (BCG) by employing various compacting methods such as reduced proctor, standard Proctor, intermediate proctor, modified proctor and super modified proctor. It was observed from the study that over compacting the soil can create fractures in the aggregate and resulting in the formation of preferential pathways, which increases the hydraulic conductivity of the soil. It was also observed from the study that the compaction has a relatively small influence on the compressibility of BCG. It was noted from the study that low hydraulic conductivity can be attained from the 70% aggregate portion of BCG weight. It was concluded that the intermediate proctor or modified proctor is the best suited for constructing a BCG barrier.

Francisca and Glatstein (2010) attempted to understand the effect of permeating fluid on the long-term effect on hydraulic conductivity of a compacted silt-bentonite mixes. Study was conducted on silt-bentonite mixes with 0, 5, and 10% of bentonite by dry weight with the permeants such as distilled water, leachate and a nutrient solution made up of 2% glucose, 0.1% NaCl, 0.1 % yeast, 0.05% $MgSO_4$, 0.08% K_2HPO_4, 0.02% KH_2PO_4 and 0.075% $FeCl_3$. The results showed no effect of permeating time for the samples mixed and permeated with distilled water; while a notable reduction in hydraulic conductivity was observed for samples permeated with nutrient solution and leachates indicating the time dependent reduction in hydraulic conductivity was due to the biological clogging.

2.13 SUMMARY AND CRITICAL APPRAISAL OF LITERATURE REVIEW

A review of literature regarding the sand types used in the making of liners, buffers and backfills indicated that

- Locally available sands were used in making the barriers
- Sand was considered a filler material, only considered for its volumetric stability in the sand-bentonite mix.
- No importance was given to assess its suitability as a barrier material in terms of its particle size distribution.

From the available literature it was observed that hydraulic conductivity is considered the most important criterion while selecting a geotechnical barrier material. Compacting a soil has been seen to reduce its hydraulic conductivity. Apart from successfully fulfilling the low hydraulic conductivity criterion, a barrier is expected to have sufficient shear strength in order to prevent excessive uneven settlements caused by the overbearing loads. As far as the shear strength is concerned, compacting the barrier material to a higher density using heavy compaction techniques was seen to be a solution in the laboratory, which by the way isn’t always possible in the site. Compacted clays were seen to be capable of low hydraulic conductivities under confinement. However, high compressibility, high desiccation shrinkage, low shear strength and low achievable density etc. are some reasons of concern while using compacted clays, which undermine its candidature as barrier material. An improvement in the engineering characteristics like shear strength, desiccation susceptibility, maximum dry density, thermal conductivity etc. has been observed when locally available soils such as sand were mixed with clays.

Compacted bentonite-sand mixtures are finding applications as geotechnical barriers in domestic waste disposal schemes, low level and high level radioactive waste disposal facilities. When a bentonite-sand mixture is compacted, sand forms the skeleton of the soil mass, giving volumetric stability, while bentonite occupies the void spaces/pore created between the sand particles. In the presence of water or any other fluid, bentonite in the void spaces adsorbs water and starts filling the void spaces thereby reducing the permeability of the medium. The extent to which a pore remains filled defines the hydro-mechanical behaviour of a bentonite-sand mixture. Bentonite being a relatively costly material, most of the studies found in the literature had a similar objective i.e. optimizing the bentonite content in the mixture while achieving low hydraulic conductivity, very few studies were reported on the influence sand has on the engineering characteristics of these mixtures. Research workers proposed various proportions of bentonite to be fulfilling the necessary hydro-mechanical criterions. While the major component, i.e. sand, was chosen almost randomly and no particular importance has been given to assess the influence of sand composition and sand particle size on the behaviour of sand-bentonite mixture. If sand gradation is an influencing parameter in the performance of a barrier and should be reckoned with, is still a matter of ambiguity. Current study sheds light on the role of different particle sizes of sand and sand types on the Atterberg limits, compaction characteristics, strength characteristics, shrinkage characteristics, compressibility characteristics and hydraulic characteristics of bentonite-sand mixtures.

Bentonite content, quality, swelling characteristics etc. were of main interest in most of the studies conducted, although unintentional, a few sand proportion ranges by dry weight were reported in the literature, as shown in Table 2.1.

From the data in Table 2.1, it can be observed that proportion of sand used in the literature repeatedly constituted of a fine sand content of 30 % to 70 % and medium sand content of 70 % to 30 % by dry weight. The same ranges were agreed upon to be used in the current study while assessing the effect of fine sand-medium sand proportioning on sand-bentonite mixes.

Table 2.1 Review on various sand particle sizes reported in literature

Study by	Medium sand content (%)	Fine sand content (%)
Borgesson et al. (2003)	17	9
Dixon et al. (1985)	7	83
Sudhakar Rao et al. (2008)	84	12
Gustafsson (2001)	45	40
	44	44
Yeo et al. (2005)	95	5
Johannesson and Nilsson (2006)	26	11
	31	15
Sällfors and Öberg-Högsta (2002)	33	52
	40	30
	35	25
Komine and Ogata (1999)	5	95
Ito and Komine (2008)	65	35
Chalermyanont and Arrykul (2005)	40	24
Hoeks et al. (1987)	56.3	31.7
	30	60.8
	40.8	55
	9.1	88.6
	5	91.8

2.14 OBJECTIVES OF THE PRESENT STUDY

Literature review indicated that "soil structure" plays a prominent role in the engineering characteristics of a soil or a mixture of soils. Particle size distribution of the soil has an undeniable influence on the soil structure. Continuing the same, particle size distribution of sand or the sand type has a definitive influence on the behaviour of the barrier materials, which for the most cases has been neglected. The primary objectives of the current study are;

1. To investigate the influence of sand particle size on the Atterberg limits, shear strength, shrinkage and standard compaction characteristics of bentonite-sand mixes made with two bentonites with varying bentonite-sand proportions.
2. To investigate the influence of sand particle size on the swelling characteristics and hydraulic characteristics of bentonite-sand mixes made with two bentonites with varying bentonite-sand proportions.

3. To investigate the influence of sand type on the consolidation characteristics of bentonite-sand mixes made with two bentonites with varying bentonite-sand proportions.
4. To understand the influence of initial compaction condition and sand particle size on the hydraulic and mechanical characteristics of bentonite-sand mixes made with two bentonites with varying bentonite-sand proportions.
5. To understand the influence of bentonite quality on the swelling, hydraulic and mechanical characteristics of different bentonite-sand mixes containing sand of different particle size.

2.15 SIGNIFICANCE OF THE STUDY

Engineered geotechnical barrier systems form an integral part of a waste disposal scheme. A better understanding of various component members used in the making of a barrier may lead to an optimized design of the barrier system. At the same time, given the huge amounts of natural/enhanced soil being employed in making the barriers, any reduction in the raw material required would result in optimizing the necessary infrastructure for mining, processing and transportation of raw material thereby reducing project costs involved. Reduced project costs can help promote the concept of engineered waste disposal. The current study is an attempt at understanding the engineering influence of different aggregate particle sizes of sand when used in a bentonite-sand mixture.

Chapter 3

MATERIALS AND METHODS

GENERAL

This chapter deals with the materials used in performing the investigation. The methods of determining various properties of the different sand-bentonite mixes have also been discussed.

3.1 MATERIALS USED IN THE STUDY

The sand used in the study was procured from a local source. Two commercially available bentonites, with different mineralogical composition, were selected for this study and procured from Rajasthan state of India and named as Bentonite-1 (B1) and Bentonite-2 (B2). The properties of bentonites are listed in Table 3.1. The data in the Table 3.1 shows that the Bentonite-2, which has a higher liquid limit, plasticity index, clay content, CEC, ESP, and SSA, is expected to swell more and exhibit a lower value of hydraulic conductivity (Mishra et al., 2011) in comparison to Bentonite-1 and termed as a high quality bentonite.

3.2 TESTING METHODOLOGY

3.2.1 Bentonite

The physical, chemical and mineralogical properties of the bentonites were determined as per the following methods and are tabulated in Table 3.1.

3.2.1.1 Atterberg limits

The Atterberg limits of the bentonites were determined according to ASTM D 4318 (2000). Representative samples of the soil were taken to determine Atterberg's limits by using the size fraction passing through 0.425 mm sieve. Casagrande apparatus was used to determine the liquid limit and plastic limit was determined with the thread-rolling method. Results are presented in Table 3.1.

3.2.1.2 Free swelling test

Free swelling tests for the bentonites were conducted according to ASTM D5890 (2001). Approximately 90 ml of DI water was poured into a 100 ml graduated cylinder. Two grams of dry bentonite was put into the cylinder and the respective DI water or solution was used to rinse down any bentonite particles adhering to the sides of the cylinder and then it was filled up to the 100 ml mark. The swollen volume of the bentonite was measured after 24 hour of exposure.

3.2.1.3 Cation exchange capacity (CEC)

The cation exchange capacity (CEC) is the quantity of exchangeable cations required to balance the negative charge on the surface of the clay particles. CEC is expressed in milliequivalent per 100 grams of dry clay. The cation exchange capacity (CEC) and exchangeable cations of the bentonites were determined by the ammonium acetate method as described by Chapman (1965) and Pratt (1965) respectively. 125 ml of 1 M ammonium acetate (NH_4OAc) was added to 25 g of soil and allowed to stand 16 hours. The soil was washed 4 times with 25 ml additions of NH_4OAc, allowing each addition to filter through but not allowing the soil to crack or dry. Exchangeable cations were determined on the leachate after diluting it to 250 ml.

3.2.1.4 Specific surface area (SSA)

Specific surface is the ratio of the surface area of a material to its mass and expressed in m^2/gm. Smaller the particle size higher is the specific surface area. Higher is the specific surface area, higher is the amount of charge on its surface and higher will be the amount of water or contaminant it can adsorb. The specific surface area of the bentonites was determined by the method described by Cerato and Lutenegger (2002). This test involved saturating a soil sample with ethylene glycol mono-ethyl ether (EGME) and then removing the excess EGME in a vacuum desiccator, until the EGME forms a monomolecular layer on the soil surface. One gram of oven dried soil was placed in a glass tare and mixed with 3 ml of EGME. The tare was placed into a vacuum desiccator and it was evacuated by a vacuum pump using a vacuum of at least 635 mm Hg. The weight of the mixture was taken at regular intervals till the weight did not vary more than 0.001 g between two successive readings. SSA was calculated according to

$$\text{Specific Surface Area (SSA)} = \frac{W_a}{0.000286 W_s}$$

Where,

W_s= Weight of soil added initially (g)

W_a= Weight of EGME retained by the sample in grams (final slurry weight - W_s)

0.000286 = Weight of EGME required to form a monomolecular layer on a square meter

3.2.1.5 X-ray diffraction (XRD) method

In XRD method the material is exposed to a filtered X-ray beam. The beam passes into the material and cause the electron in the atoms of the minerals to vibrate and reflect the beams through successive planes. The method involves increasing of incidence angle and monitoring the intensity of the diffracted X-radiation until a maximum value of the diffracted intensity is achieved. The X-ray diffraction maximum is detected whenever the following equation is satisfied;

$n\lambda = 2d \sin\theta$, n = 1,2, 3..., λ = wave length, d = space between the diffracting planes, θ= angle of diffraction. Figure 3.1 and 3.2 shows X-ray diffraction patterns of Bentonite-1 and Bentonite -2.

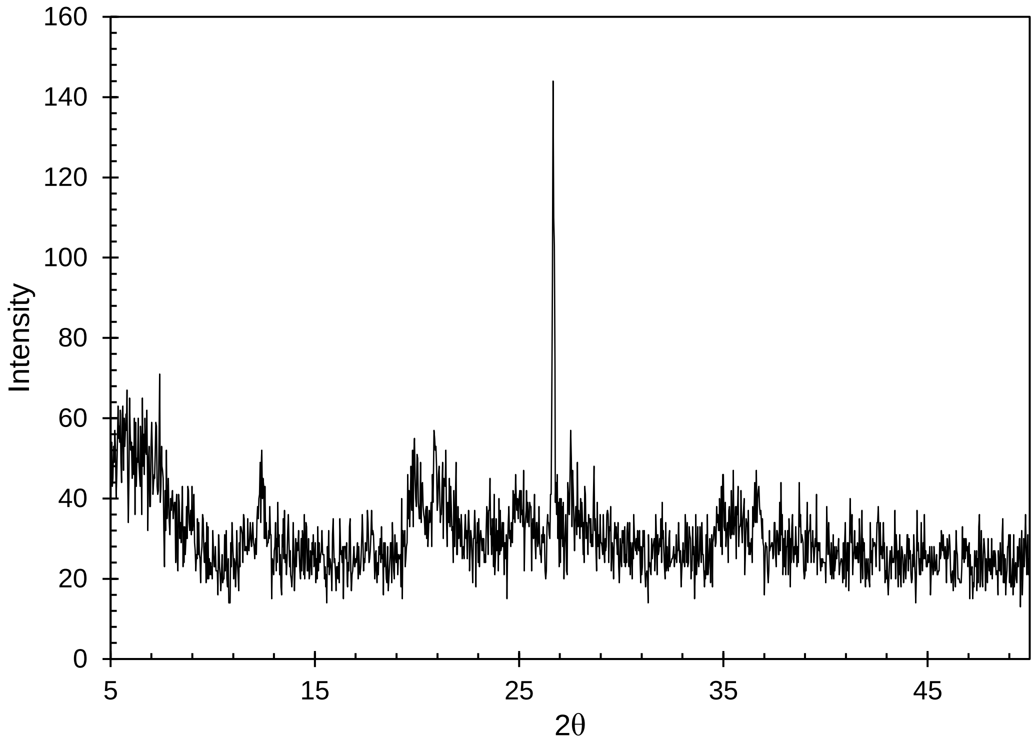


Figure 3.1 X-ray diffraction (XRD) result of Bentonite-1

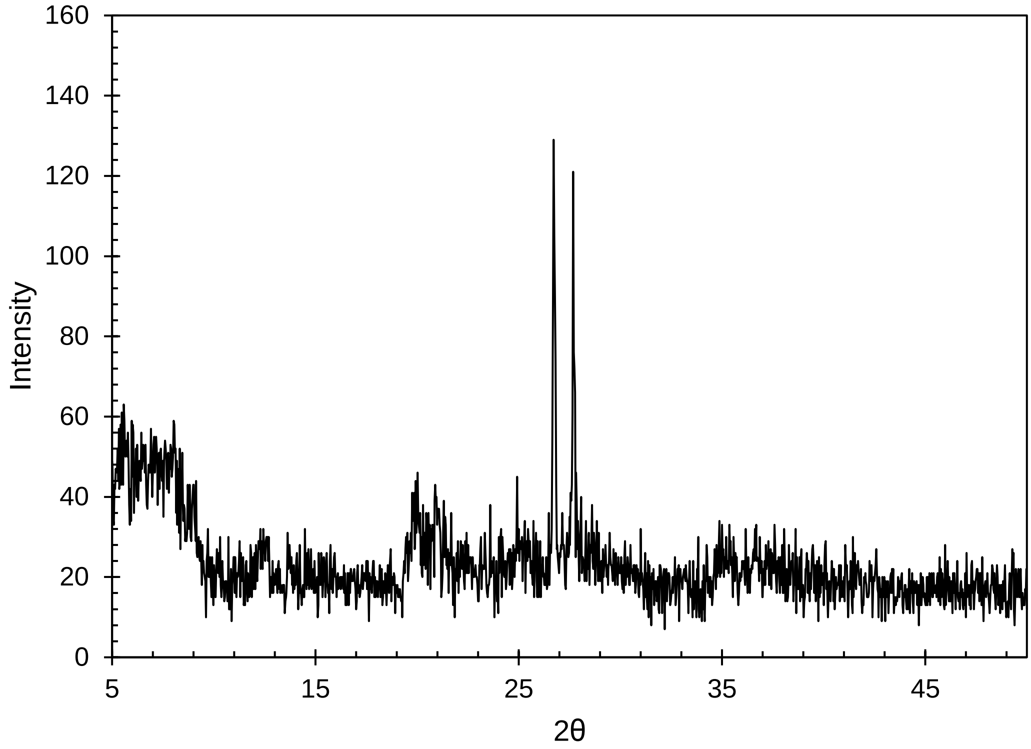


Figure 3.2 X-ray diffraction (XRD) result of Bentonite-2

Table 3.1 Properties of bentonites used in this study

Property	**Bentonite-1**	**Bentonite-2**
Liquid limit (%)	346.1	609.2
Plastic limit (%)	33.0	41.5
Plasticity index	313.1	567.7
Shrinkage limit (%)	23	10.4
Specific gravity	2.80	2.82
Clay content (%)	52.2	68.0
Silt content (%)	43.4	28.3
Cation exchange capacity (CEC) (meq/100gm)	37.3	54.6
Na^+	20.5	34.2
K^+	3.5	1.8
Ca^{2+}	10.8	16.9
Mg^{2+}	2.5	1.7
Exchangeable sodium percentage (ESP)	54.9 %	62.6 %
Specific surface area (m^2/g)	365.2	526.5

3.2.2 Sand and sand-bentonite mixes

3.2.2.1 Sieve analysis

After washing the sand with distilled water it was sieved following the guidelines provided in ASTM C 136M (2014) and separated into three groups, i.e. fine sand, medium sand and coarse sand, Table 3.2 presents the classification of sand.

Table 3.2 Classification of sands

Classification of sands	Size of sand particles (mm)	Specific gravity (G)
Fine sand (FS)	0.075 – 0.425	2.63
Medium sand (MS)	0.425 - 2	2.68
Coarse sand (CS)	2 – 4.75	2 .69

3.2.2.2 Specific gravity

The specific gravity of the sand fractions was determined by following the guidelines in ASTM D 854 (2014) with the help of Pycnometer and tabulated in Table 3.2. The specific gravity of fine sand (FS) and medium sand (MS) mixed to both the bentonites separately in various proportions, ranging from 10 to 50% and used for this investigation, was determined.

3.2.2.3 Atterberg limits

The Atterberg limits of the various sand-bentonite mixes were determined according to ASTM D 4318 (2000). Liquid limit of representative samples was determined using cone penetration test as suggested by Sivapullaiah and Sridharan (1985), while plastic limit was determined with the thread-rolling method.

3.2.2.4 Standard proctor compaction test

Compaction tests were performed as per as ASTM D 698 (2012) to determine the maximum dry density (MDD) and optimum moisture content (OMC) for sand-bentonite mixes. The compaction parameters obtained were used to prepare specimens for other tests like consolidation test and unconfined compression test to determine the engineering properties.

3.2.2.5 Consolidation test

Consolidation test was carried out on sand-bentonite mixes in order to assess the hydraulic conductivity and compressibility of the mixtures. Indirect determination of the hydraulic conductivity from consolidation tests has several advantages over other permeability tests. Advantages are

(1) vertical pressures simulating those in field can be applied;
(2) can measure vertical deformations;
(3) can test sample under a range of vertical stresses;
(4) thin samples permit shorter testing time;
(5) Cost effective method for obtaining hydraulic conductivity data over a range of sample states.

However, it has some disadvantages over other methods. They are

(1) Some soil types may be difficult to trim into consolidation ring;
(2) Thin samples may not be representative;
(3) Potential for side wall leakage;

Despite of some disadvantages, the consolidometer permeability test is potentially the most useful among the other methods viz. rigid wall permeameter and flexible wall (triaxial) permeameter because of the flexibility it offers for testing specimens under a range of confining stresses and for accurate determination of the change in sample thickness as a result of both seepage forces and chemical influence on the soil structure. Furthermore, the thinner samples relative to the other test type means that the pore fluid replacement can be achieved in a short time for a given hydraulic gradient.

The hydraulic conductivity can be calculated from the consolidation test results by fitting Terzaghi's theory of consolidation (Terzaghi, 1923) to the observed laboratory time-settlement observation and extracting the hydraulic conductivity from calculated coefficient of consolidation. The fitting operation was carried out using Taylor's square root method. A question may arise, how the hydraulic conductivity calculated by Terzaghi's theory is comparable to that determined directly by permeability tests. Terzaghi (1923) made such comparison when he first developed the theory; he found satisfactory agreement. Casagrande and Fadum (1944) reported that they always found satisfactory agreement provided that there was a distinct change in curvature when the primary settlement curve merged with the secondary settlement curve. Taylor (1948) presented comparison for remolded specimens of Boston blue clay, based on the square root fitting method, and showed that the measured hydraulic conductivity generally exceeded the calculated values. He attributed this difference in hydraulic conductivity to Terzaghi's assumption that the sole cause of delay in compression in the time required for the water to be squeezed out, i.e. to the hydraulic conductivity of the clay. Taylor (1948) concluded that the structure of clay itself possessed a time dependent resistance to compression so that the total resistance to volume change came partly from the structural resistance of the clay itself. By attributing all of the resistance to low hydraulic conductivity, Terzaghi's theory must inevitably lead to an underestimate of the hydraulic conductivity. On the basis of several experiments Mesri and Olson (1971) concluded that the calculated hydraulic conductivity was low only by 5 to 20 % for both remoulded and undisturbed clay provided the clay is normally consolidated at the time of determination.

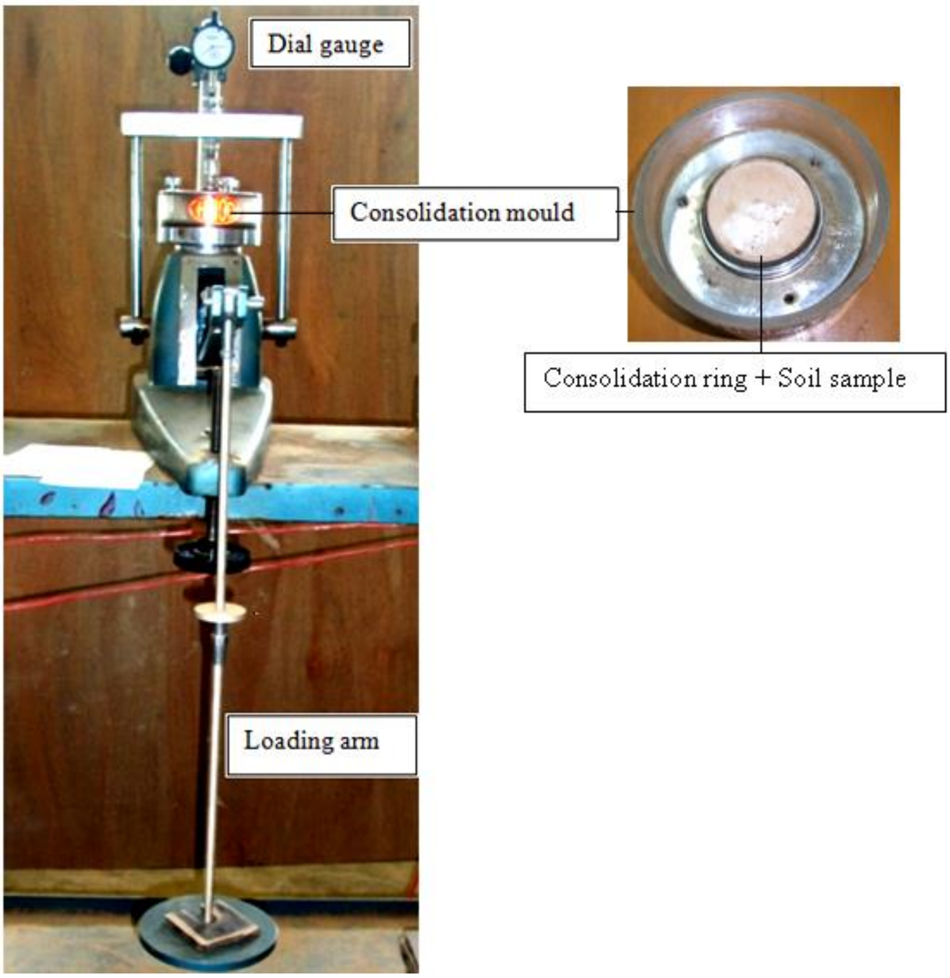


Figure 3.3 Oedometer test setup

In regards to the determination of the hydraulic conductivity of clayey soil, the consolidation test has been widely used (Newland and Allely, 1960; Mesri and Olson, 1971; Budhu, 1991; Sivapullaiah et al., 2000). This test generally provides the hydraulic conductivity comparable with the permeability test (Terzaghi, 1923; Casagrande and Fadum, 1944) although slightly underestimates the hydraulic conductivity compared with the permeability test (Taylor, 1948; Mitchell and Madson, 1987).

For every mix proportion 3 samples were made, each mixed with different water content. Each sample was packed in an airtight polythene bag and left for a period of 24 hrs for equilibrium in a desiccator, while the mixing water contents were 5% dry of OMC, OMC and 5% wet of OMC. Consolidation samples were made by compacting the sample to its corresponding MDD. Consolidation test was conducted in accordance with ASTM D 2435 (2011). The dimensions of consolidation ring were 60 mm internal diameter and 20 mm height, silicone grease was applied to the inner surface of ring to eliminate the friction between the ring and the soil sample. A porous stone and filter paper were placed both at the bottom and top of the soil specimen. The entire assembly was placed in the consolidation cell and positioned in the loading frame with a seating pressure of 4.9 kPa as shown in Figure 3.3, DI water was added at top cap and allowed to swell until the swelling seized, and corresponding vertical displacement with time was measured. The pressure increment ratio was maintained as 1.0 and the pressure increment was done after a period of 24 hrs. The pressure increment was done in the following order 4.9, 9.8, 19.6, up to 784.5 kPa.

3.2.2.6 Determination of swelling potential and swelling pressure

Swelling pressure and swelling potential was determined from the consolidation test. A surcharge load of 4.9 kPa was applied to the sample compacted at their respective initial density and water content and then the saturating with deionized water and allowed to swell. During the swelling process the swelling amount with time were recorded. The measurements continue until the swelling increment reach negligible values. At this point a standard consolidation test was conducted by applying incremental loads starting with 4.9 kPa and ending with 784.5 kPa. The pressure required to revert the specimen to its initial void ratio was determined as the swelling pressure, which is defined as the value of pressure required to keep the sample at zero swelling after saturating it with saturating fluid. The swelling potential is defined as the percentage swelling of the soil.

The details of this method have been described by Sridharan et al. (1986). The point SP in Fig. 3.4 corresponds to swelling pressure of the compression curve

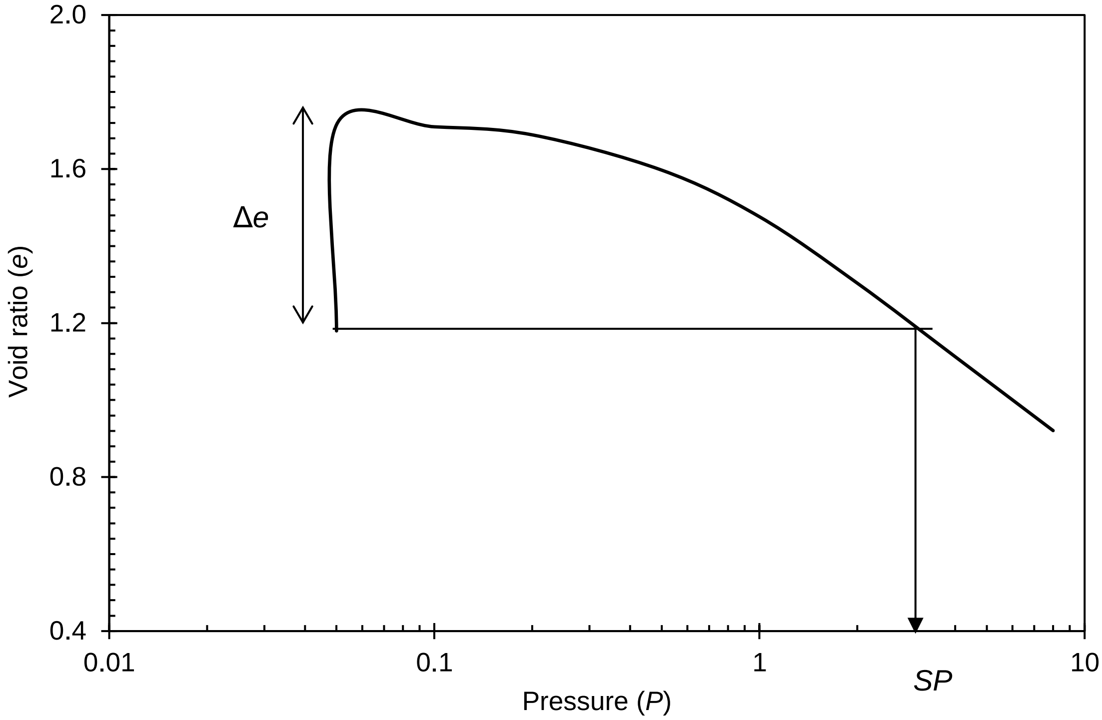


Figure 3.4. Determination of swelling pressure and swelling potential

Swelling potential (*SP*) for the samples was calculated as;

$$\text{Swelling Potential}\,(SP) = \frac{\Delta e}{1+e_0} \qquad \text{(Eq. 3.6)}$$

where,

Δe is the change in the void ratio of the sample due to swelling and e_o is the initial void ratio before swelling.

3.2.2.7 Determination of hydraulic conductivity and compressibility

For each pressure increment the change in the thickness of soil sample was measured from the readings of the dial gauge. Then the change in the void ratio corresponding to an increase in the overburden pressure was calculated by the Eq.3.1,

$$e = \frac{\Delta H(1+e_0)}{H} \qquad \text{(Eq.3.1)}$$

Where,

ΔH = Change in the thickness of sample due to increase in pressure

H = Initial thickness of the sample,

e_o = Initial void ratio

From the calculated void ratios, a plot of void ratio, e vs log of pressure, P, was plotted. The compression index (C_c) was calculated from the slope of this curve, or

$$\text{Compression index } C_c = -\frac{e_i - e_j}{\log \frac{P_i}{P_j}} \quad \text{(Eq.3.2)}$$

Where,

e_i = Void ratio corresponds to a consolidation pressure of P_i

e_j = Void ratio corresponds to a consolidation pressure of P_j

From the consolidation test result, a time-settlement curve was obtained at each pressure increment. The coefficient of consolidation (c_V) was obtained using Taylor's (1948) square root time (√T) method.

The co-efficient of volume change (m_v) can be calculated by the formula,

$$m_v = \frac{a_v}{(1+e_0)} \quad \text{(Eq.3.3)}$$

Where,

a_V = coefficient of compressibility = $\Delta e / \Delta\sigma$

$\Delta\sigma$ = Change in pressure

Δe = Change in void ratio

The hydraulic conductivity, k, was calculated using the Eq.3.4 for various pressure increments using the coefficient of consolidation (c_V) and coefficient of volume change, m_V

$$k = c_v m_v \gamma_w \quad \text{(Eq.3.4)}$$

Where, γ_w is the unit weight of the pore fluid

Coefficient of consolidation (c_v) has been determined by the square root of time fitting method given by Taylor (1948).

$$c_v = \frac{D^2 T_v}{t_{90}} \quad \text{(Eq.3.5)}$$

t_{90} = Time at 90% degree of consolidation

$D = H/2$ for double drainage

= H for single drainage

T_v = Time factor (0.848 for 90 % of consolidation).

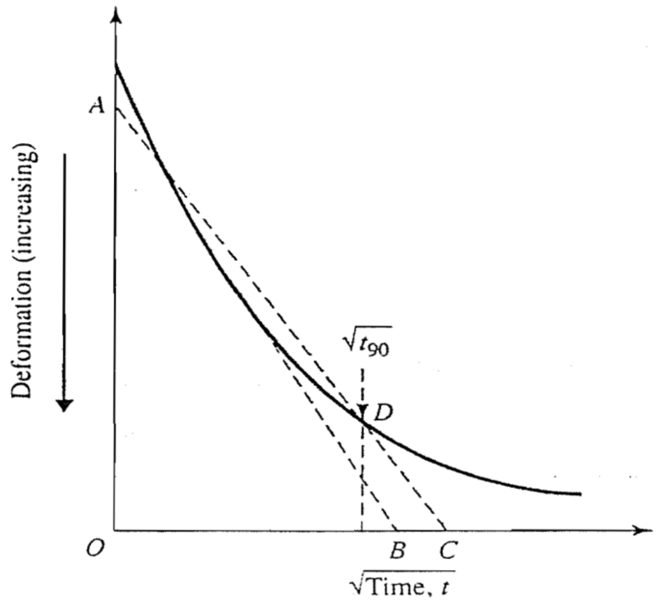


Figure 3.5 Taylors square root-of time fitting method (Taylor, 1948)

3.2.2.8 Unconfined compressive strength (UCS) test

Hydraulic conductivity, chemical-interaction characteristics and compressibility characteristics etc. get the lime light when speaking about barriers and not very many literature are available on the strength characteristics of geotechnical barriers. Shear strength of the compacted soil is a necessary parameter while designing soil structures, it forms the basis of resistance offered by soil to structural loading. Unconfined compressive strength test was carried out on sand-bentonite mixes in order to assess the shear strength characteristics of the mixtures in accordance with ASTM D 2166 (2013). Dimensions of the compacted samples was maintained as follows, height 76 mm and diameter 38 mm. Compaction density and water content to be mixed with the sample were taken from standard compaction results. In order to understand the influence of water content and sand particle size on the strength characteristics three different compaction conditions were chosen, namely 5% dry of OMC-MDD, OMC-MDD and 5% wet of OMC-MDD, in case of fine sand-bentonite mixes and medium sand-bentonite mixes. Three compacted samples were made for every compaction condition. The average strength of these 3 has been reported as the unconfined compressive strength. Once the influence of the water content on fine sand-bentonite and medium sand-bentonite mixes has been understood, second phase of the study, i.e. understanding the influence of sand gradation on the sand-bentonite mixture characteristics, has been conducted using fine sand-medium sand-bentonite samples compacted at respective OMC-MDD conditions.

3.2.2.9 Shrinkage test

Shrinkage or loss of volume due to reduction in water content is unavoidable while dealing with clay rich soils and in these case sand-bentonite mixtures. Influence of clay content, compaction density and mixing water content on the shrinkage characteristics of sand-bentonite is well reported in Daniel and Wu (1993). The study has been classified into 2 stages. Stage 1 is about assessing the influence of grain size of sand and water content on the shrinkage behaviour of sand-bentonite mixtures. To accomplish these objectives three different compaction conditions were chosen, namely 5% dry of OMC-MDD, OMC-MDD and 5% wet of OMC-MDD, in case of fine sand-bentonite mixes and medium sand-bentonite mixes. Stage 2 is to assess the influence of sand gradation on the shrinkage characteristics and to achieve this fine sand-medium sand-bentonite mixtures were made with different fine sand – medium sand proportions while varying the bentonite content in the mixture from 10 to 50 percent by dry weight. Compaction condition OMC-MDD was chosen for this phase of the study. For all the mixtures described above, compacted samples were made with the following dimensions, height 76 mm and diameter 38 mm. Three compacted samples were made for every compaction condition. These samples were left to air dry for a period of 24 hrs and are shifted to a hot air oven maintained at 60^0 C for a period of 24 hours. The temperature of the oven was raised to 105^0 C to facilitate complete drying. Upon oven drying these samples were allowed to cool in a desiccator. After the cooling period, samples were measured for their dimensions using Vernier calipers. From the obtained measurements, linear shrinkage, radial shrinkage and volumetric shrinkage were calculated and the average of three samples was reported.

Linear shrinkage (%) = $\frac{\Delta H \times 100}{H}$

Radial shrinkage (%) = $\frac{\Delta D \times 100}{D}$

Volumetric shrinkage (%) = $\frac{\Delta V \times 100}{V}$

ΔH = Change in height of sample in cm H = Initial thickness of the sample

ΔD = Change in Diameter of sample in cm D = Initial Diameter of the sample

ΔV = Change in volume of sample in cm^3 V = Initial volume of the sample

Chapter 4

RESULTS AND DISCUSSION

This chapter presents the results of various tests performed on sand-bentonite mixtures. Atterberg limits, standard Proctor compaction test, one dimensional consolidation test, unconfined compressive strength test and shrinkage test were performed on different sand-bentonite mixes with a bentonite content ranging from 10 to 50% by their dry weight.

4.1 EFFECT OF SAND CONTENT AND PARTICLE SIZE ON THE BEHAVIOR OF SAND-BENTONITE MIXTURES

This section deals with the assessment of influence of sand particle size and content on the engineering behavior of sand-bentonite mixtures.

4.1.1 ATTERBERG LIMITS

Atterberg limits are the oldest and most commonly used tests in the field of soil engineering (Sridharan and Rao, 1975). Liquid limit test is essentially a measure of viscous resistance or shear strength of a soil, which becomes soft as it approaches the liquid state (Sowers et al., 1959). Liquid limit of a sand-clay mixture primarily depends upon its clay content and the type of clay mineral present in the sand-clay mixture. Sivapullaiah and Sridharan (1985) observed that plasticity depends not only on the type and amount of the clay mineral but also on the interaction between clay and soil particles, and this needs to be considered keeping in view that the sand doesn’t contribute to water holding capacity. Liquid limit of a soil mixture is influenced by the size of soil particles and no influence of particle shape has been found. In the present study, liquid limit and plastic limit were determined in accordance with ASTM D 4318 (2000). Fine sand-bentonite and medium sand-bentonite mixtures for both bentonite-1 and bentonite-2 were prepared with bentonite content ranging from 10 to 50% in the mixture by dry weight. As the mixes were having high sand content, cone penetration test was carried out to determine the liquid limit of sand-bentonite mixes (Sivapullaiah and Sridharan, 1985).

Atterberg limits of fine sand-bentonite mixtures and medium sand-bentonite mixtures are shown in the Table 4.1. For the sake of simplicity, the medium sand, fine sand, bentonite-1 and bentonite-2 have been referred to as MS, FS, B1 and B2, respectively in the further discussion. Data in the table shows that irrespective of the sand type, the liquid limit increases with increase in the bentonite content in the mixture. As the liquid limit depends upon the net attractive forces between the bentonite particles, an increase in the bentonite content increases the liquid limit of mixture. Similarly, as the liquid limit of a soil is its water holding capacity, the surface area plays a significant role in defining the liquid limit. As the surface area of bentonite is much higher in comparison to sand, increase in the bentonite content in the mixture also increases the specific surface area of the mixture and consequently increases the liquid limit. However, it was observed that the variation in liquid limit was not linear even though the clay content in the mixes varied linearly. In addition to this, the data in Table 4.1 also shows that the mixes containing FS exhibits higher liquid limits as compared to those mix with MS, irrespective of the quality and percentage of bentonite used. However, the difference in the liquid limit was much prominent for the mixes containing B2 in comparison to mixes containing B1.

Table 4.1 Summary of Atterberg limits of fine sand-bentonite and medium sand-bentonite mixtures

	Mix. Proportions (Sand:Bentonite)	**Bentonite-1 (B1)**				**Bentonite-2 (B2)**			
		LL (%)	**PL (%)**	**PI (%)**	**SL (%)**	**LL (%)**	**PL (%)**	**PI (%)**	**SL (%)**
Medium sand (MS)	0:100	346.1	33.0	313.1	23	609.2	41.5	567.7	10.4
	50:50	69.0	25.1	43.9	24.5	145.2	18.4	126.8	25.3
	60:40	54.8	20.6	34.2	29.3	125	17.0	108	29.6
	70:30	49.4	19.3	30.1	31.3	97.5	20.3	77.2	37.0
	80:20	33.4	*	*	28.3	73.8	18.8	55	38.1
	90:10	32.4	*	*	30.4	47.3	*	*	34.3
Fine sand (FS)	0:100	346.1	33.0	313.1	23	609.2	41.5	567.7	10.4
	50:50	79.7	19.5	60.2	22.1	171.0	21.7	149.3	23.5
	60:40	61.4	17.0	44.4	29.4	139.2	23.9	115.3	32.3
	70:30	48.1	18.8	29.3	33	102.3	25.1	77.2	37.3
	80:20	41.7	*	*	37.2	74.3	33.3	41.0	40.4
	90:10	32.8	*	*	35.6	48.1	33	15.1	39.7

* Test could not be performed

Similarly, the data in Table 4.1 also shows that plasticity index of sand-bentonite mixtures increased with an increase in the bentonite content. However, the plastic limit was affected marginally due to increase in the bentonite content in the mixture. The data for the shrinkage limit shows that a higher value of shrinkage limit was observed for the fine sand mixes in comparison to those with medium sand of same bentonite content. At the shrinkage limit, the capillary water present in the pore space starts to evaporate (Sridharan and Prakash, 2000). Further, since the individual pore spaces between the soil grains is large for medium sand in comparison to the fine sand, water starts to evaporate at higher water content for medium sand mixes resulting in a lower value of shrinkage limit. The data also shows that with increase in the bentonite content in the mixture the shrinkage limit decreases. As the bentonite content in the mixture increases, it starts filling the void space between the individual sand grains as a result the size of individual pore size gets decreased resulting in a lower value of shrinkage limit.

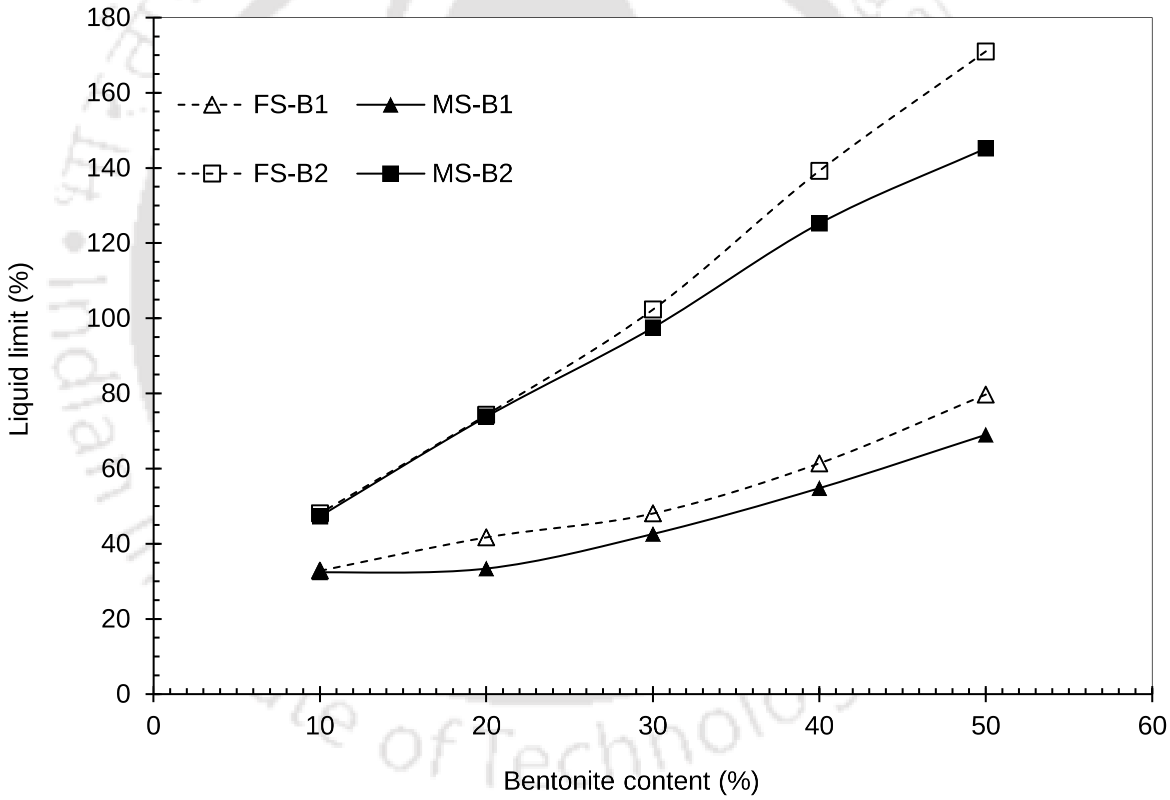


Figure 4.1 Variation of liquid limit with bentonite content

Data also shows that the type of bentonite present in the mixtures also influences the shrinkage limit of the soil. When the pore spaces are filled with bentonite of higher quality, marked by a higher liquid limit, swelling capacity and specific surface area, the shrinkage limit increases. When a bentonite with a high specific surface area is present in the mixtures, it will absorb more water and thereby prevent evaporation leading to a higher value of shrinkage limit. Shrinkage limit of a soil is a physical phenomenon mostly dependent on the relative packing of particle as opposed to other Atterberg limits. Shrinkage limit results of FS-B2 and MS-B2 mixes were seen to exhibit an increasing trend in shrinkage limit with increasing sand content in the mixture and especially mixes with fine sand exhibited relatively higher shrinkage limits.

Upon comparing the plasticity characteristics exhibited by bentonite and sand-bentonite mixtures, it can be seen that mixing sand with bentonite resulted in reduced plasticity as is evident from the reduction in liquid limit and plasticity index values. Sand-bentonite mixtures exhibited a higher shrinkage limit values compared to pure bentonite, indicating a reduced susceptibility to volume changes with changes in water content.

4.1.2 COMPACTION CHARACTERISTICS

All the sand-bentonite mixes were compacted with standard compactive effort in accordance with ASTM D 698 (2012). Results of the compaction tests are shown in the Table 4.2. Bentonite quality does seem to affect the compaction behaviour of sand-bentonite mixtures, from the results the following observations were made;

1) For the same bentonite-sand content, mixtures with FS and MS exhibited different optimum moisture content (OMC) and maximum dry density (MDD) indicating a possible influence of sand particle size on the compaction characteristics of sand-bentonite mixtures,
2) OMC was found to be increasing with bentonite content for all the mixtures irrespective of bentonite quality,
3) Mixtures containing 20% bentonite exhibited the highest MDD,
4) With increasing bentonite content, MDD was increasing for the mixtures with 10-20% bentonite contents in case of B1 and 10-30% in case of B2,
5) For a given bentonite content, FS mixtures exhibited relatively higher OMC and lower MDD as compared to MS mixtures,
6) Mixtures containing B2 exhibited a relatively higher OMC and lower MDD signifying the effect of bentonite quality on compaction characteristics, even though the effect was small.

Comparison the OMC and MDD data for all the sand-bentonite mixtures has shown that with increase in the bentonite content the OMC increased, whereas, the MDD decreased. A bi-model compaction plot was observed for sand-bentonite mixtures. In the first stage, the dry density decreased with increase in the moisture content and then it increased with a further increase in the moisture content to achieve the OMC and MDD value. This unusual dry density-moisture content relationship can be due to the formation of the diffuse double layer of montmorillonite (Dixon et al., 1985). As the water content increases during compaction the diffuse double layer starts to develop resulting in an increase in the repulsive forces. Due to increase in the repulsive force the volume of soil mixture increases resulting in a decrease in the dry density. Once the diffuse double layer develops fully, a further addition of water does not increase the repulsive force, which results in an increase in the dry density of soil-bentonite mixture.

Compaction characteristics exhibited by B1 and B2 are presented alongside FS-B1, MS-B1, FS-B2 and MS-B2 mixtures in Table 4.2. Comparing bentonite and sand-bentonite mixtures, a clear difference in terms of OMC and MDD can be noted. Irrespective of the sand type being mixed with bentonite, a higher MDD was observed with sand-bentonite mixtures compared to 100% bentonite.

Table 4.2 Summary of compaction test results of fine sand-bentonite and medium sand-bentonite mixtures

	Mix. Proportions (S:B)	**Bentonite-1 (B1)**		**Bentonite-2 (B2)**	
		OMC (%)	**MDD (g/cc)**	**OMC (%)**	**MDD (g/cc)**
Medium sand (MS)	0:100	33.0	1.230	32.0	1.280
	50:50	22.5	1.565	22.9	1.598
	60:40	19.0	1.628	21.6	1.624
	70:30	16.0	1.662	17.5	1.657
	80:20	15.1	1.710	16.5	1.651
	90:10	14.5	1.671	16.9	1.611
Fine sand (FS)	0:100	33.0	1.230	32.0	1.280
	50:50	22.5	1.585	20.9	1.555
	60:40	20.5	1.595	20.2	1.582
	70:30	18.0	1.655	18.8	1.607
	80:20	18.4	1.701	18.5	1.612
	90:10	17.2	1.640	18.4	1.579

4.1.3 CONSOLIDATION CHARACTERISTICS

4.1.3.1 Time-Swelling characteristics of sand-bentonite mixes

One dimensional consolidation tests were conducted on the medium sand -bentonite and fine sand -bentonite mixtures mixed in various proportion. Two different types of bentonite (namely bentonite-1 or B1 and bentonite-2 or B2) were used in the study. The bentonite content was varied from 10 to 100% by dry weight in the mixtures. The test samples were prepared at three different compaction conditions, namely OMC-MDD, 5% dry of OMC-MDD and 5% wet of OMC-MDD. Under a constant load, upon access to water, bentonite present in the compacted sample adsorbs water into its outer layers and a change in volume of sample can be observed. The rate of change and the total change in volume relative to initial volume of sample is known to be dependent upon factors like compaction condition, bentonite content, nature of pore fluid used in the testing etc. Current study attempts to understand the influence of sand particle size on the time-swelling relationship of compacted sand-bentonite mixtures. Compacted samples placed in the oedometer setup were allowed to swell by inundating the soil sample with deionized (DI) water. Samples were allowed to swell under a seating pressure of 4.9 kPa, till the difference between two consecutive readings taken 24 hours apart was almost negligible.

4.1.3.1.1 Effect of bentonite content and initial compaction conditions on time-swelling relationship for FS-B1 and MS-B1 mixes

Sand-bentonite-1 mixtures took about 96 hours for swelling to be completed. Time-swelling relationship for FS-B1 and MS-B1 mixtures is shown in Figs. 4.2 through Figs. 4.7. Swelling at any point of time is calculated as the ratio of change in volume observed and initial volume of the sample and is expressed in percentage. In spite of different compaction conditions, bentonite contents and sand types used, path traced by log time-swelling plots were seen to be following a ‘S’ curve (Sridharan and Gurtug, 2004). The three different phases in swelling, i.e. initial swelling, primary swelling and secondary swelling, could be identified by their different swelling rates. Transition from one phase to another doesn’t appear to be as smooth as can be seen in the literature which probably can be attributed to the inevitable uneven pore distribution in the compacted samples. Initial swelling is due to the swelling of bentonite within the voids created by sand particles and does not reflect in swelling volume. The primary swelling starts at the end of initial swelling and contributes the most to the swelling volume. During secondary swelling, log time-swelling plot becomes asymptotic to X-axis. Secondary swelling would help in understanding the long-term swelling of compacted expansive soils.

Comparing the Figs. 4.2 through Figs. 4.4 indicate that the swelling potential of compacted FS-B1 mixes primarily depends on the bentonite content of the mixture and mixing water content (Mishra et al., 2008). As increase in the bentonite content is resulting in increase of expansive mineral (montmorillonite) content in the mixture, an increasing the bentonite content resulted in a higher swelling potential. The affinity of bentonite towards the water decreases with increasing the initial water content and consequently its ability to swell reduces. This can be observed in this study as the swelling potential for FS-B1 mixtures compacted at 5% dry of OMC-MDD being the highest followed by those compacted at OMC-MDD and lastly trailing by those compacted at 5% wet of OMC-MDD.

Swelling behavior of MS-B1 mixtures can be seen in Figs. 4.5 through Figs. 4.7. In terms of factors affecting swelling potential, a trend similar to FS-B1 mixtures can be observed. Comparing FS-B1 and MS-B1 mixtures, a clear difference can be observed in the swelling potential values with MS-B1 mixtures resulting in a lower swelling potential (almost 3-4 times less) in comparison to FS-B1. This low swelling potential value of MS-B1 mixtures can be attributed to the presence of relatively larger voids in the MS-B1 mixtures demanding a relatively higher bentonite quantity necessary to fill these voids before any increase in volume can be observed. FS-B1, MS-B1 mixes were found to be following a “S” trend for mixtures with bentonite content greater than 30%. Samples compacted on the dry of OMC were seen to be exhibiting a higher time to complete initial and primary swelling, followed by those compacted at OMC-MDD and 5% wet of OMC-MDD respectively. Time required for initial swelling and primary swelling to complete was seen to be decreasing with decreasing bentonite content for both FS-B1 and MS-B1 mixes. FS-B1 mixtures with 50% bentonite content compacted at 5% dry of OMC-MDD, OMC-MDD and 5% wet of OMC-MDD required about 11, 10 and 9 minutes for initial swelling to complete; whereas, it took 4270, 2880 and 1440 minutes to complete the primary swelling, respectively. MS-B1 mixes exhibited relatively lower initial and primary swelling times. MS-B1 mixtures with 50% bentonite content compacted at 5% dry of OMC-MDD, OMC-MDD required about 10.1 and 10 minutes for initial swelling to complete and 2880 and 2050 minutes for primary swelling to complete, respectively.

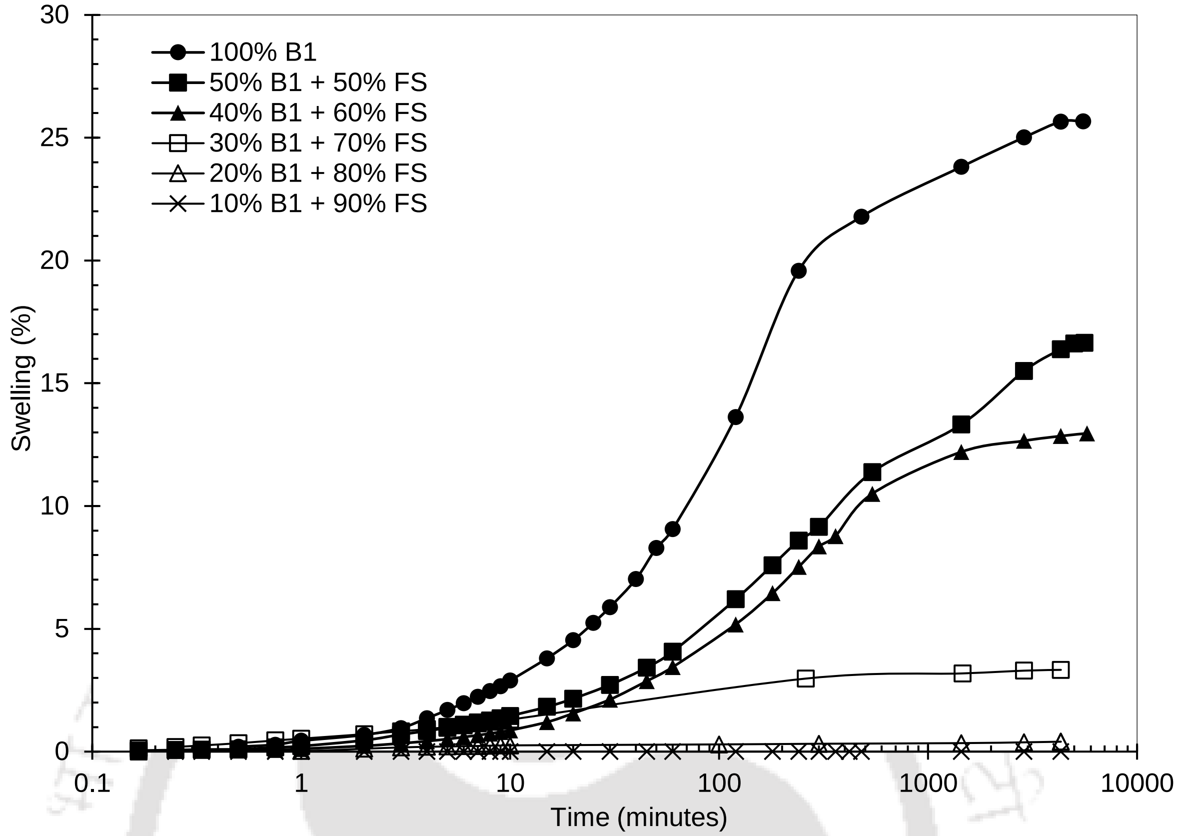


Figure 4.2 Time-Swelling plot for FS-B1 mixes compacted at 5% dry of OMC-MDD

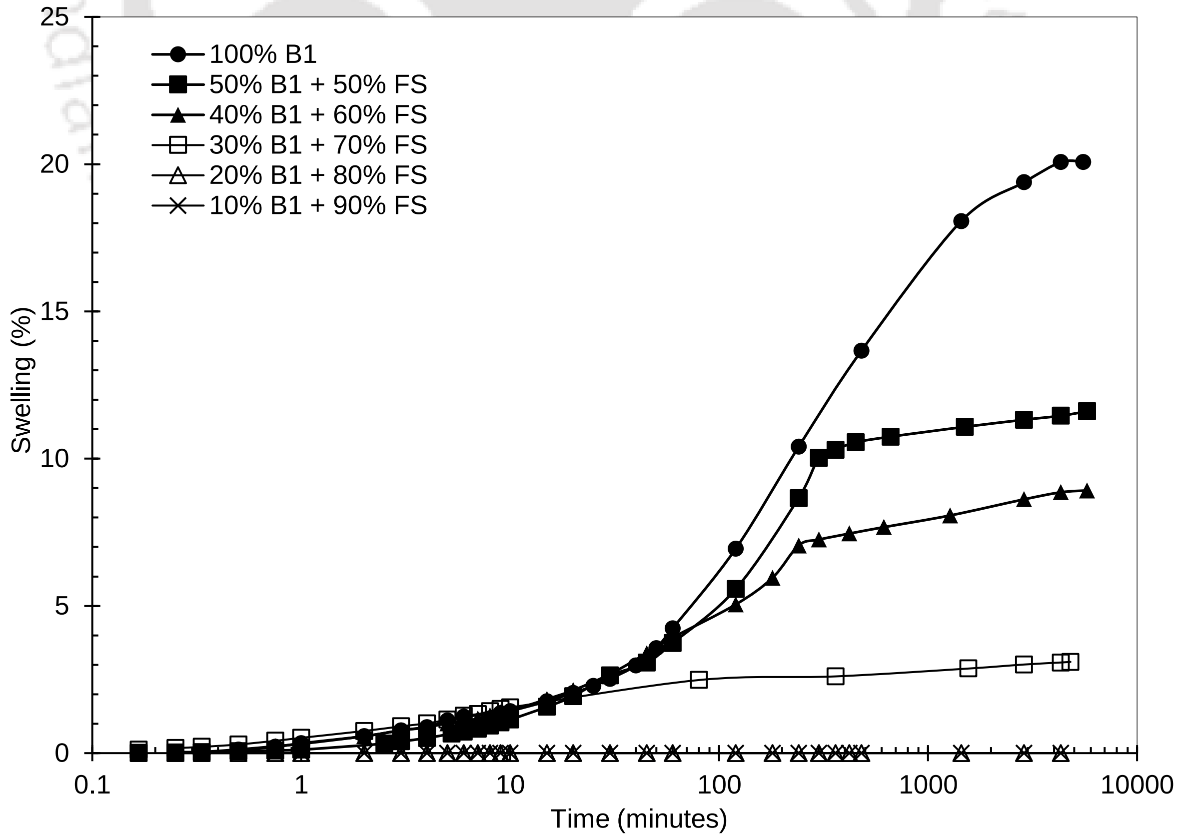


Figure 4.3 Time-Swelling plot for FS-B1 mixes compacted at OMC-MDD

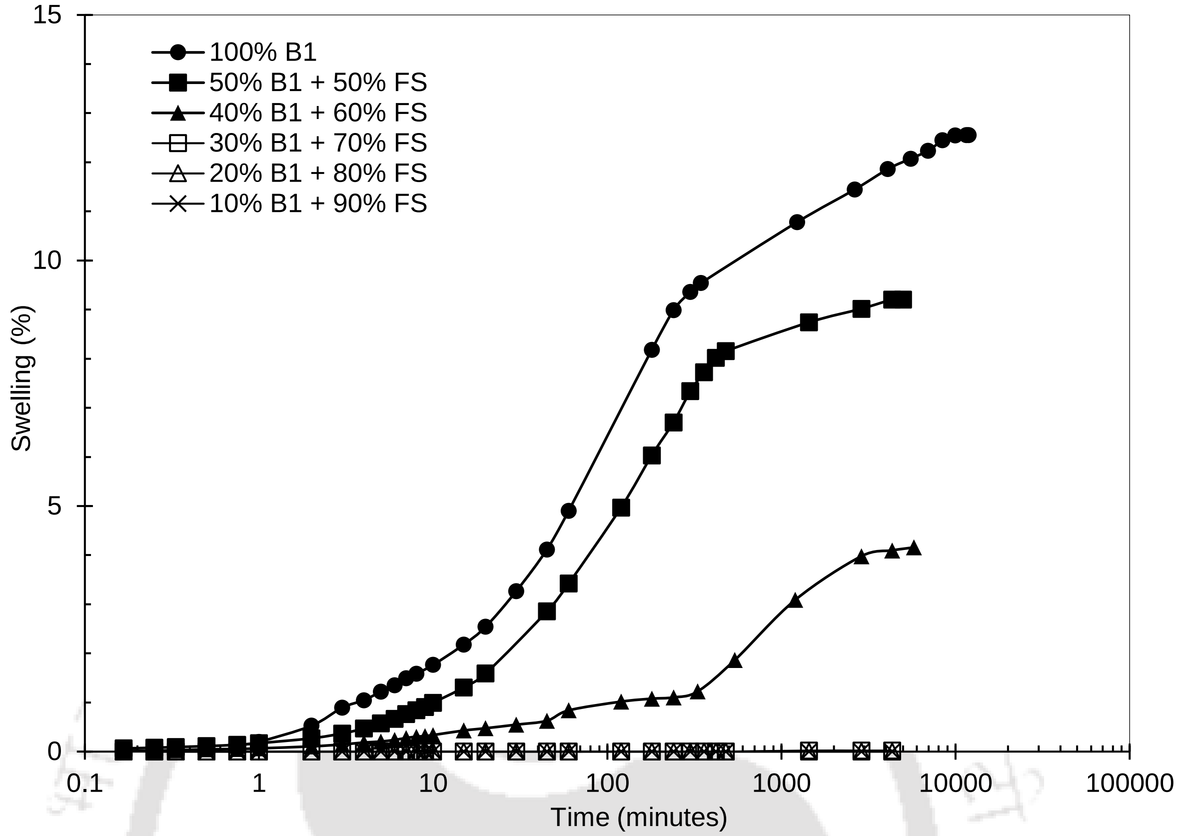


Figure 4.4 Time-Swelling plot for FS-B1 mixes compacted at 5% wet of OMC-MDD

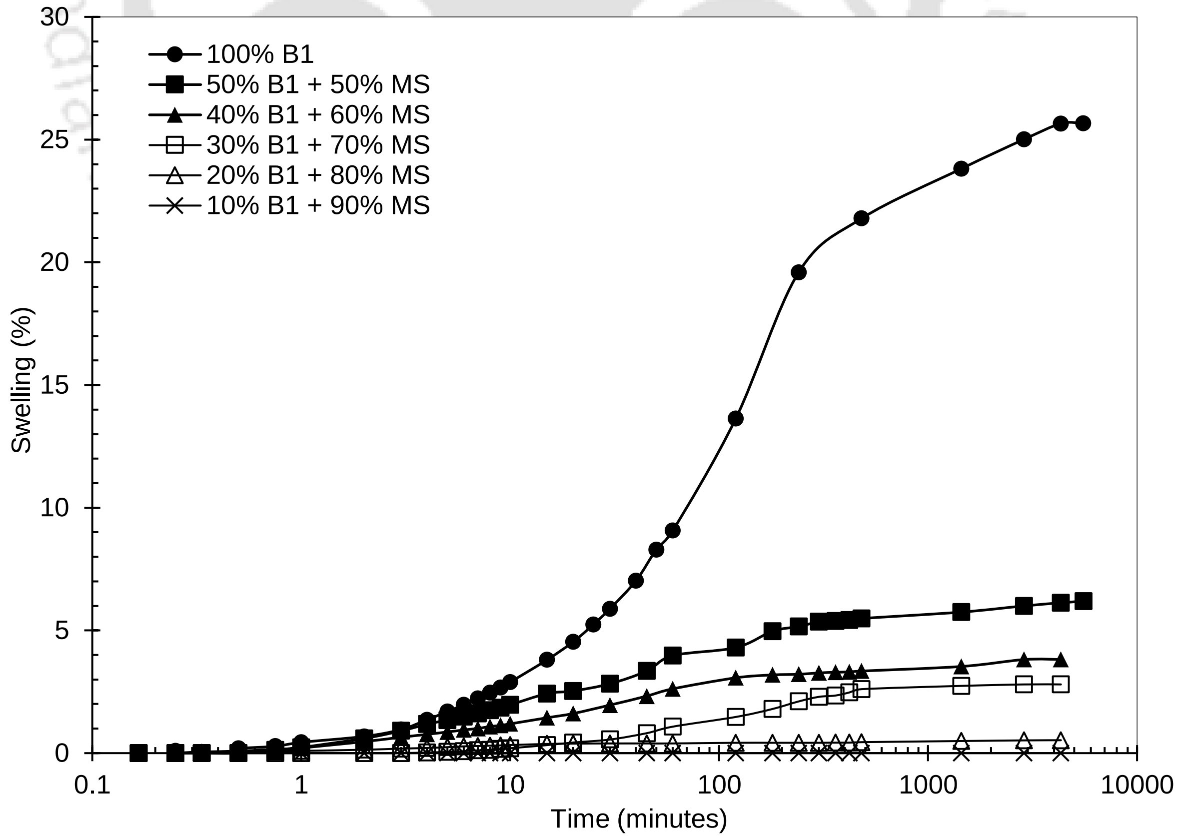


Figure 4.5 Time-Swelling plot for MS-B1 mixes compacted at 5% dry of OMC-MDD

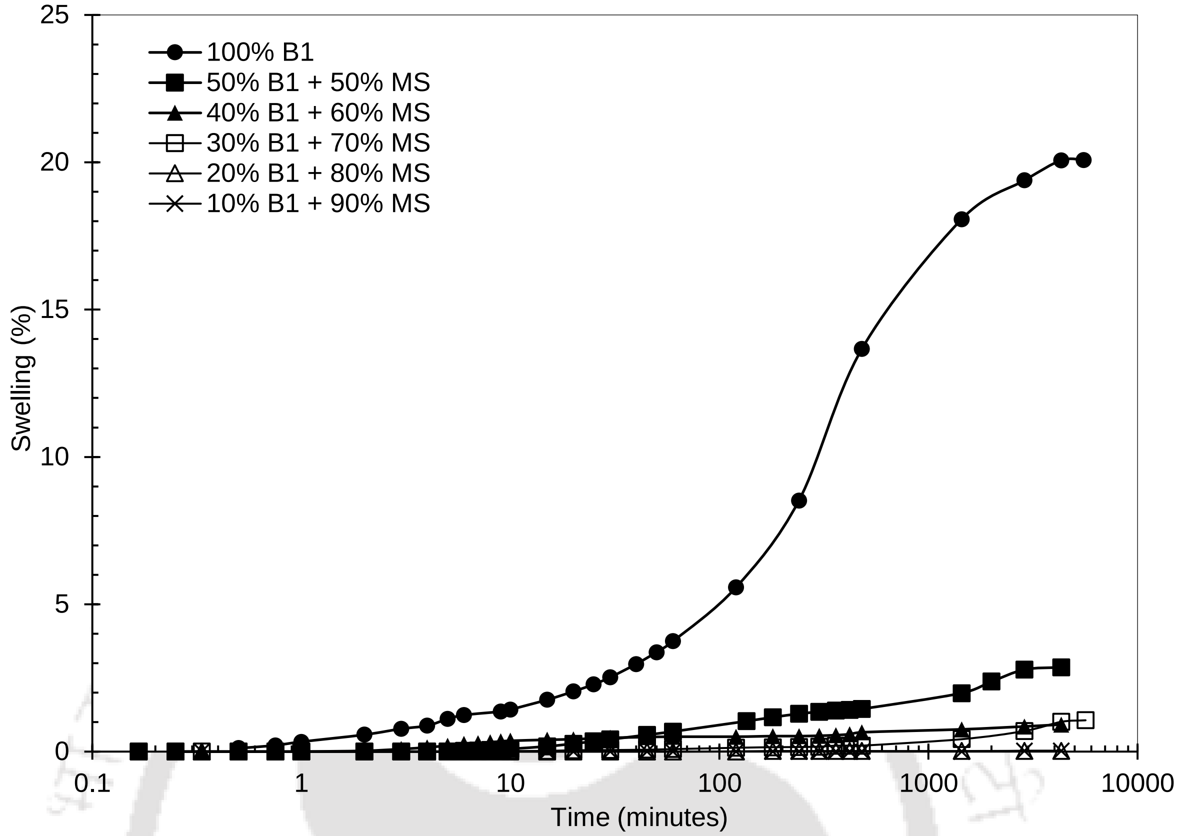


Figure 4.6 Time-Swelling plot for MS-B1 mixes compacted at OMC-MDD

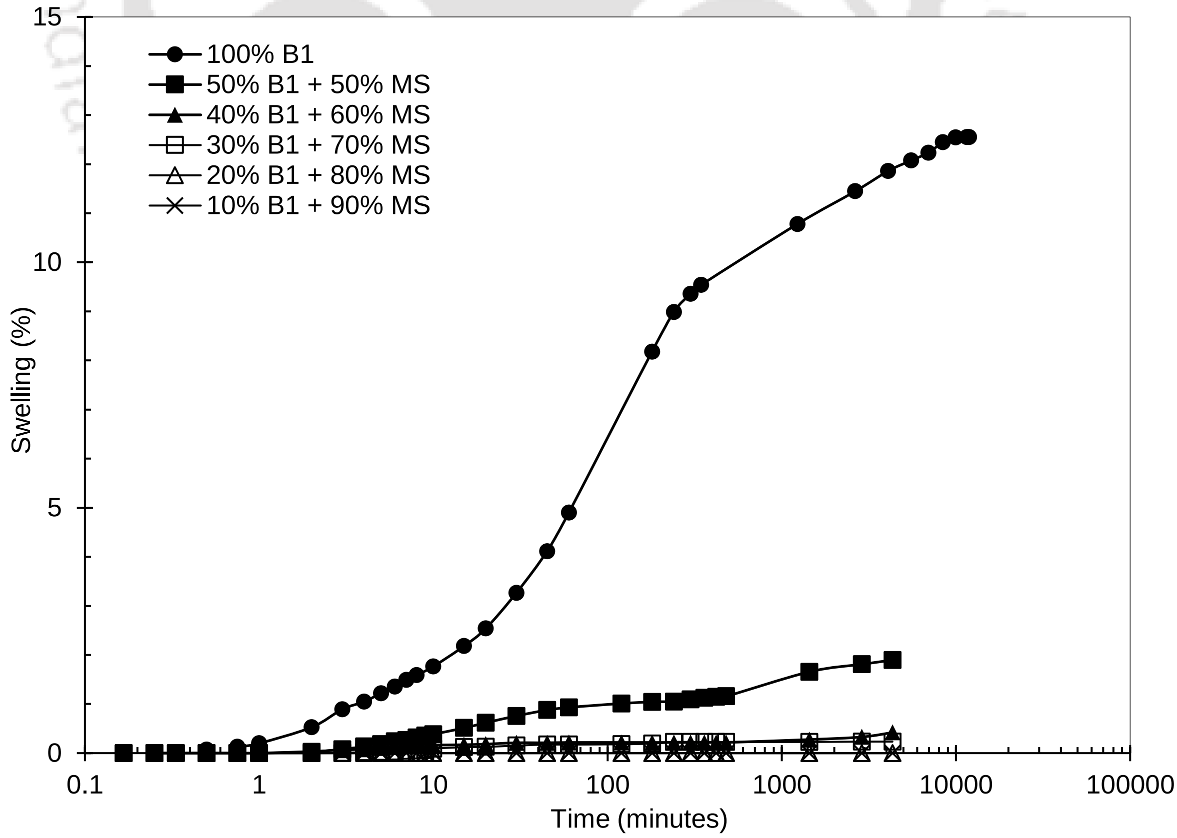


Figure 4.7 Time-Swelling plot for MS-B1 mixes compacted at 5% wet of OMC-MDD

Alongside presenting the influence of initial compaction condition and type of sand on the swelling characteristics of sand-bentonite-1 mixtures, Figs. 4.2 through Figs. 4.7 also present the influence of bentonite content in the mixtures. Mixtures with 100% bentonite content exhibited highest swelling potential compared to other sand-bentonite proportions and swelling potential was found to be reducing with decreasing bentonite content for all compaction conditions.

4.1.3.1.2 Effect of bentonite content and initial compaction conditions on time-swelling relationship of FS-B2 and MS-B2 mixes

Time-Swelling relationship for FS-B2 and MS-B2 mixtures is shown in Figs. 4.8 through Figs. 4.13. Sand-bentonite-2 mixtures took about 192 hours for swelling to complete. FS-B2 and MS-B2 mixtures exhibited swelling trends similar to FS-B1 and MS-B1 mixtures. Swelling potential exhibited by FS-B2 and MS-B2 mixtures was higher compared to FS-B1, MS-B1 mixtures. Sridharan and Gurtug (2004) observed that initial, primary and secondary swelling are proportional to plasticity of the soil. Since the plasticity of FS-B2 and MS-B2 mixes is higher than FS-B1 and MS-B1 mixes, higher swelling potential observed in case of FS-B2 and MS-B2 mixes can be justified. Bentonite content has an important role in the swelling characteristics exhibited by various FS-B2 and MS-B2 mixtures. Mixtures with 100% bentonite content exhibited highest swelling potential compared to other sand-bentonite proportions, as has been the case with FS-B1 and MS-B1 mixtures.

Similar to the behavior observed for mixtures with B1, the FS-B2, MS-B2 mixes were found to be following a "S" trend for mixtures with bentonite content greater than 30%. Samples compacted on the dry of OMC were seen to be exhibiting a higher initial and primary swelling time, followed by those compacted at OMC-MDD and 5% wet of OMC-MDD respectively. Time required for initial swelling and primary swelling to complete was seen to be decreasing with decreasing bentonite content, as has been the case with both FS-B1 and MS-B1 mixes. FS-B2 mixtures with 50% bentonite content compacted at 5% dry of OMC-MDD, OMC-MDD and 5% wet of OMC-MDD required about 10, 10 and 8 minutes for initial swelling to complete and 7240, 5880 and 5760 minutes for primary swelling to complete, respectively. MS-B2 mixes exhibited relatively lower initial and primary swelling times similar to MS-B1 mixes.

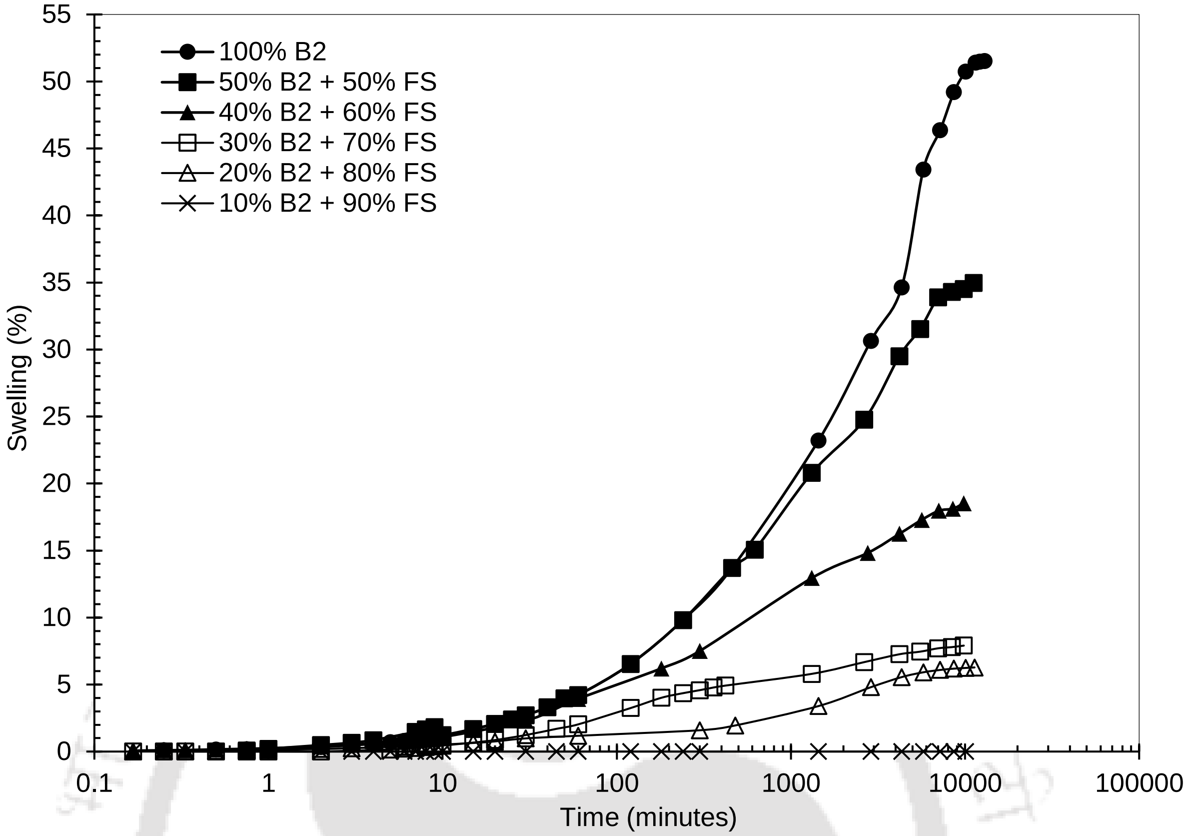


Figure 4.8 Time-Swelling plot for FS-B2 mixes compacted at 5% dry of OMC-MDD

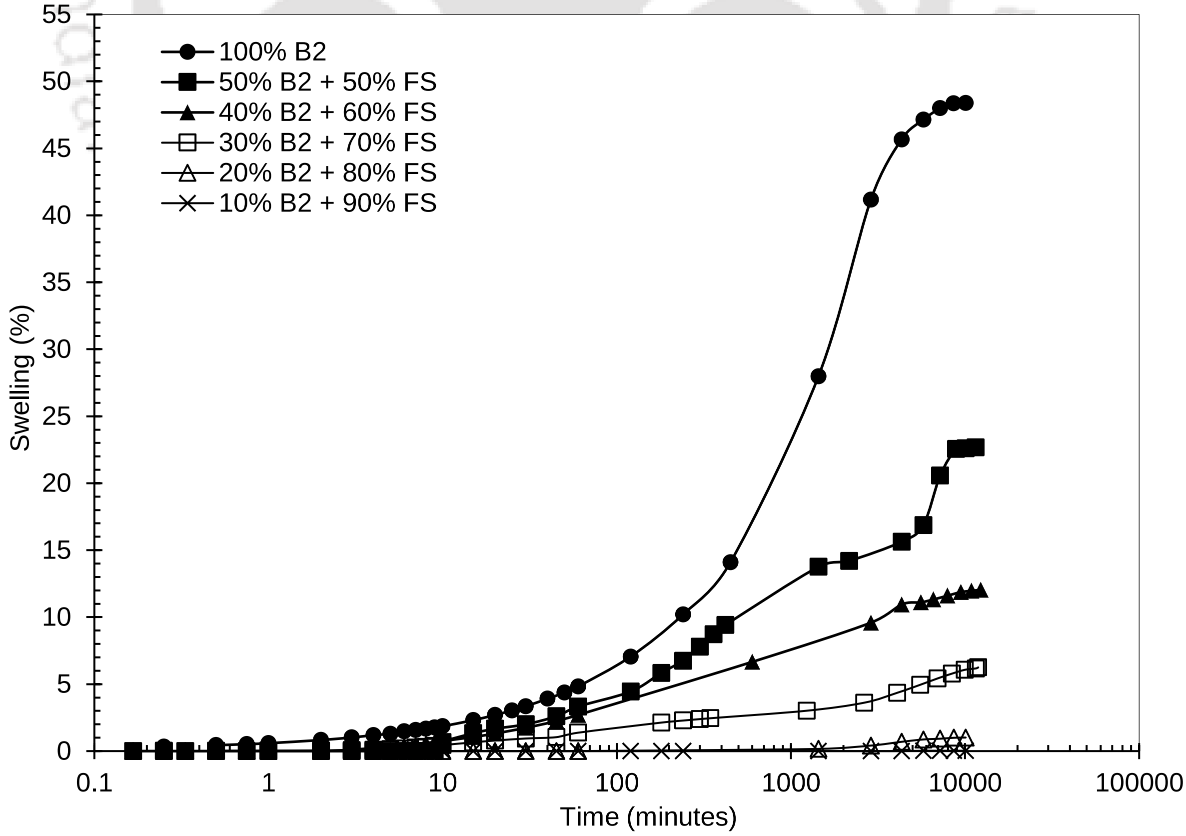


Figure 4.9 Time-Swelling plot for FS-B2 mixes compacted at OMC-MDD

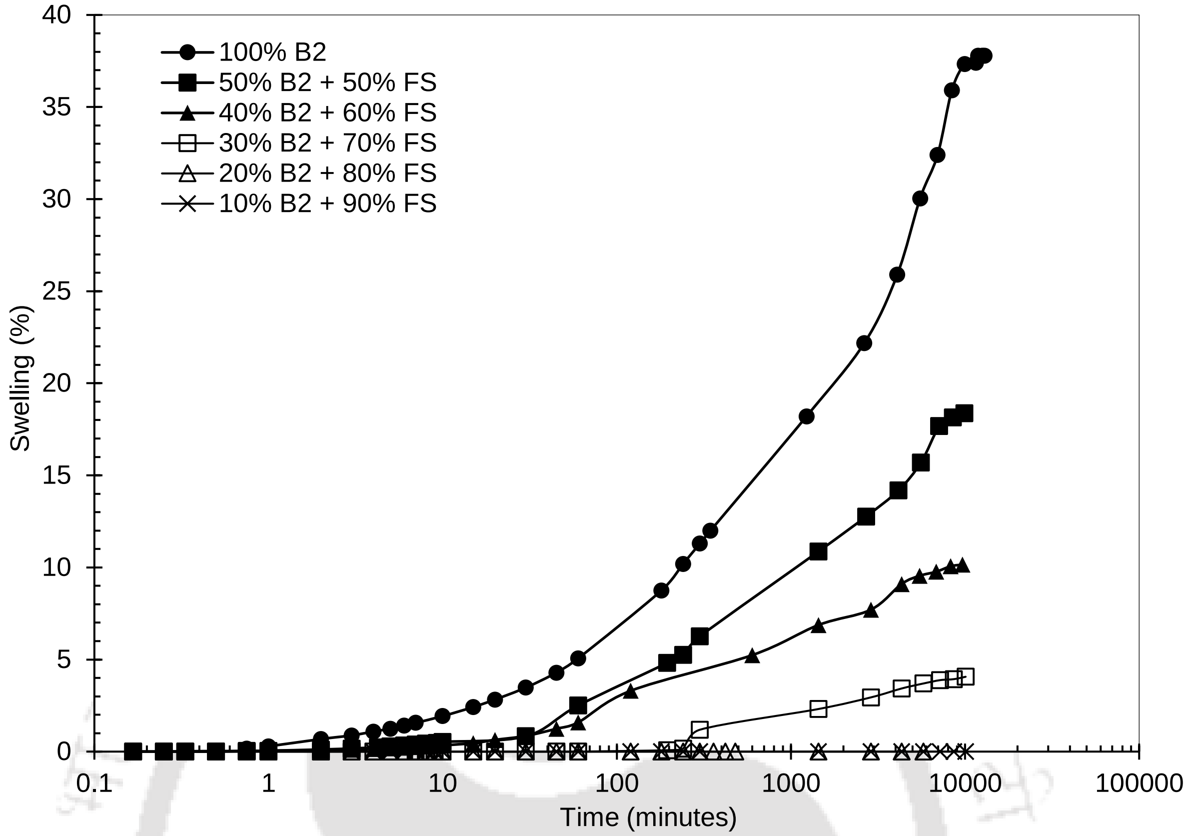


Figure 4.10 Time-Swelling plot for FS-B2 mixes compacted at 5% wet of OMC-MDD

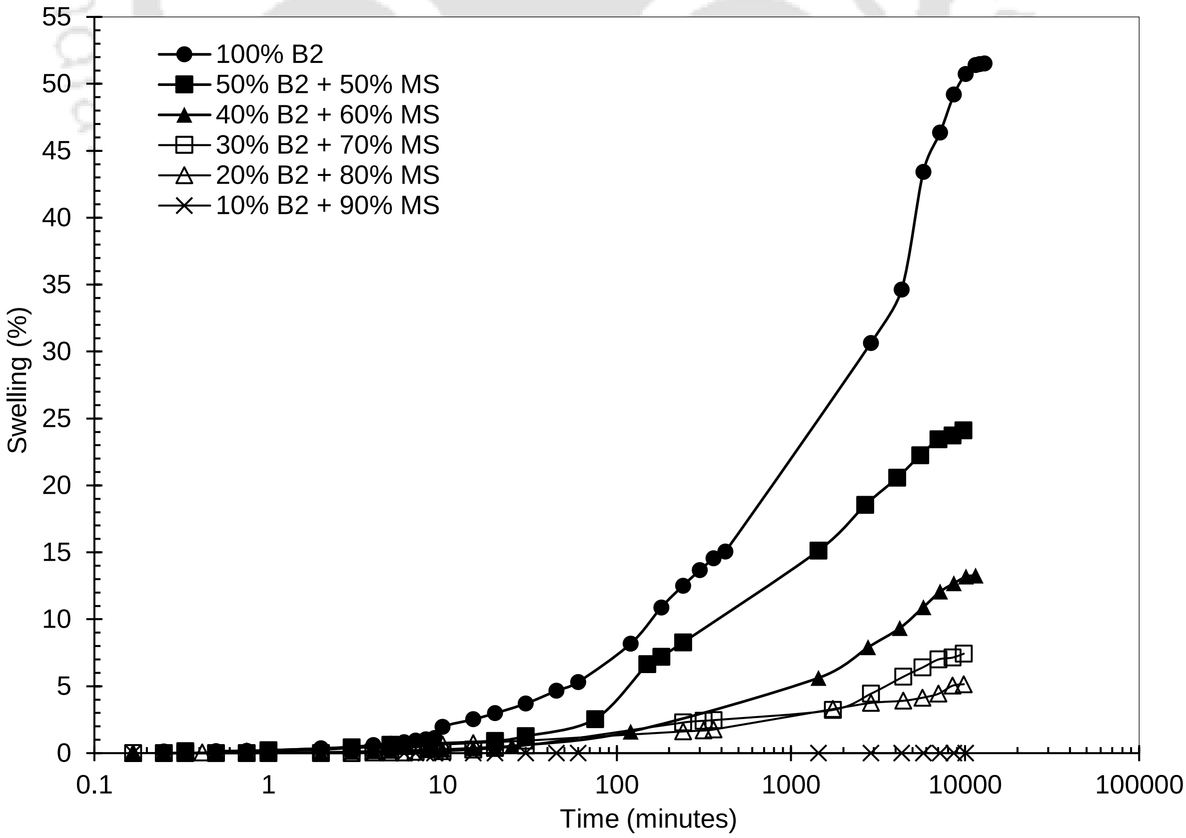


Figure 4.11 Time-Swelling plot for MS-B2 mixes compacted at 5% dry of OMC-MDD

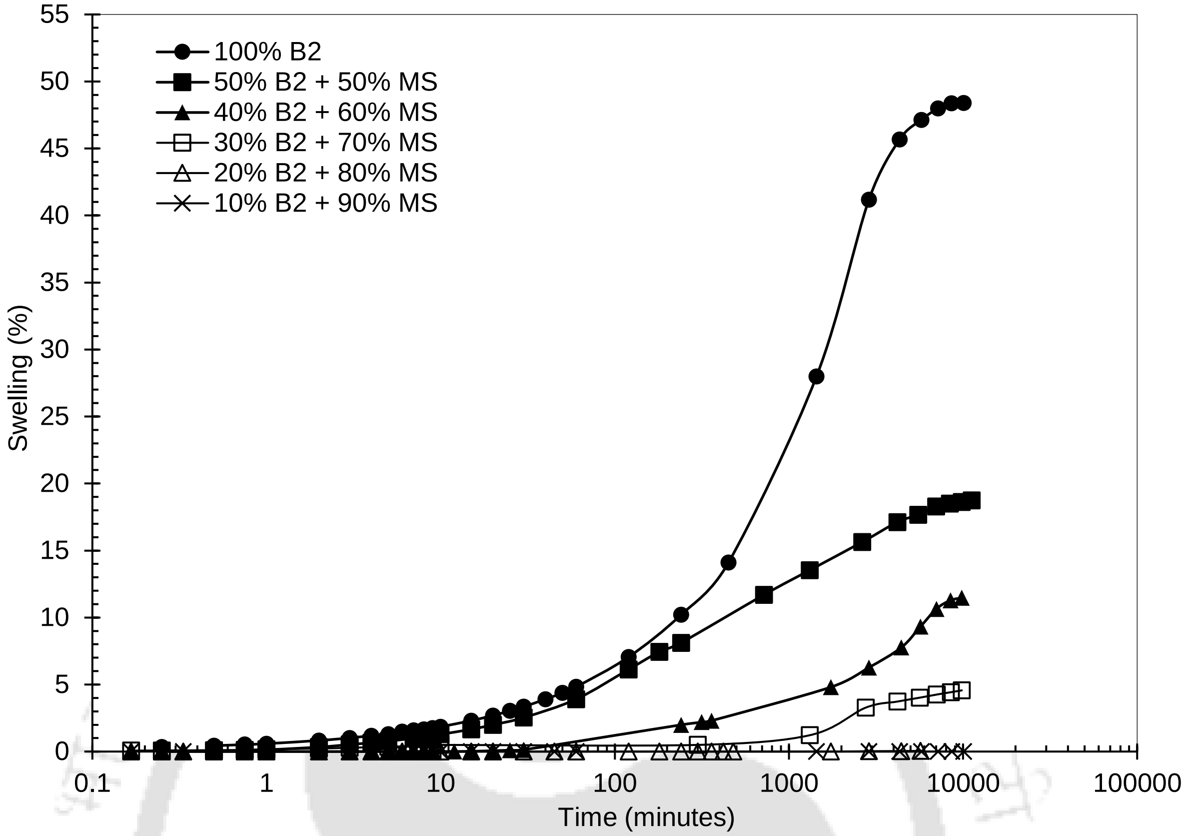


Figure 4.12 Time-Swelling plot for MS-B2 mixes compacted at OMC-MDD

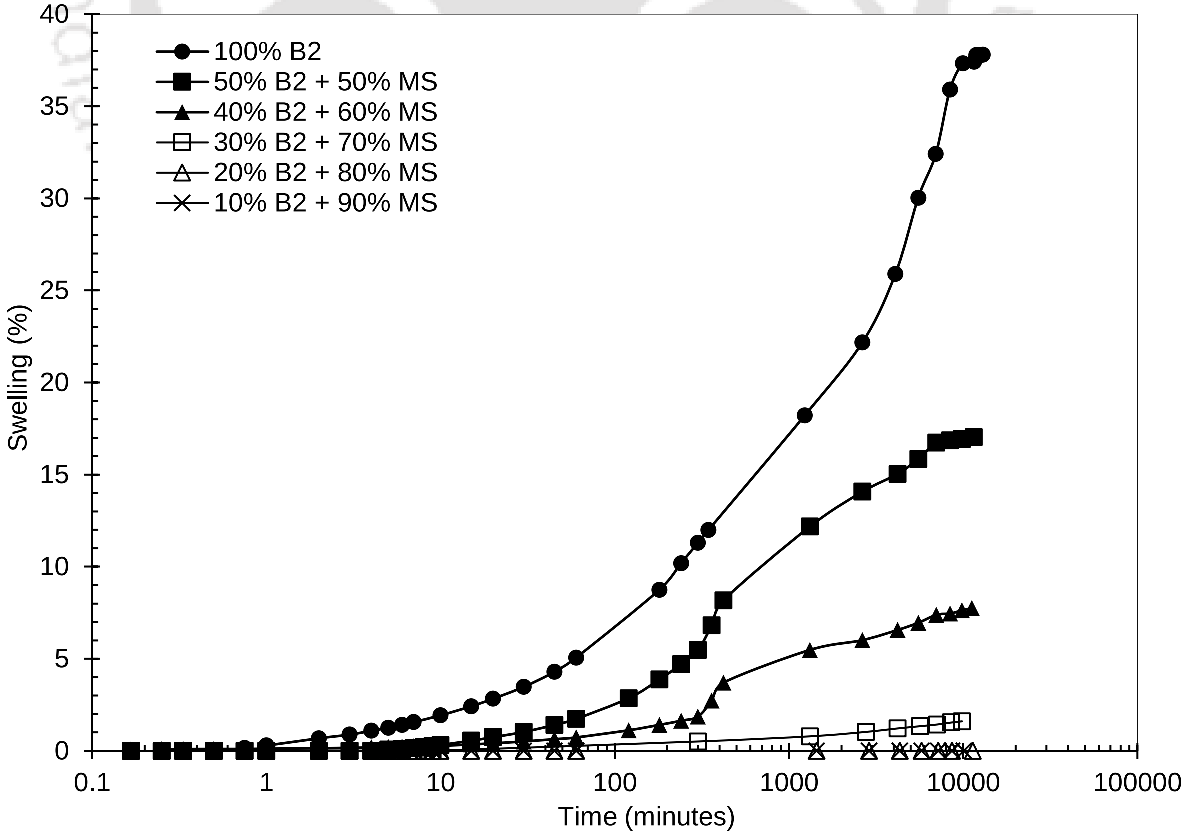


Figure 4.13 Time-Swelling plot for MS-B2 mixes compacted at 5% wet of OMC-MDD

MS-B2 mixtures with 50% bentonite content compacted at 5% dry of OMC-MDD, OMC-MDD and 5% wet of OMC-MDD required about 12, 10 and 9 minutes for initial swelling to complete and 7020, 5520 and 4250 minutes for primary swelling to complete, respectively.

4.1.3.2 Swelling potential of sand-bentonite mixes

Compacted samples placed in the oedometer setup and allowed to swell by inundating the soil sample with DI water under a nominal pressure of 4.9 kPa, till the difference between two consecutive readings on the dial gauge taken 24 hours apart differ nominally.

4.1.3.2.1 Swelling potential of FS-B1 and MS-B1 mixtures

Sand-bentonite-1 mixtures took about 96 hours for swelling to complete. Swelling data for sand-bentonite-1 mixtures is as shown in Table 4.3. Samples compacted on the dry side of OMC exhibited higher swelling volume followed by those compacted at OMC and lastly trailing by those compacted on wet side of OMC for all mix proportions. For any given proportion of bentonite in the mixtures, FS-B1 mixtures exhibited a relatively higher swelling potential in comparison to MS-B1 mixtures. Data also suggested that mixes with bentonite proportion less than 20% were relatively incapable of swelling implying that bentonite content available was not sufficient for filling all the voids created by the sand skeleton.

Table 4.3 Summary of swelling potential results of FS-B1 and MS-B1 mixtures

	Mix. Proportions (S:B)	**Swelling potential (%)**		
		Compaction condition		
		MDD-OMC (%)	**MDD-5% dry of OMC (%)**	**MDD-5% wet of OMC (%)**
Medium sand	**0:100**	20.07	25.67	12.55
	50:50	2.86	6.19	1.90
	60:40	1.06	3.81	0.42
	70:30	1.01	2.80	0.02
	80:20	0.05	0.40	0.02
	90:10	0.02	0.03	0.01
Fine sand	**0:100**	20.07	25.67	12.55
	50:50	11.61	16.64	9.20
	60:40	8.92	12.96	4.16
	70:30	3.10	3.33	0.04
	80:20	0.07	0.53	0.02
	90:10	0.03	0.05	0.01

Comparing mixtures with 100% B1 content with other bentonite proportions indicated a notable reduction in the swelling ability with the introduction of sand in the mixtures. Mixes with 100% bentonite outrun the nearest competition (mixes with 50% bentonite) by at least 2-8 times in terms of swelling potential and the gap was seen to be widening with decreasing the bentonite content in the mixtures.

4.1.3.2.2 Swelling potential of FS-B2 and MS-B2 mixtures

When a compacted soil sample is allowed to hydrate, the outermost layers adsorb water rapidly, swell and act as a barrier preventing the inner layers from getting saturated easily. The inner layers are saturated by diffusion of water from outermost layers to the inner layers. As the swelling nature of soil improves, the time needed for swelling process to complete also increases. Bentonite-2 being a high swelling bentonite, FS-B2 and MS-B2 mixtures took about 192 hours for the swelling to complete. Swelling data for sand-bentonite-2 mixtures is as shown in Table 4.4. It was observed that samples compacted on the dry side of OMC exhibited a higher swelling volume followed by those compacted at OMC for all mix proportions. Comparing mixtures with 100% B2 content with other bentonite proportions indicated a notable reduction in the swelling potential. Mixes with 100% bentonite outrun the nearest competition (mixes with 50% bentonite) by 2-3 times in terms of swelling potential, the trend observed is similar to those of FS-B1 and MS-B1 mixtures.

Table 4.4 Summary of swelling potential results of FS-B2 and MS-B2 mixtures

	Mix. Proportions (S:B)	**Swelling potential (%)**		
		Compaction condition		
		MDD-OMC (%)	**MDD-5% dry of OMC (%)**	**MDD-5% wet of OMC (%)**
Medium sand	**0:100**	48.37	51.52	37.78
	50:50	18.74	24.10	17.03
	60:40	11.47	13.26	7.75
	70:30	4.56	7.43	1.60
	80:20	0.09	5.15	0.07
	90:10	0.01	0.04	0.01
Fine sand	**0:100**	48.37	51.52	37.79
	50:50	22.67	34.96	18.38
	60:40	12.03	18.53	10.15
	70:30	6.25	7.91	4.06
	80:20	1.01	6.28	0.08
	90:10	0.03	0.07	0.01

4.1.3.3 Swelling pressure of sand-bentonite mixes

4.1.3.3.1 Swelling pressure of FS-B1 and MS-B1 mixtures

In engineered barrier applications, bentonite–soil mixtures are preferred over other locally available clays because of their capability for high swelling and 'self-healing' nature. Swelling pressure plays a prominent role in deciding the material to be used as a barrier material. Table 4.5 summarizes the swelling pressure characteristics exhibited by FS-B1 and MS-B1 mixtures. Mixes compacted on the dry side of OMC exhibited higher swelling pressures. Mixes with high bentonite contents (50% and 40%) exhibited higher swelling pressures and especially those mixes with fine sand displayed relatively higher swelling pressure compared to their medium sand counterparts. Given their particle size, fine sands when compacted are incapable of forming larger voids as opposed to medium sands giving rise to numerous small pores, these numerous small pores when filled with bentonite and upon hydration result in higher volume changes resulting in a higher swelling pressure. Irrespective of the sand particle size, mixes with bentonite content less than 20% showed a general lack of appreciable swelling.

Mixtures with 100% B1 content exhibited a higher swelling pressure for all compaction conditions compared to other bentonite proportions, availability of a higher amount of swelling minerals being the reason behind it.

Table 4.5 Summary of swelling pressure results of FS-B1 and MS-B1 mixtures

	Mix. Proportion (S:B1)	**Swelling Pressure (kPa)**		
		Compaction condition		
		MDD-OMC	**MDD-5% dry of OMC**	**MDD-5% wet of OMC**
Medium sand	**0:100**	272.2	360.4	258.7
	50:50	96.0	106.1	88.7
	60:40	51.8	106.9	45.5
	70:30	33.2	96.2	25.4
	80:20	15.2	17.7	11.8
	90:10	1.1	1.5	0.9
Fine sand	**0:100**	272.2	360.4	258.7
	50:50	246.9	282.6	217.5
	60:40	230.5	272.8	215.2
	70:30	81.3	140.5	59.6
	80:20	16.1	18.2	12.1
	90:10	1.3	1.8	1.1

4.1.3.3.2 Swelling pressure of FS-B2 and MS-B2 mixtures

Swelling characteristics exhibited by sand-bentonite-2 mixtures are summarized in Table 4.6. Mixes compacted on the dry side of OMC exhibited higher swelling pressures. Mixes with high bentonite contents (50% and 40%) exhibited higher swelling pressures. Fine sand-bentonite mixes resulted in a relatively higher swelling pressure again, indicating that particle size of aggregate matters while selecting the material to be mixed with bentonite. FS-B2 and MS-B2 mixtures with their relatively high swelling pressure showed that swelling nature of soil-bentonite mixtures is clearly influenced by bentonite quality. Mixtures with 100% B2 resulted in substantially higher swelling pressures for all initial compaction conditions considered, revealing the impact of expansive nature of clay minerals towards swelling processes.

Table 4.6 Summary of swelling pressure results of FS-B2 and MS-B2 mixtures

	Mix. Proportion (S:B2)	**Swelling Pressure (kPa)**		
		Compaction condition		
		MDD-OMC	**MDD-5% dry of OMC**	**MDD-5% wet of OMC**
Medium sand	**0:100**	664.0	711.22	604.78
	50:50	340.5	388.4	335.3
	60:40	242.2	300.1	219.1
	70:30	134.4	215.8	50.4
	80:20	23.5	79.8	21.2
	90:10	0.0	10.2	0.0
Fine sand	**0:100**	664.0	711.22	604.78
	50:50	372.2	431.7	343.4
	60:40	344.4	359.0	332.3
	70:30	179.5	201.0	71.5
	80:20	52.6	94.7	21.6
	90:10	7.8	10.1	5.0

4.1.3.4 Effect of bentonite content and initial compaction conditions on *e*-log *k* relationship for various sand-bentonite mixes

4.1.3.4.1 Effect of bentonite content and initial compaction conditions on *e*-log *k* relationship for FS-B1 and MS-B1 mixes

Hydraulic characteristics are perhaps the most sought after parameters while dealing with geotechnical barrier materials. Figures 4.14 through Figure 4.16 show the effects of initial compaction condition and bentonite content on the relationship between void ratio (*e*) and hydraulic conductivity (*k*) for FS-B1 mixtures. Results show that the hydraulic conductivity of the mixtures decreases with the decrease in the void ratio. With decrease in the void ratio the space available for the flow of water reduces, the flow path becomes more tortuous and consequently the hydraulic conductivity decreases. All the figures indicate that the initial compaction condition of the mixtures has a significant effect on the hydraulic conductivity of the mixtures. Mixtures compacted at 5% dry of OMC–MDD exhibited a higher value of hydraulic conductivity in comparison to other compaction conditions for the same mixture proportion. Since the diffuse double layers of bentonite does not develop fully for the samples compacted on the dry side of OMC, the bentonite particles of the mixtures remain in a flocculated state. The flow paths are relatively open which result in a higher value of hydraulic conductivity in comparison to the mixtures compacted at OMC and 5% wet of OMC for the same proportion. When compacted on the wet of OMC, the diffuse double layer develops fully and the particles becomes more dispersed and the flow paths become more tortuous which results in a lower value of hydraulic conductivity. Results show that the effect of the initial compaction condition on the hydraulic conductivity is more prominent for the mixtures with higher bentonite content. FS-B1 mixtures exhibited a range of hydraulic conductivity values starting with 5.5×10^{-12} to 5.3×10^{-8} m/sec, average hydraulic conductivity requirement for a landfill liner application being less than 1×10^{-9} m/sec.

Analyzing the influence of bentonite content on hydraulic characteristics of FS-B1 mixtures, bentonite in the mixtures generally occupies the void space present between the sand grains. Once the bentonite swells, due to hydration of water, it fills the void space. The degree of filling these void spaces depends upon the amount of bentonite present in the void as well as its swelling capacity. Since the same bentonite was used for all these mixtures, the degree of filling of these voids depends entirely on the amount of bentonite present in the mixture. Result for all the mixtures indicate that irrespective of the initial compaction condition, mixtures with higher bentonite contents exhibited lower hydraulic conductivity. As higher amount of bentonite is present in the void space for 50% B1+50% FS mixtures, bentonite fills the void space more effectively in comparison to other mixtures and gives rise to a lower value of hydraulic conductivity. Result also shows that the difference in hydraulic conductivity for 50% B1+50% FS and 40% B1+60% FS is very less, which indicates that 40% bentonite is well enough to fill the void space completely. Samples compacted at 5% wet of OMC displayed lowest hydraulic conductivity while those compacted at 5% dry of OMC displayed highest conductivity and samples compacted at OMC remained intermittent.

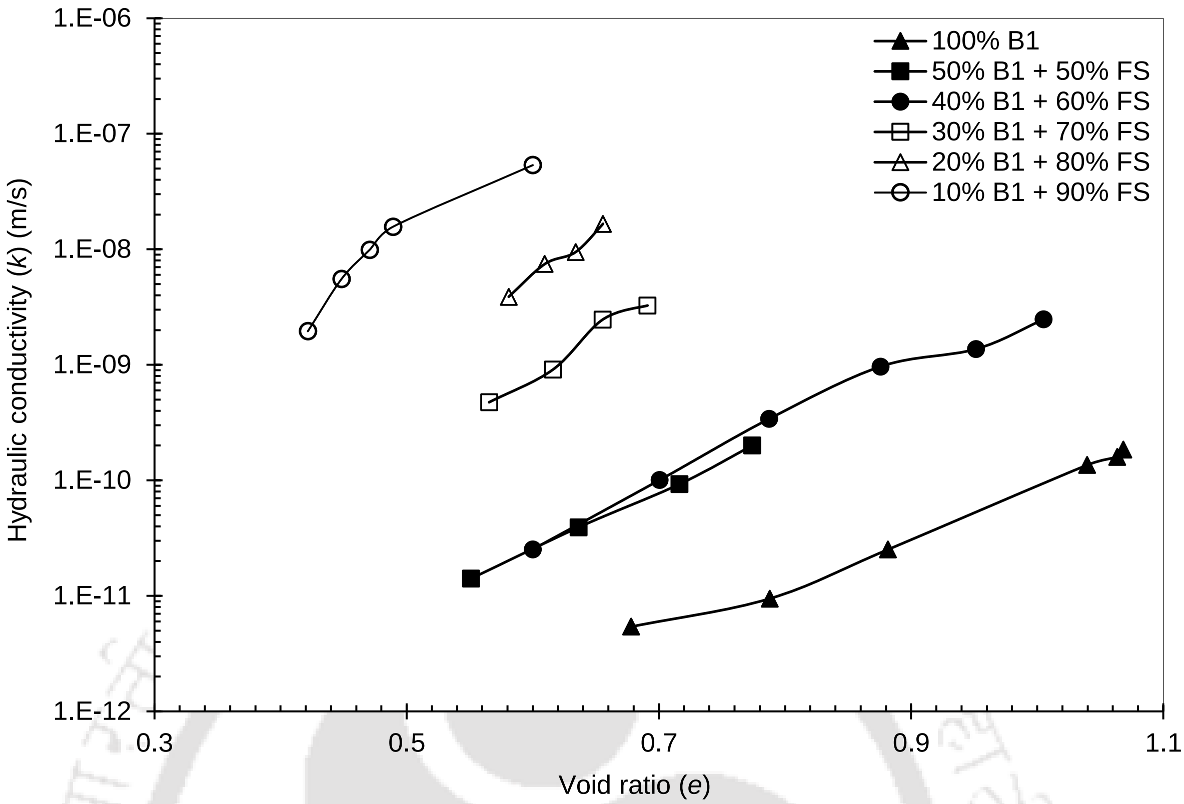


Figure 4.14 *e*-log *k* plot for FS-B1 mixes compacted at 5% dry of OMC-MDD

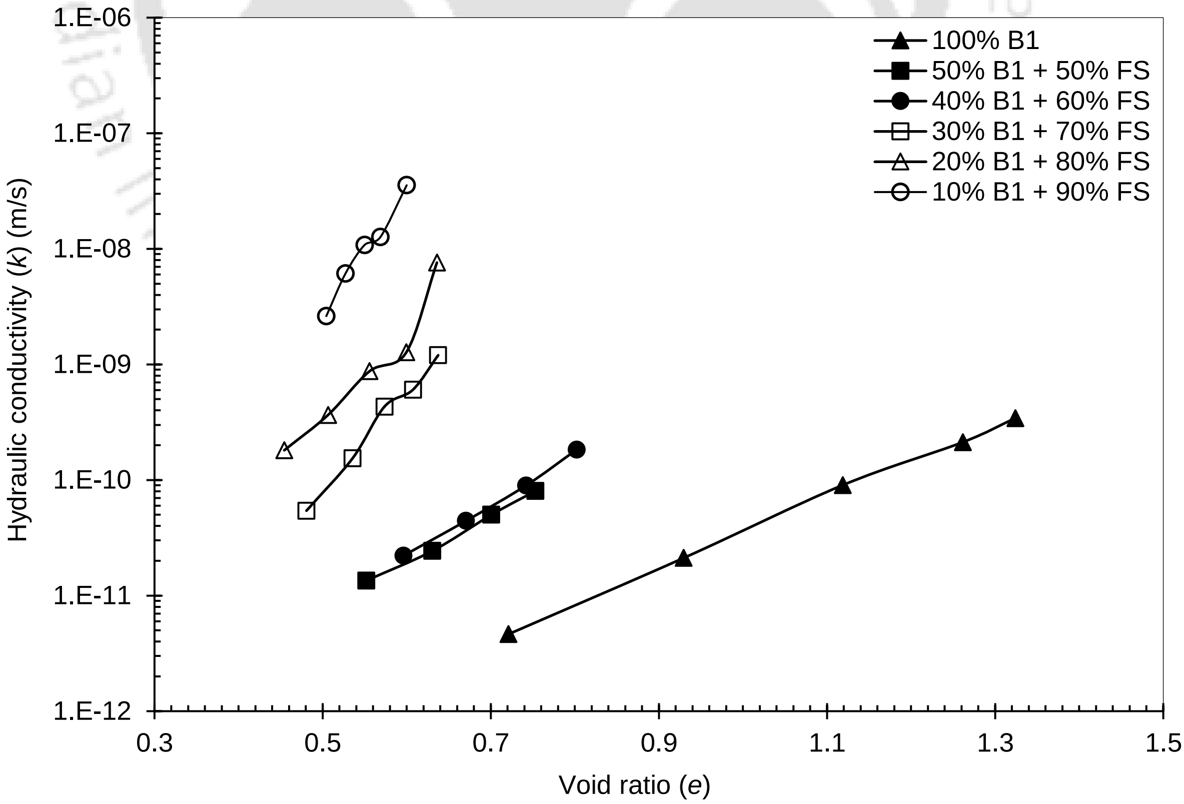


Figure 4.15 *e*-log *k* plot for FS-B1 mixes compacted at OMC-MDD

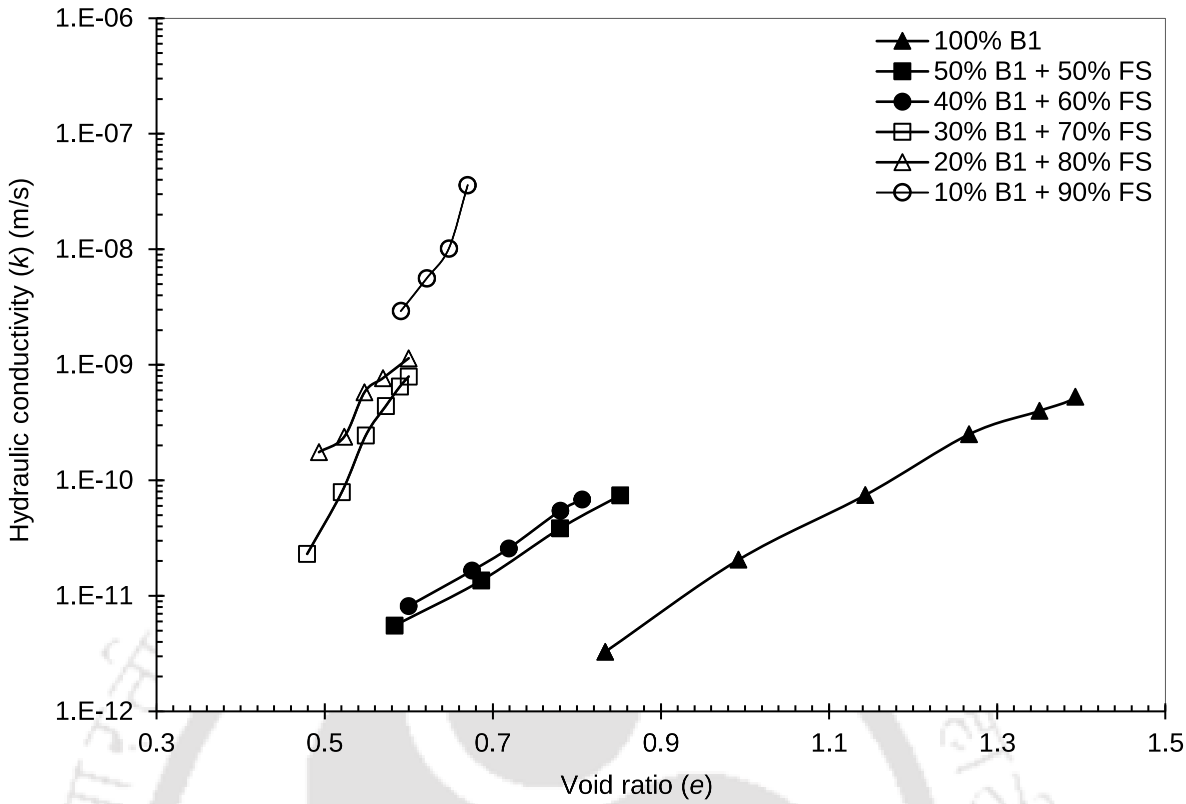


Figure 4.16 *e*-log *k* plot for FS-B1 mixes compacted at 5% wet of OMC-MDD

Benson and Daniel (1990) attributed this phenomenon to the formation of soil clods at low moulding water content and their gradual breakdown with increasing water content resulting in a lower hydraulic conductivity. FS-B1 mixture with 20% bentonite content seems to be fulfilling the basic criterion and can be suggested for landfill liner application with proper attention to initial mixing water content.

Comparing mixtures with 100% B1 and other B1 proportions, a substantial difference in the swelling potential and swelling pressure were observed. However, for the hydraulic behaviour, mixtures with 100% B1 exhibited lowest hydraulic conductivity for all compaction conditions. Mixtures with 100% B1 exhibited almost 10-fold lower hydraulic conductivity compared to 50% B1 + 50% FS mixes.

Hydraulic characteristics of medium sand-bentonite-1 mixtures are represented in Figs. 4.17 through Figs. 4.19. The figures present the effect of initial compaction condition and bentonite content on the relationship between void ratio (*e*) and hydraulic conductivity (*k*) for MS-B1 mixtures. Results show that the effect of the initial compaction condition on the hydraulic conductivity is more prominent for the mixtures with higher bentonite content. MS-B1 mixtures exhibited a wide range of hydraulic conductivities from $1 x 10^{-11}$ to $1.3 x 10^{-7}$ m/sec, minimum hydraulic conductivity requirement for a landfill liner application being 1x10^{-9} m/sec. In comparison to FS-B1 mixes, for any given mix proportion, MS-B1 mixtures exhibited a slightly higher hydraulic conductivity indicating that bentonite couldn't fill the voids sufficiently as it did in the case of FS-B1 mixtures. MS-B1 mixture with 30% bentonite content seems to be fulfilling the basic criterion and can be suggested for landfill liner application with proper attention to initial mixing water content.

Upon comparing the FS-B1 and MS-B1 mixtures for their suitability as a landfill liner material, it is clear that a relatively higher bentonite content is necessary in case of MS-B1 mixes to achieve the similar level of water tightness compared to their fine sand counterparts. Figure 4.20 shows the effect of sand proportion and particle size on the hydraulic conductivity of sand–bentonite-1 mixture at a particular void ratio.

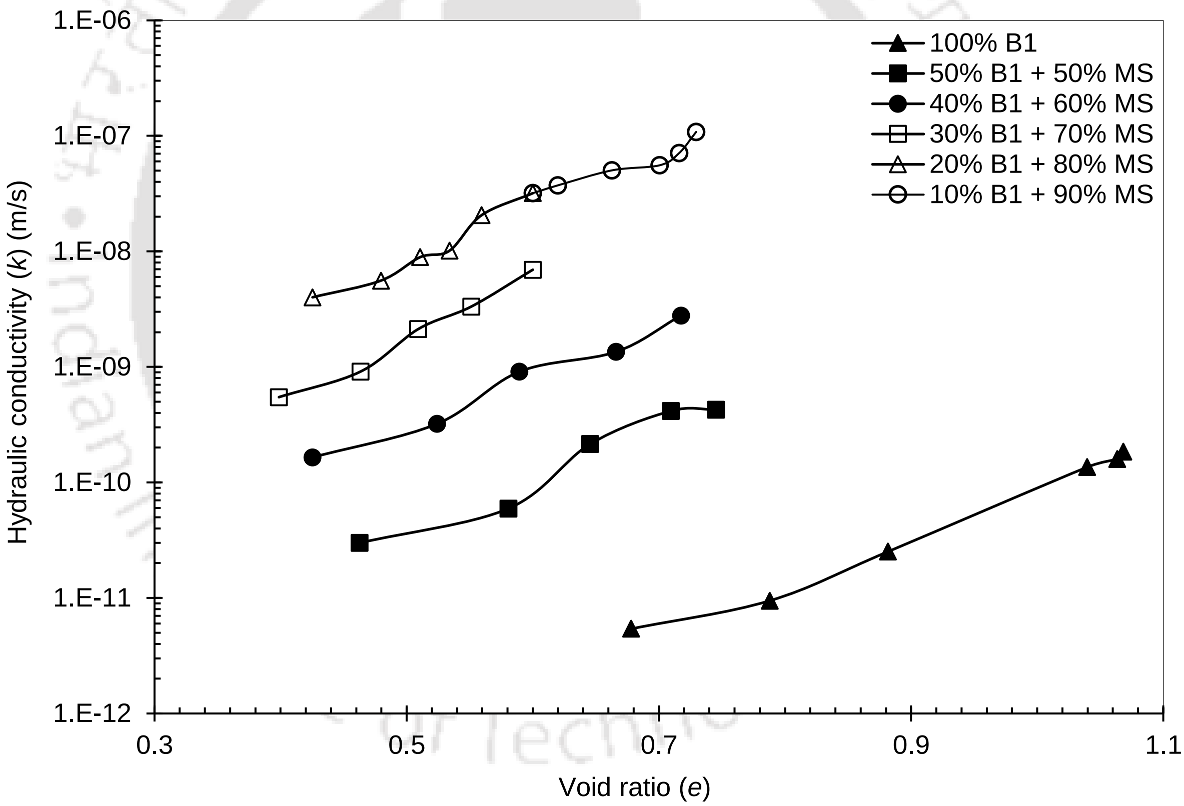


Figure 4.17 *e*-log *k* plot for MS-B1 mixes compacted at 5% dry of OMC-MDD

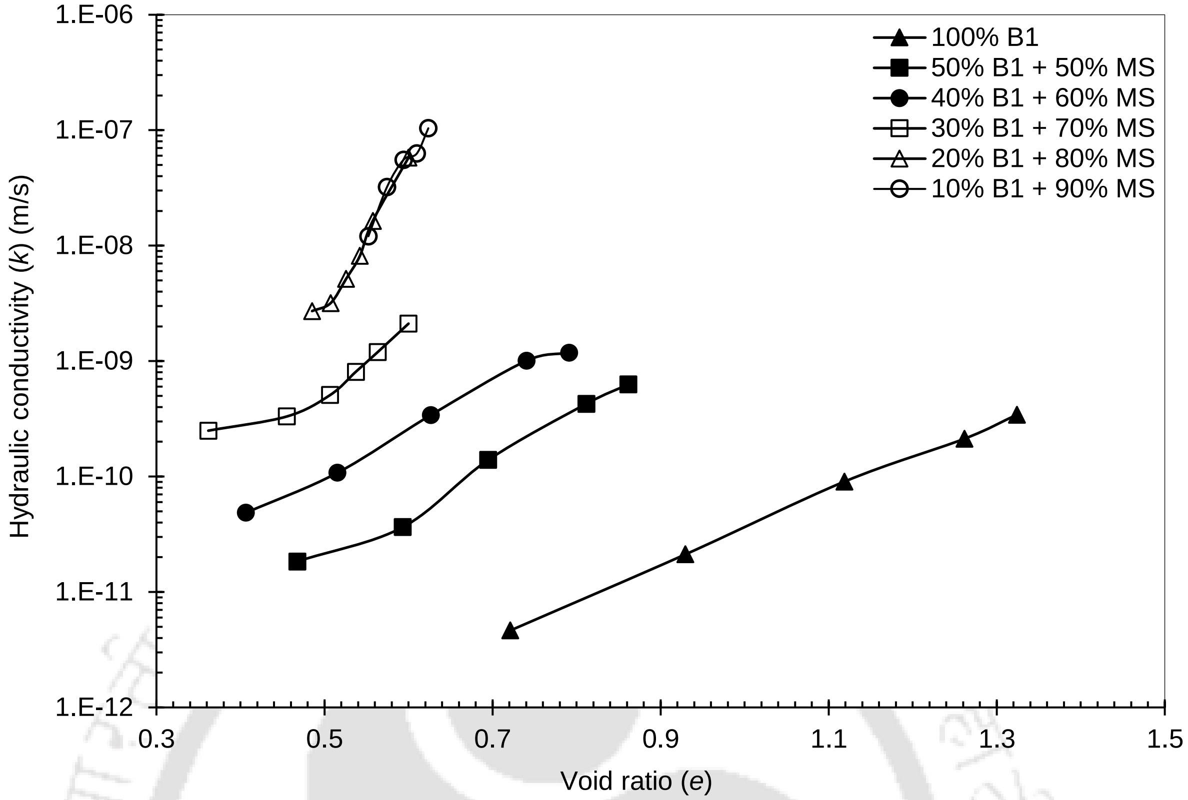


Figure 4.18 *e*-log *k* plot for MS-B1 mixes compacted at OMC-MDD

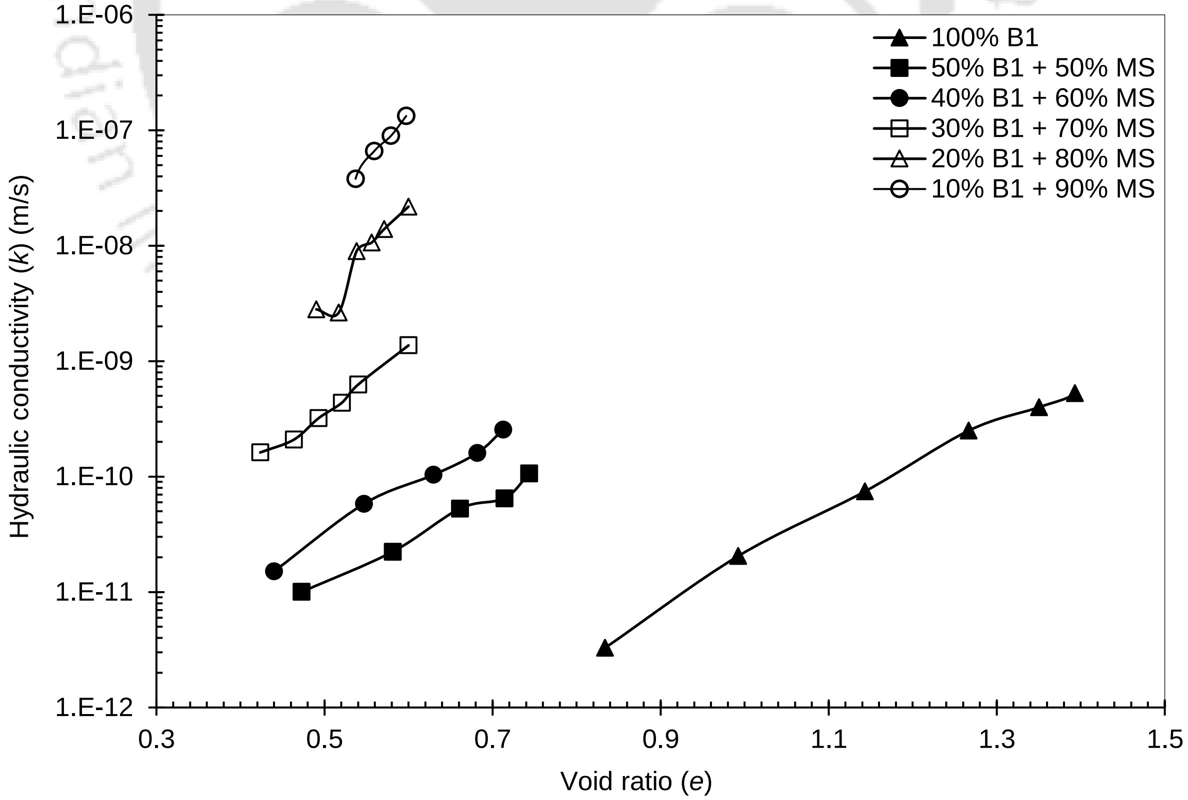


Figure 4.19 *e*-log *k* plot for MS-B1 mixes compacted at 5% wet of OMC-MDD

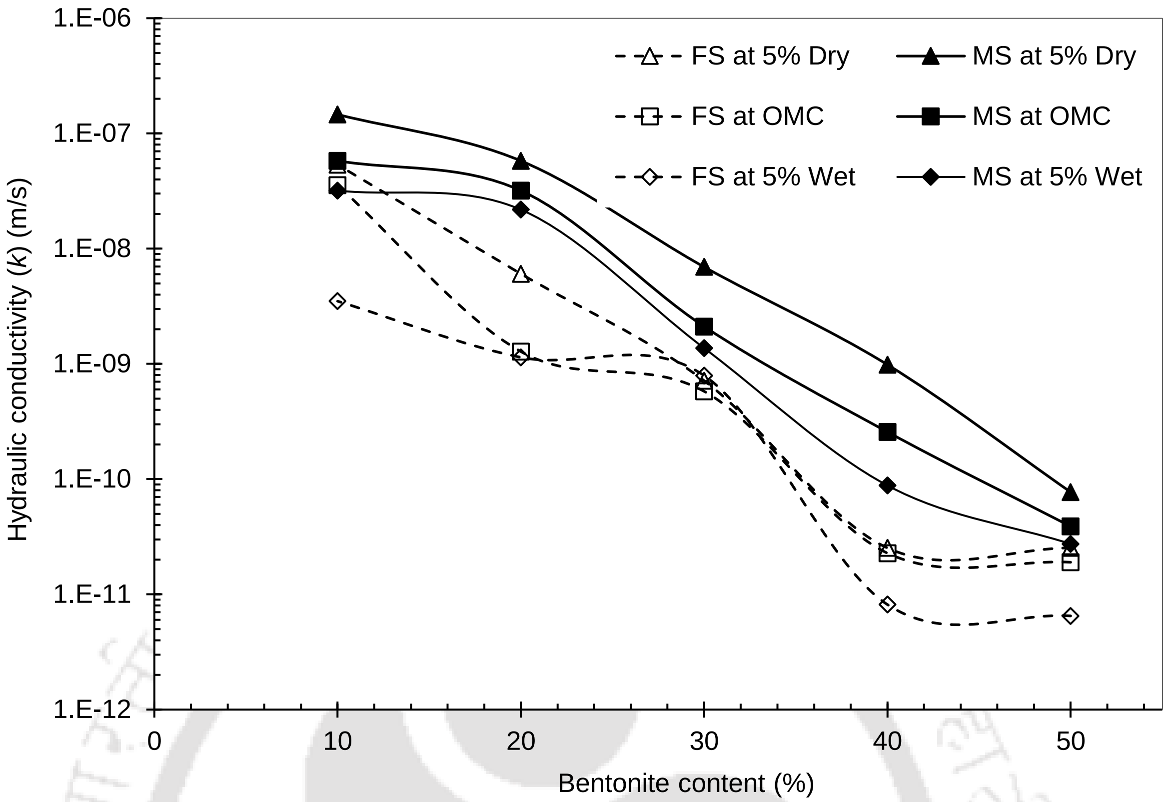


Figure 4.20 Bentonite content-hydraulic conductivity for sand-bentonite-1 mixtures at a void ratio of 0.60

Figure 4.20 compares the hydraulic conductivity values of different FS-B1 and MS-B1 mixtures, mixed in various proportions at a void ratio of 0.6. FS-B1 mixtures consistently exhibited lower hydraulic conductivities relative to MS-B1 mixtures. Mixtures with 100% B1 content exhibited consistently a lower hydraulic conductivity compared to other MS-B1 mixtures. Mixtures with 100% B1 exhibited almost 10-20 fold lower hydraulic conductivity compared to 50% B1 + 50% MS.

4.1.3.4.2 Effect of bentonite content and initial compaction conditions on *e*-log *k* relationship for FS-B2 and MS-B2 mixes

Hydraulic characteristics of FS-B2 mixtures compacted at three different compaction conditions i.e. OMC-MDD, 5% wet of OMC-MDD and 5% dry of OMC-MDD are represented in Figs. 4.21 through Figs. 4.23. These figures present the effect of compaction conditions and bentonite content on the relationship between void ratio (e) and hydraulic conductivity (k) for FS-B2 mixtures. FS-B2 mixtures exhibited a wide range of hydraulic conductivity values starting with 3.3×10^{-12} to 1.90×10^{-8} m/sec. As far as the effect of compaction conditions is concerned, FS-B2 mixtures followed a similar path as FS-B1 mixtures did i.e. samples compacted on wet side of OMC-MDD exhibited lowest k for all bentonite contents followed by those compacted at OMC-MDD and trailing by those compacted on dry of OMC-MDD. Upon comparison it was observed that for any given bentonite content, FS-B2 mixes exhibited lower hydraulic conductivity than FS-B1 mixes indicating that bentonite quality does influences the hydraulic conductivity of sand-bentonite mixtures. FS-B2 mixture with 20% bentonite content seems to be fulfilling the basic criterion and can be suggested for landfill liner application with attention to initial mixing water content.

Hydraulic characteristics of MS-B2 mixtures compacted at three different compaction conditions i.e. OMC-MDD, 5% wet of OMC-MDD and 5% dry of OMC-MDD are represented in Figs. 4.24 through Figs. 4.26. MS-B2 mixtures exhibited a wide range of hydraulic conductivity values starting with 3.2×10^{-12} to 7.6×10^{-9} m/sec, minimum hydraulic conductivity requirement for a landfill liner application being 1×10^{-9} m/sec. As far as the effect of compaction conditions is concerned, MS-B2 mixtures followed a similar path as MS-B1 mixtures. Upon comparison, it is observed that for any given bentonite content, MS-B2 mixes performed better than MS-B1 mixes indicating that bentonite quality does influence the hydraulic conductivity of sand-bentonite mixtures. Medium sand-bentonite-2 mixture with 20% bentonite content seems to be fulfilling the basic criterion and can be suggested for landfill liner application with proper to initial mixing water content.

Mixtures with 100% B2 content exhibited a consistently lower hydraulic conductivity compared to other FS-B2 and MS-B2 mixtures. Though the exhibited void ratios were different, upon considering the hydraulic conductivity values, mixtures with 100% B2 exhibited almost similar hydraulic conductivities compared to 50% FS +50% B2 and 50% MS +50% B2 mixes.

Upon comparison of hydraulic characteristics of FS-B2 and MS-B2 mixes at a particular void ratio as shown in Fig. 4.27, it is clear that at higher bentonite contents (30% and above) the influence of sand particle size on hydraulic characteristics is of little importance, in other words, in mixes with low bentonite contents sand particle size influences hydraulic characteristics. Comparing sand-bentonite-1, sand-bentonite-2 mixes revealed that as the expansive nature of bentonite improves, hydraulic benefits obtained using fine sand diminishes.

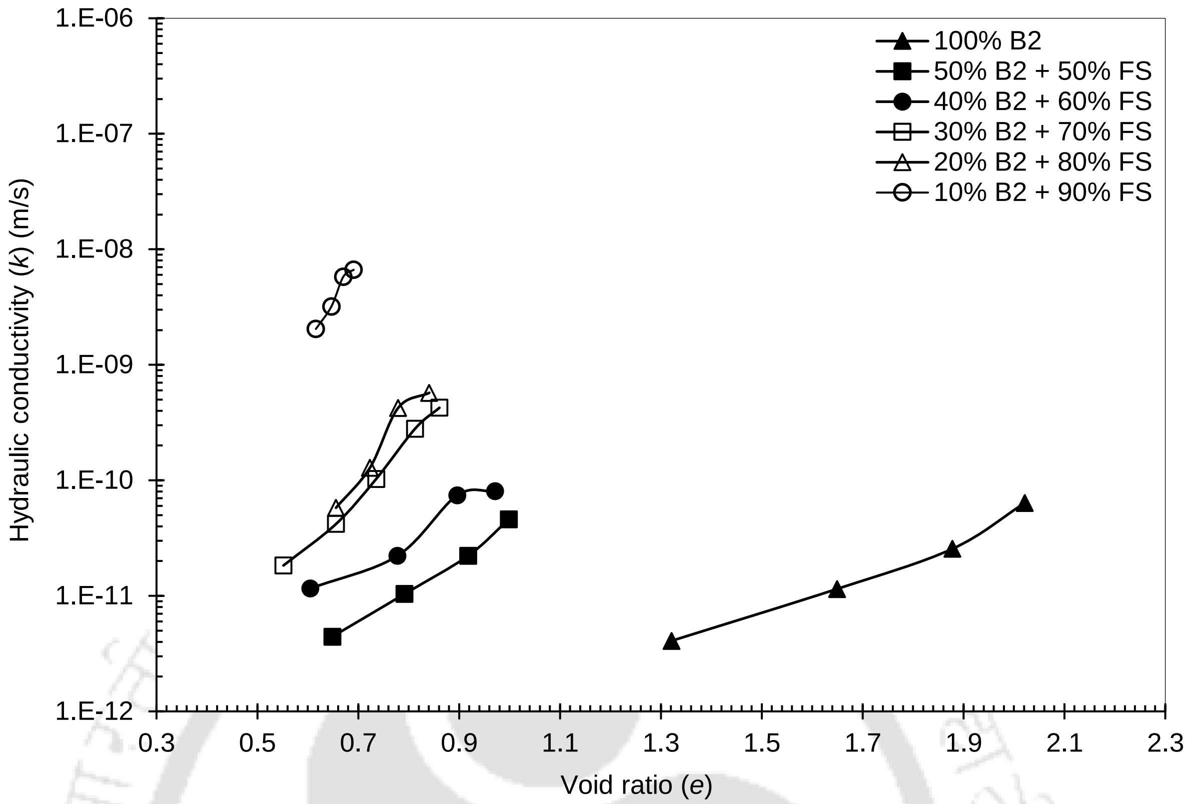


Figure 4.21 *e*-log *k* plot for FS-B2 mixes compacted at 5% dry of OMC-MDD

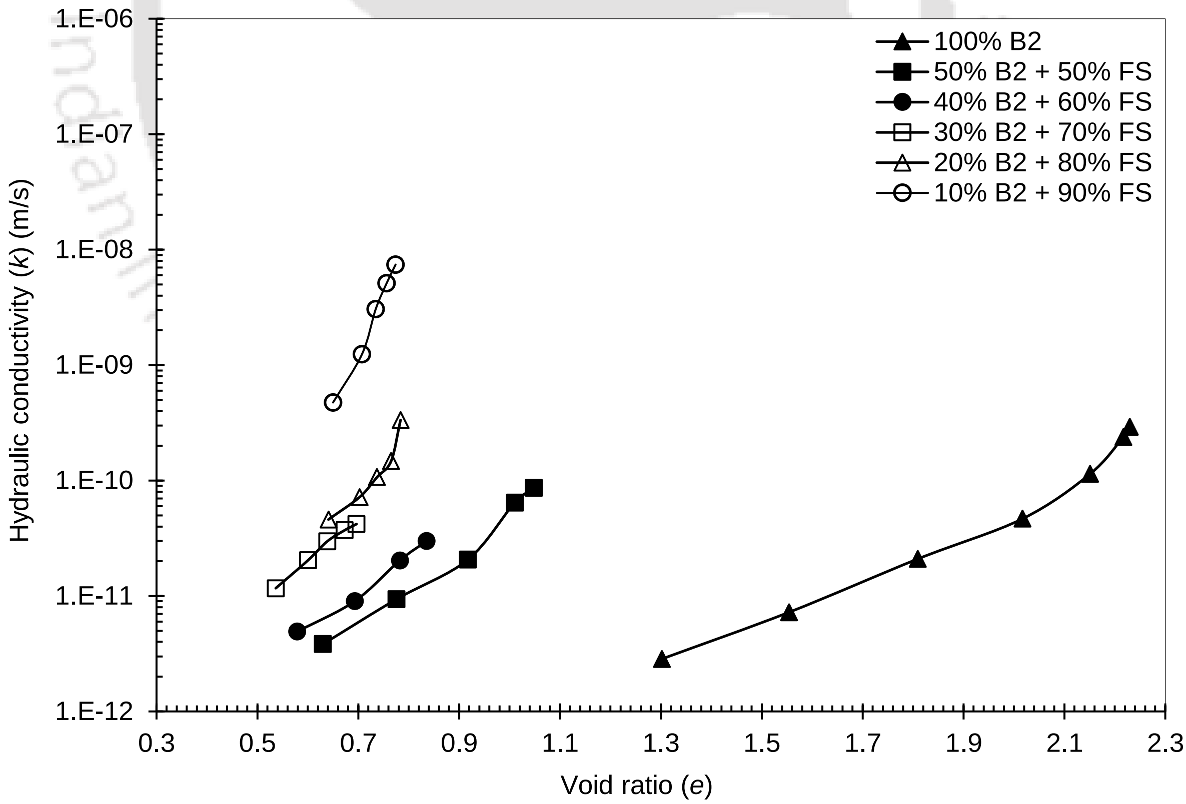


Figure 4.22 *e*-log *k* plot for FS-B2 mixes compacted at OMC-MDD

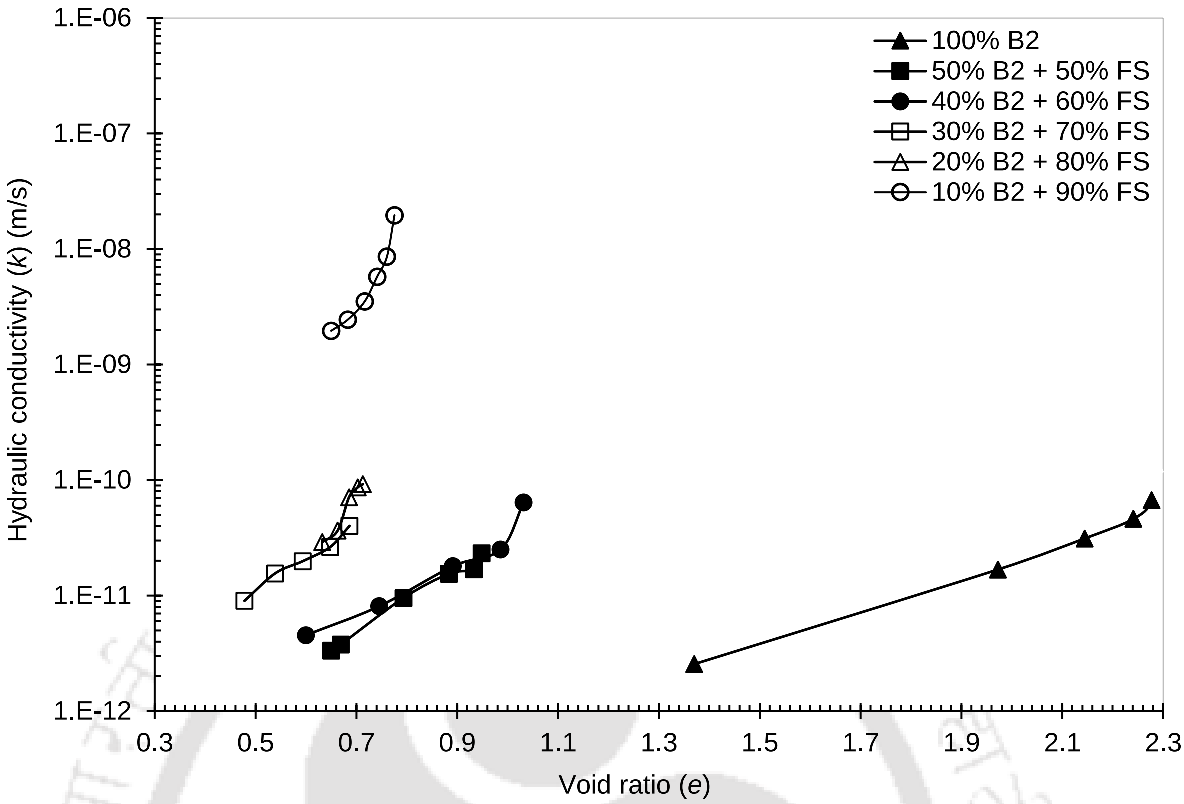


Figure 4.23 *e*-log *k* plot for FS-B2 mixes compacted at 5% wet of OMC-MDD

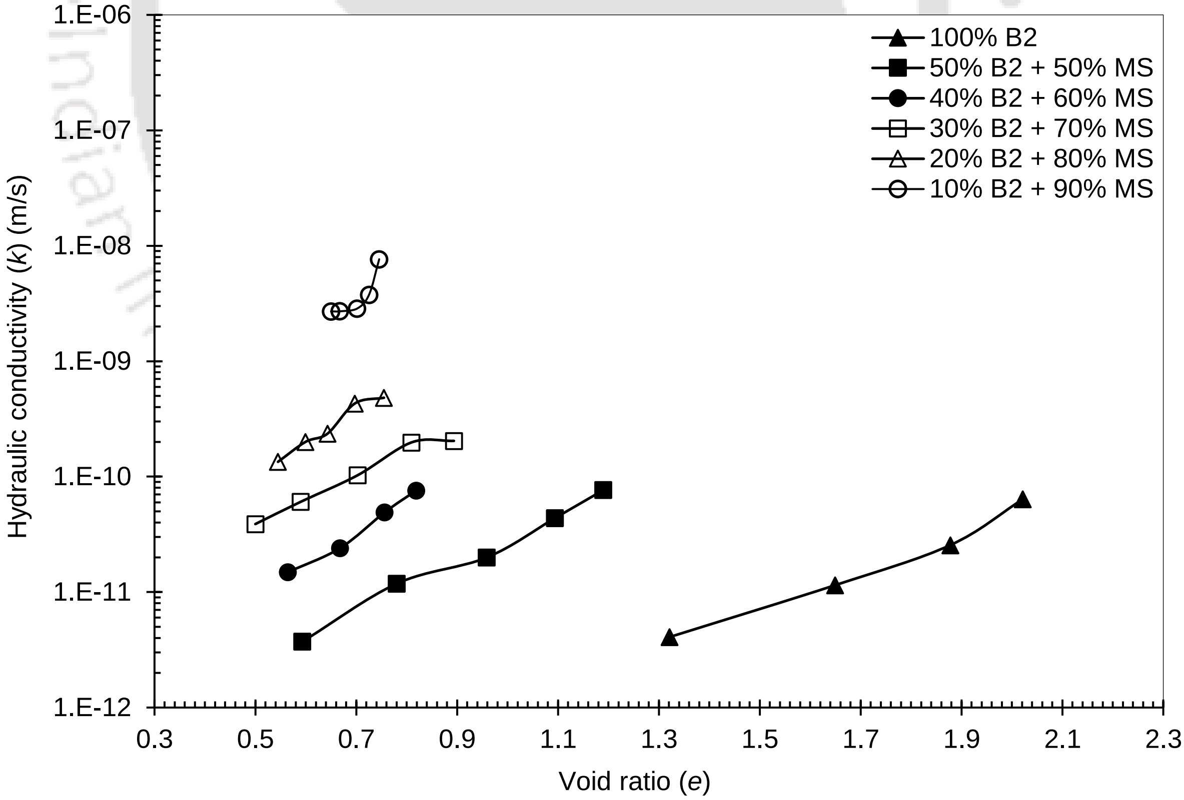


Figure 4.24 *e*-log *k* plot for MS-B2 mixes compacted at 5% dry of OMC-MDD

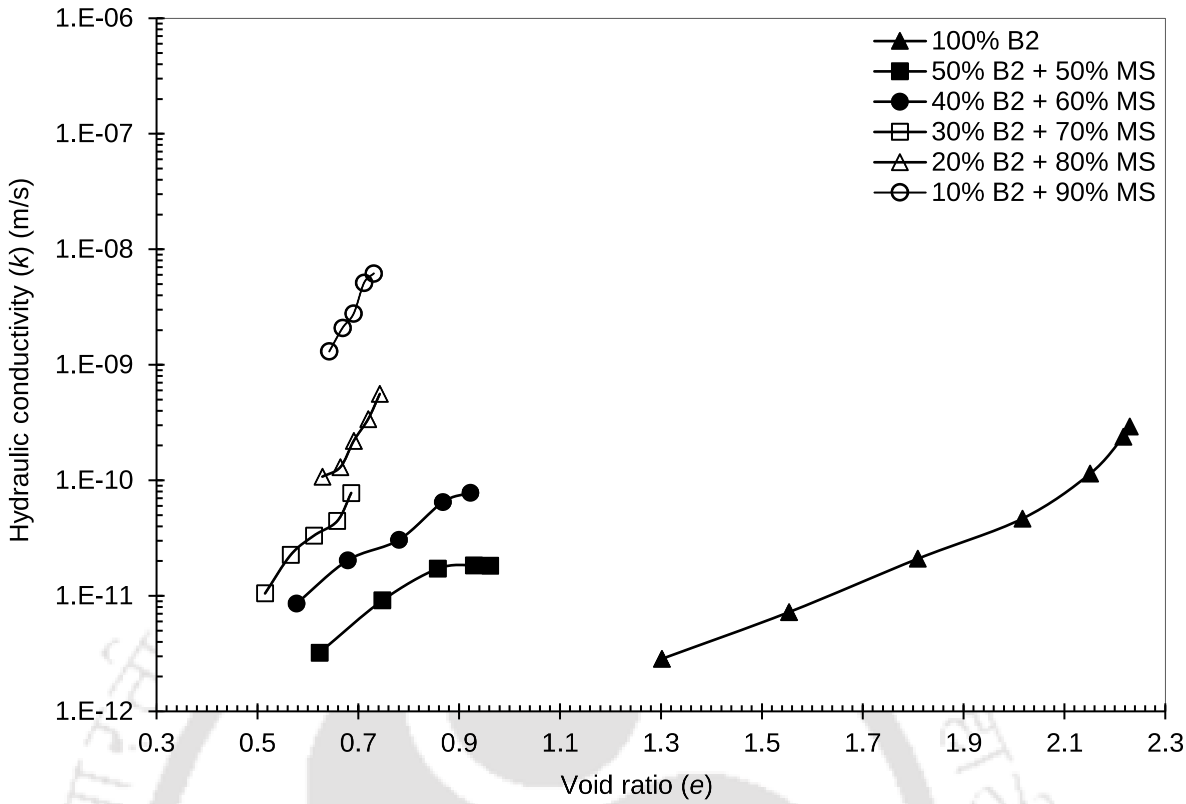


Figure 4.25 *e*-log *k* plot for MS-B2 mixes compacted at OMC-MDD

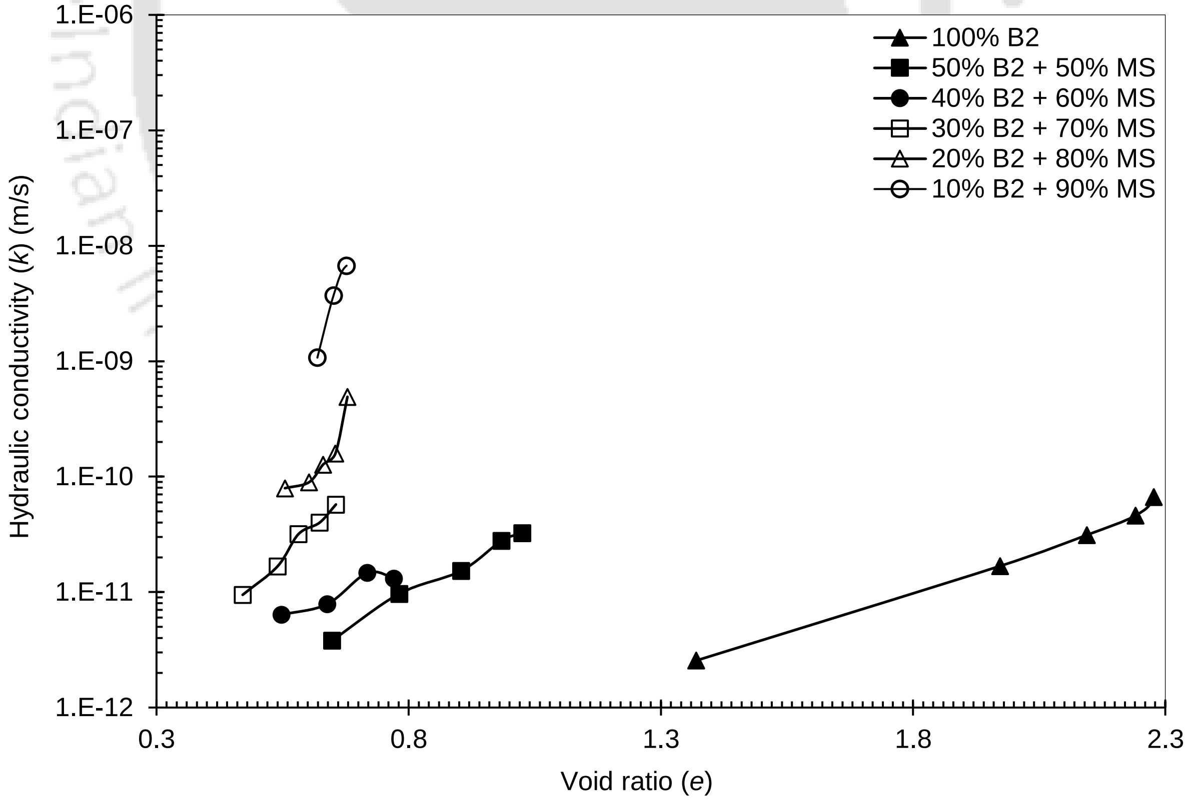


Figure 4.26 *e*-log *k* plot for MS-B2 mixes compacted at 5% wet of OMC-MDD

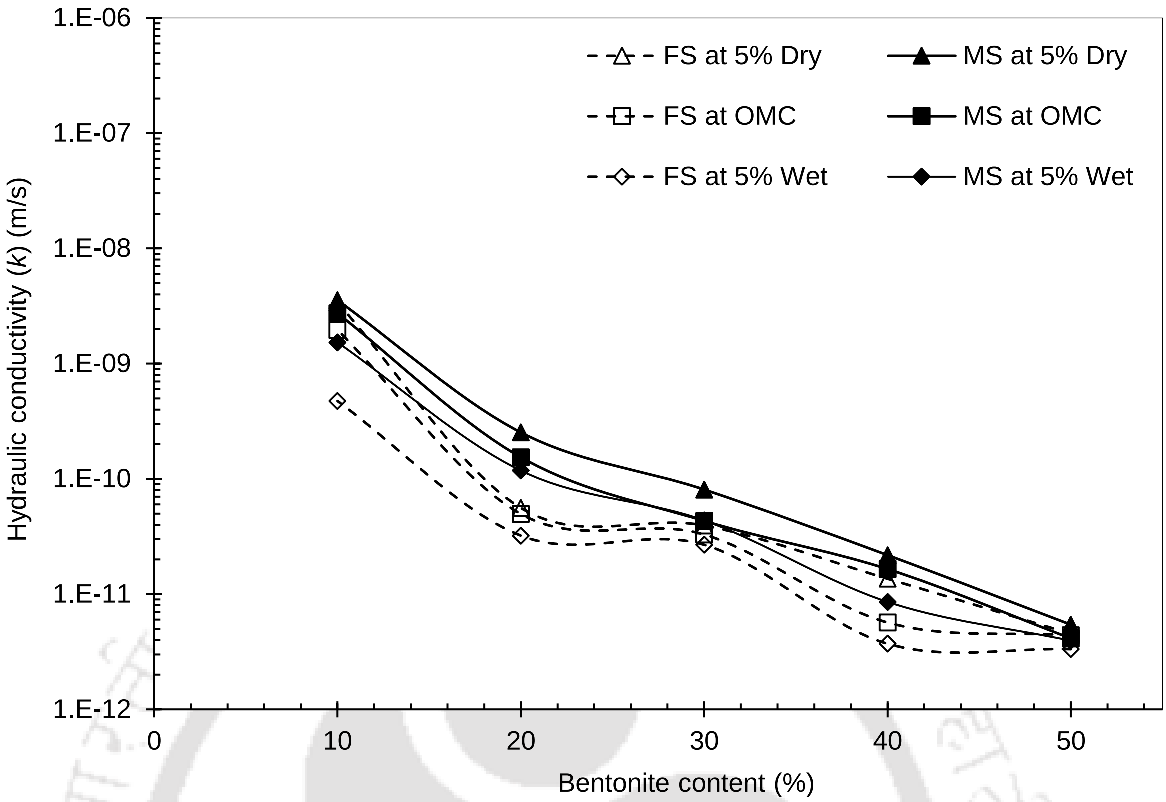


Figure 4.27 Bentonite content-hydraulic conductivity for sand-bentonite-2 mixtures at a void ratio of 0.65

4.1.3.5 Effect of bentonite content and initial compaction conditions on *e*-log *P* relationship for sand-bentonite mixes

One dimensional consolidation tests were conducted on the medium sand-bentonite and fine sand-bentonite mixtures. Two different types of bentonite (namely bentonite-1 or B1 and bentonite-2 or B2) were used for the test. The bentonite content was varied from 10% to 50% in the mixtures, with an increment of 10%. The samples were prepared at three different compaction conditions, namely MDD-OMC, MDD-5% dry of OMC and MDD-5% wet of OMC. This test signifies the effect of overburden pressure on the compressibility characteristics of sand-bentonite mixtures.

4.1.3.5.1 Effect of bentonite content and initial compaction conditions on *e*-log *P* relationship for FS-B1 and MS-B1 mixes

Void ratio-Pressure relationship exhibited by various FS-B1 mixes compacted at three different compaction conditions are represented in Figs. 4.28 through Figs. 4.30. Mixtures with higher bentonite content exhibited a higher value of initial void ratio. With decrease in the bentonite content the initial void ratio for the mixtures also decreased. The bentonite in the mixtures occupies the void spaces formed between the sand grains. Once the bentonite starts swelling, it starts filling the void spaces. As the bentonite content increases, it gradually fills the void spaces completely and then it starts pushing up the solid sand grain resulting in a higher volume change and a higher void ratio. As the overburden pressure starts to act on the mixtures, the pressure compresses the swollen bentonite, which results in a decrease in the void ratio. Since the reduction in the void ratio is mainly due to the compression of the swollen bentonite, mixtures with higher bentonite contents undergo a relatively higher degree of compression. Result shows that for any compaction condition the compressibility of the mixture decreases with decrease in the bentonite content. Plots indicate that initial compaction conditions have a definite influence on the void ratio-pressure relationship of the sand-bentonite mixtures. Result also shows that the mixes compacted at 5% dry of OMC-MDD exhibited relatively higher initial void ratio followed by those compacted at OMC-MDD and 5% wet of OMC-MDD, respectively. At lower mixing water contents, affinity of bentonite towards water is very high and as mixing water content raises the affinity reduces. Since bentonite present in the voids has a higher affinity towards water at lower water contents, to neutralize this affinity, it adsorbs a larger amount of water on to its surface and undergoes a higher volume change that is reflected as higher initial void ratio. As the mixing water content is increased, the necessity to neutralize the affinity also reduces leading to a lower amount of water being adsorbed on to the surface of bentonite which subsequently reflects in a lower volume change and hence a lower void ratio.

Void ratio-Pressure relationship exhibited by various MS-B1 mixes compacted at three different compaction conditions are plotted in Figs. 4.31 through Figs. 4.33. Similar to the various FS-B1 mixtures, the results for the various MS-B1 mixtures shows that with an increase in the overburden pressure the void ratio decreases. Mixtures with higher bentonite content exhibited a higher initial void ratio. In comparison to the medium sand-bentonite mixture, a higher initial void ratio was observed for the same proportion of fine sand-bentonite mixtures. This could be due to the difference in the size of the individual voids being formed between the sand grains. The mixtures containing medium sized sand has individual void spaces produced between the sand grains and these voids are larger in comparison to those produced by fine grained sand mixtures. Since number of voids are large for fine sand mixture, the sum of the individual voids or the void ratio is generally higher for fine sand mixtures. In addition to that, bentonite also gets completely filled within the individual void of the fine sand-bentonite mixtures and further increases the void ratio after absorbing water and increasing its own volume. Medium sand mixes displayed a relatively low initial void ratio owing to the fact that a few large voids are present in the compacted sample as compared to a higher number of small voids present in the fine sand mixes. Similarly, the initial compaction conditions also showed to have an influence on compressibility behavior of MS-B1 mixtures. Mixes with B1 content less than 20% indicated that the amount of bentonite present in the mix was not sufficient enough to fill the voids completely and hence compressibility characteristics was controlled by sand.

It is evident from the Figs. 4.28 through Figs. 4.33 that mixtures with 100% B1 exhibits highest initial void ratio for all compaction conditions compared to other sand-bentonite proportions and highest volume change with pressure indicating a higher compressible nature of 100% bentonite mixture.

4.1.3.5.2 Effect of bentonite content and initial compaction conditions on *e*-log *P* relationship for FS-B2 and MS-B2 mixes

Void ratio-Pressure relationship exhibited by various FS-B2 mixes and compacted at three different compaction conditions are represented in Figs. 4.34 through Figs. 4.36. Similar to the various FS-B1 mixtures, the results for the various FS-B2 mixtures show that with an increase in the overburden pressure the void ratio decreases and mixtures with higher bentonite content exhibited a higher value of initial void ratio. In comparison to the FS-B1 mixtures irrespective of compaction criteria, a higher initial void ratio was observed for the same proportion of FS-B2 mixtures reflecting the effect of high swelling nature of bentonite-2. It can be noticed that the virgin compression line is relatively steeper for all the FS-B2 mixtures when compared with FS-B1 mixtures. It can be observed from the figures that the mixtures with a B2 content of 20% and less are less compressible indicating that the amount of B2 in these mixtures is insufficient in filling the voids formed in the fine sand skeleton.

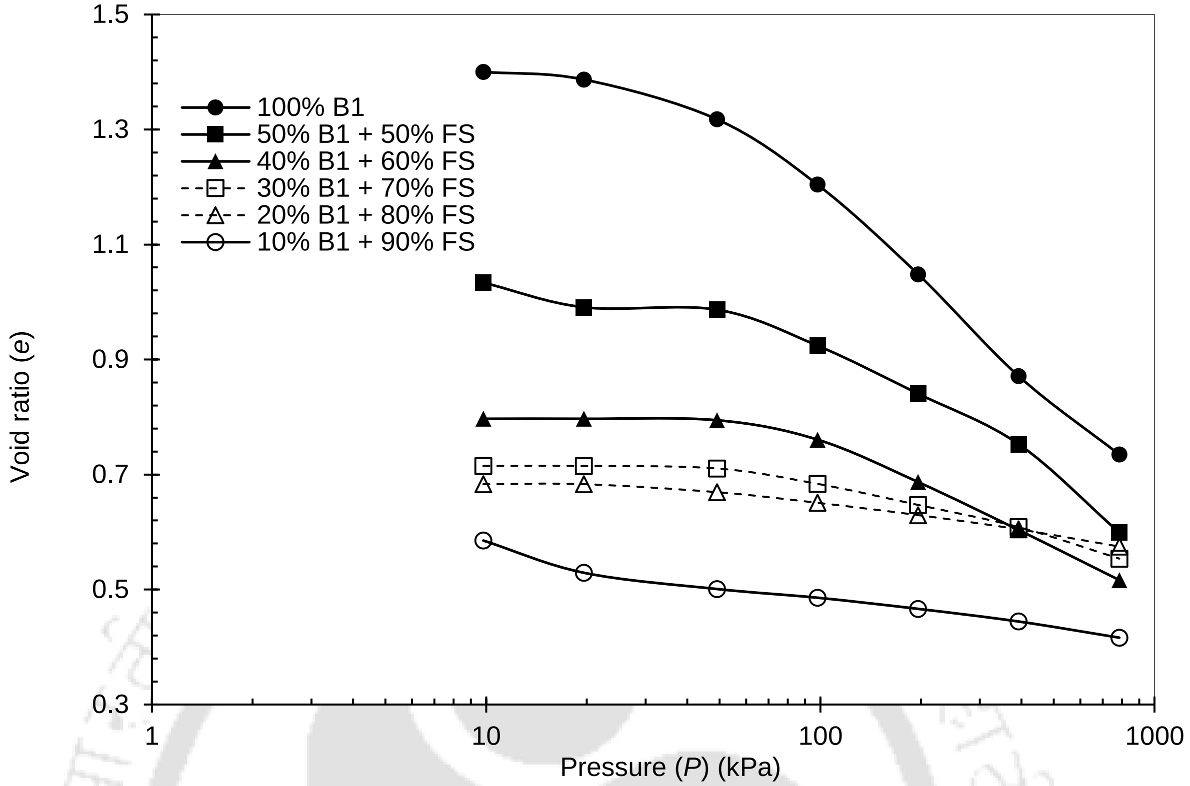


Figure 4.28 Effect of bentonite content on *e*-log *P* for FS-B1 samples compacted at 5% dry of OMC-MDD

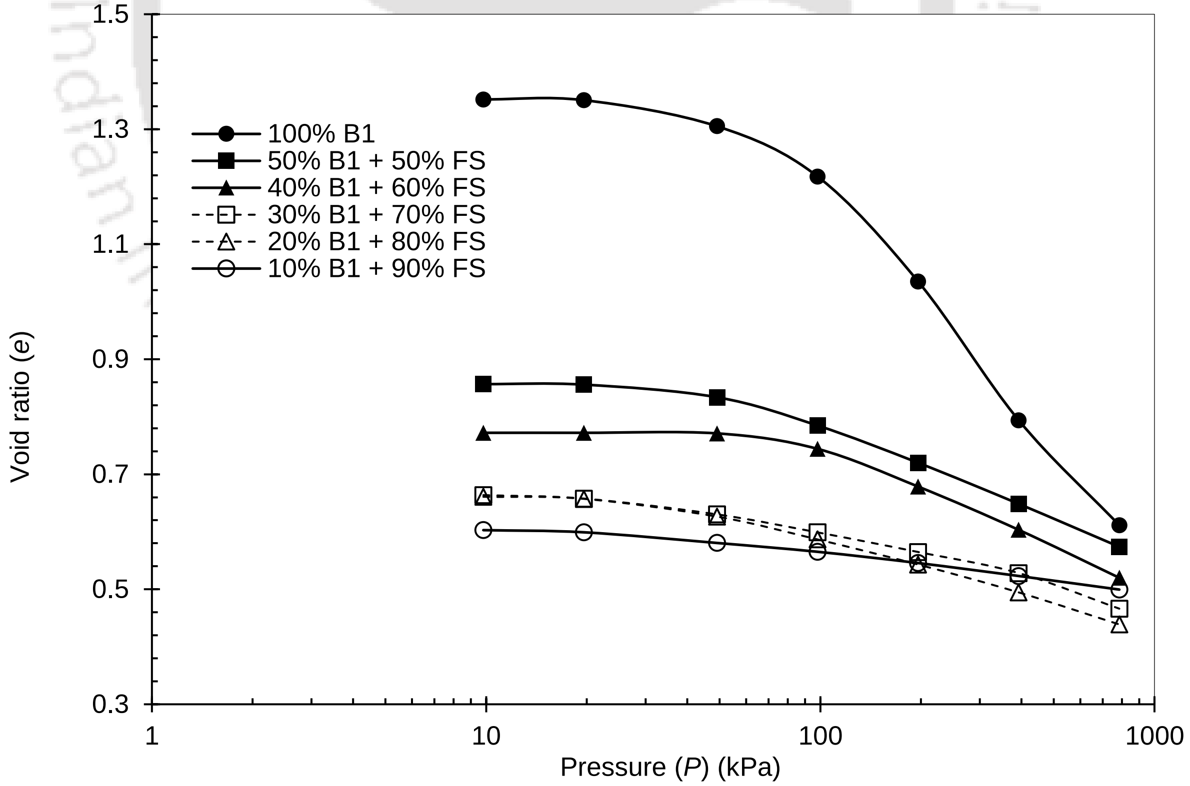


Figure 4.29 Effect of bentonite content on *e*-log *P* for FS-B1 samples compacted at OMC-MDD

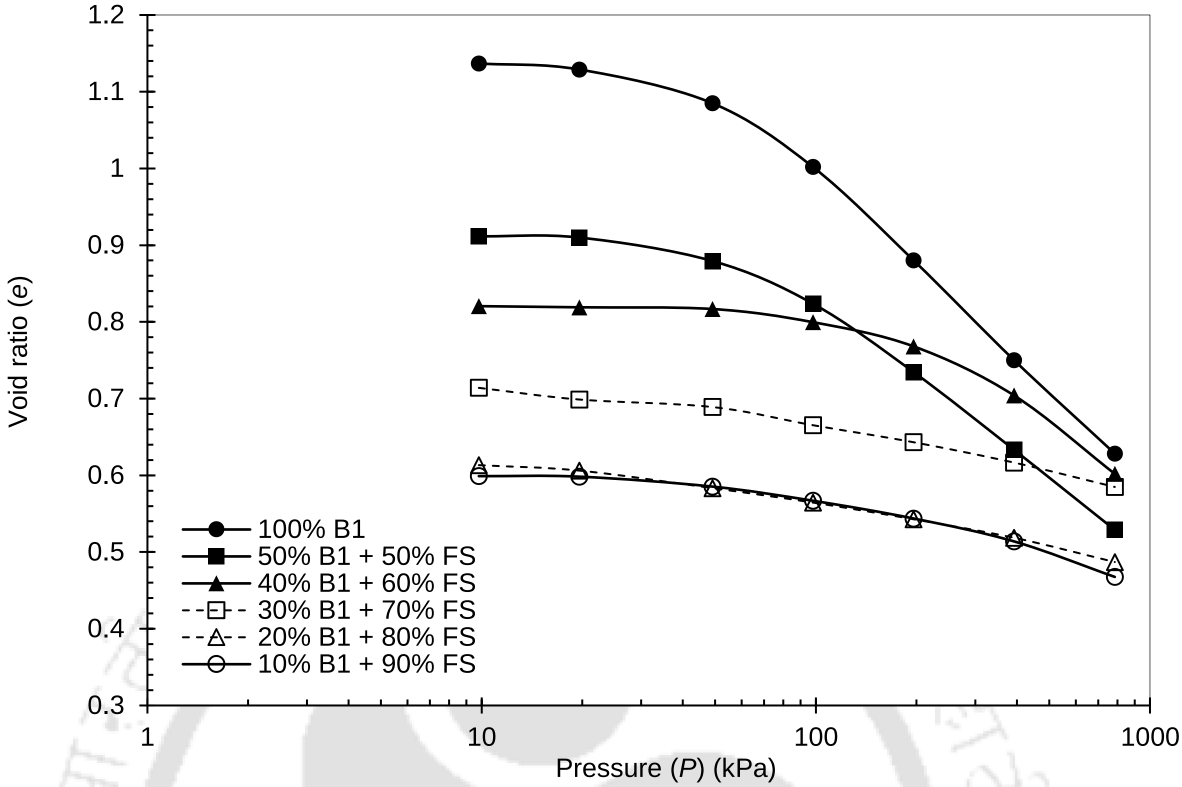


Figure 4.30 Effect of bentonite content on *e*-log *P* for FS-B1 samples compacted at 5% wet of OMC-MDD

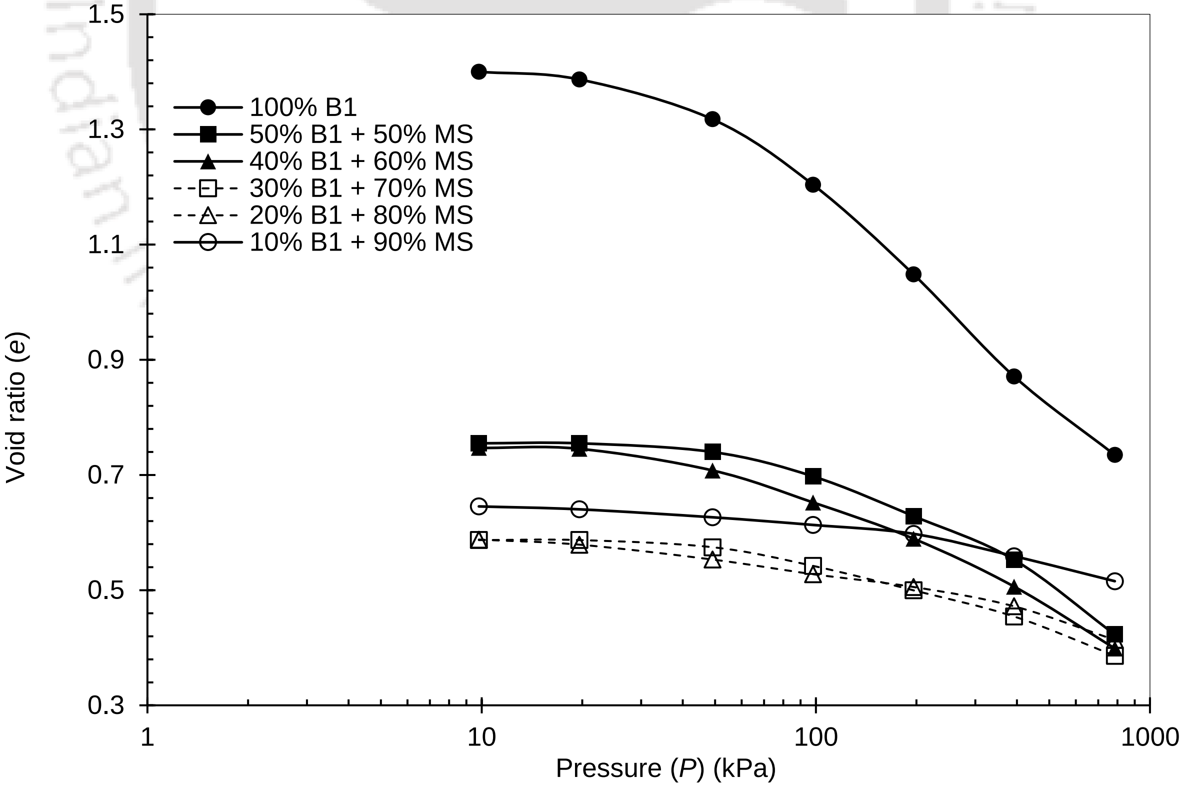


Figure 4.31 Effect of bentonite content on *e*-log *P* for MS-B1 samples compacted at 5% dry of OMC-MDD

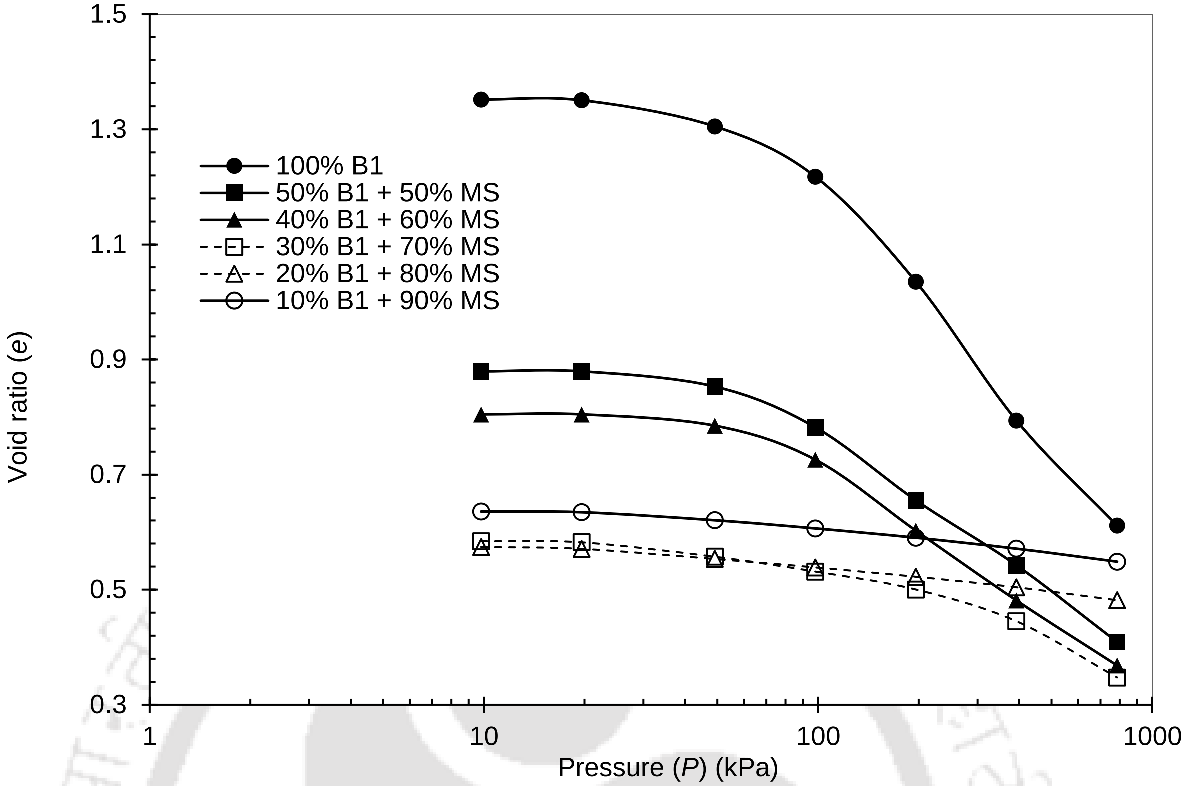


Figure 4.32 Effect of bentonite content on *e*-log *P* for MS-B1 samples compacted at OMC-MDD

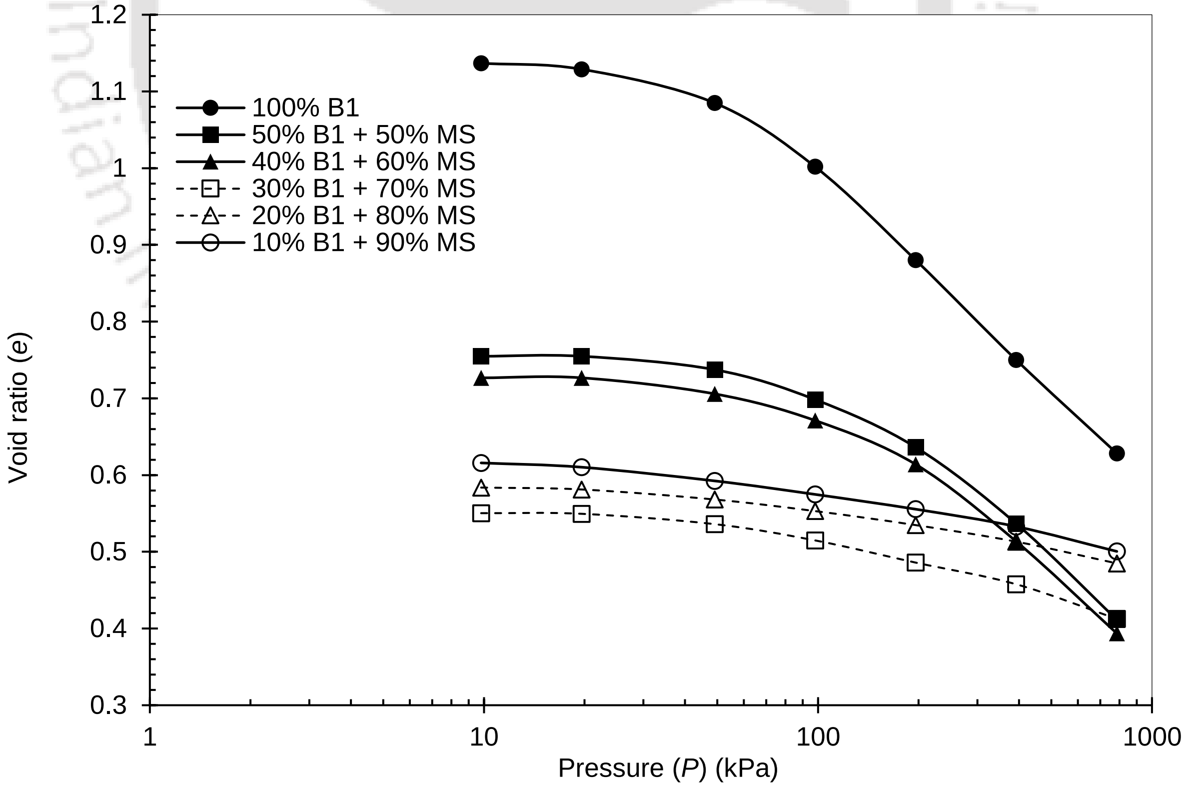


Figure 4.33 Effect of bentonite content on *e*-log *P* for MS-B1 samples compacted at 5% wet of OMC-MDD

Void ratio-Pressure relationship exhibited by various MS-B2 mixes compacted at three different compaction conditions are represented in Figs. 4.37 through Figs. 4.39. In terms of initial void ratio, slope of virgin compression line and final void ratio, response exhibited MS-B2 mixtures is similar to FS-B2 mixtures. Irrespective of initial void ratio and compaction criteria, final void ratio of all the mixes are falling in a narrow range indicating the compressible nature of B2. Mixtures compacted on the dry side of OMC are exhibiting higher initial void ratio's. It is observed that irrespective of the molding water content the mixtures exhibited final void ratios in a very narrow range compared to their B1 counterparts. For both fine sand and medium sand mixes with a B2 content of 20% and less indicate a sand domination in terms of load carrying mechanism, compressibility, initial and final void ratios.

Mixtures with 100% B2 exhibited highest initial void ratios compared to other sand-bentonite proportions, a similar observation was made in case of B1 mixes. Bentonite-2 being a high expansive soil, volume changes with pressure were found to be relatively higher compared to B1 mixes.

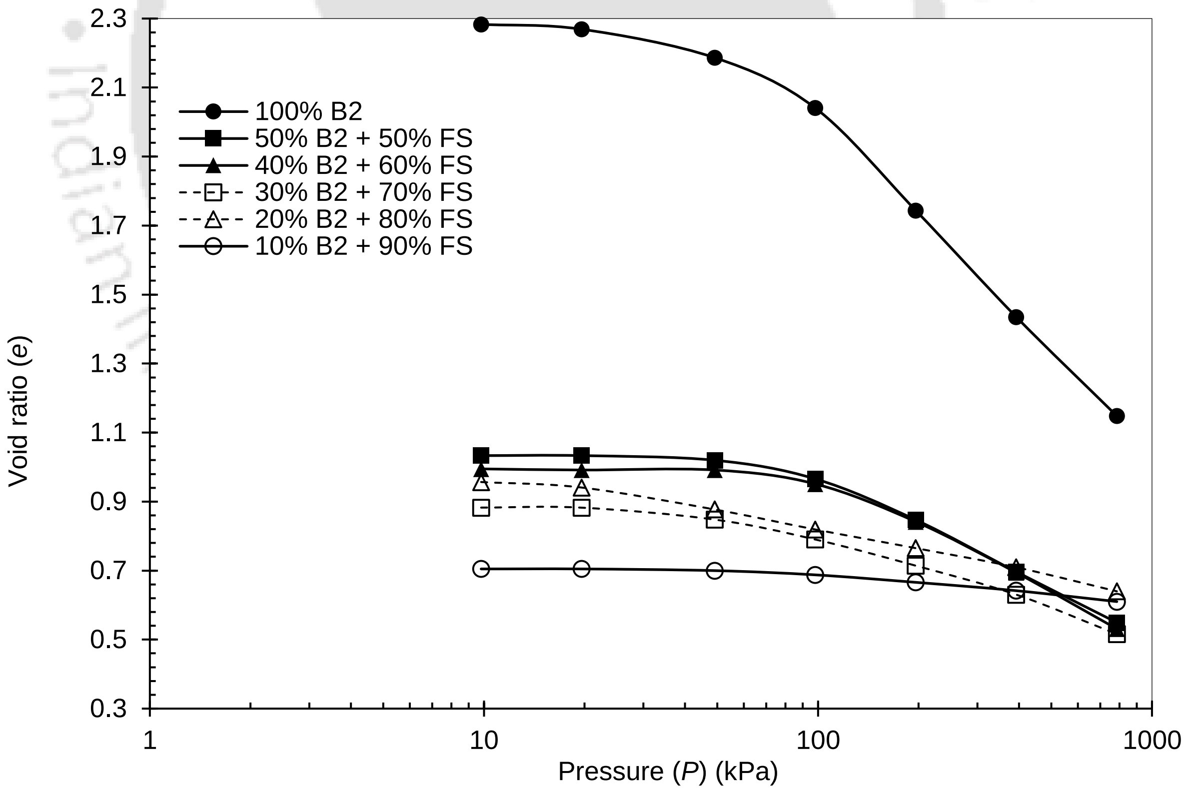


Figure 4.34 Effect of bentonite content on *e*-log *P* for FS-B2 samples compacted at 5% dry of OMC-MDD

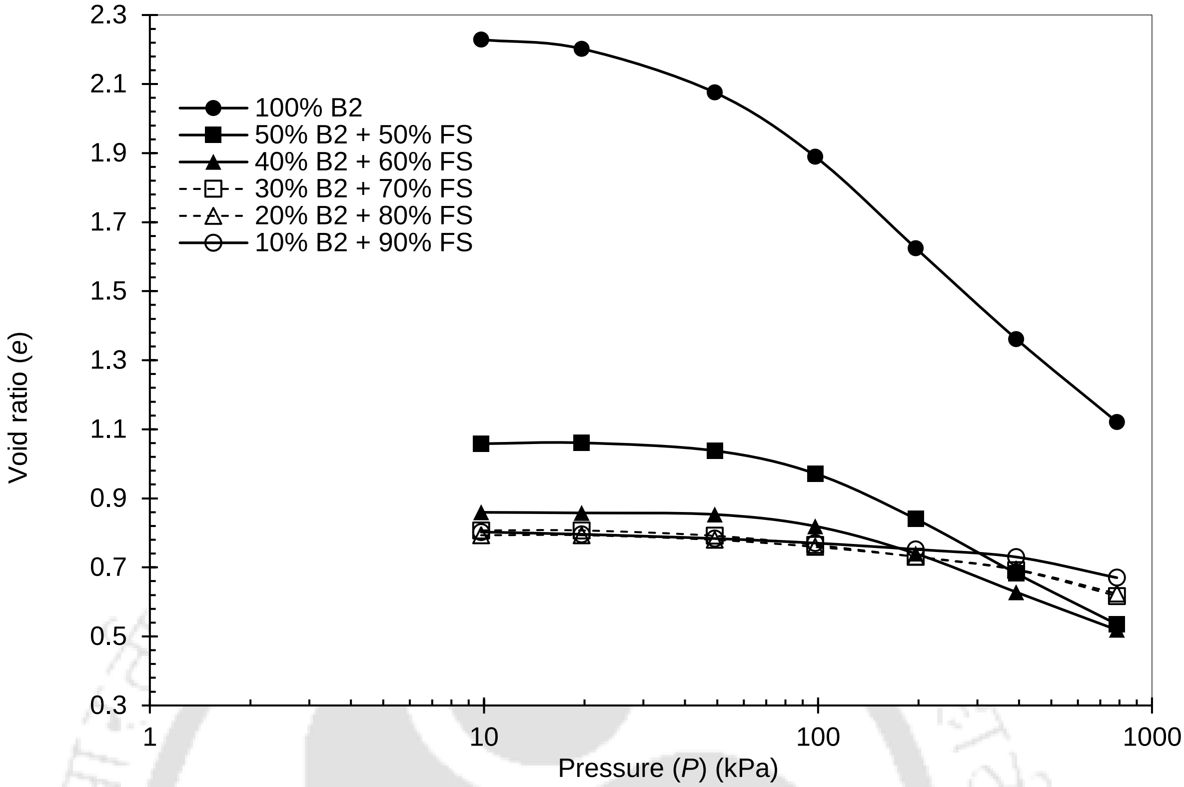


Figure 4.35 Effect of bentonite content on *e*-log *P* for FS-B2 samples compacted at OMC-MDD

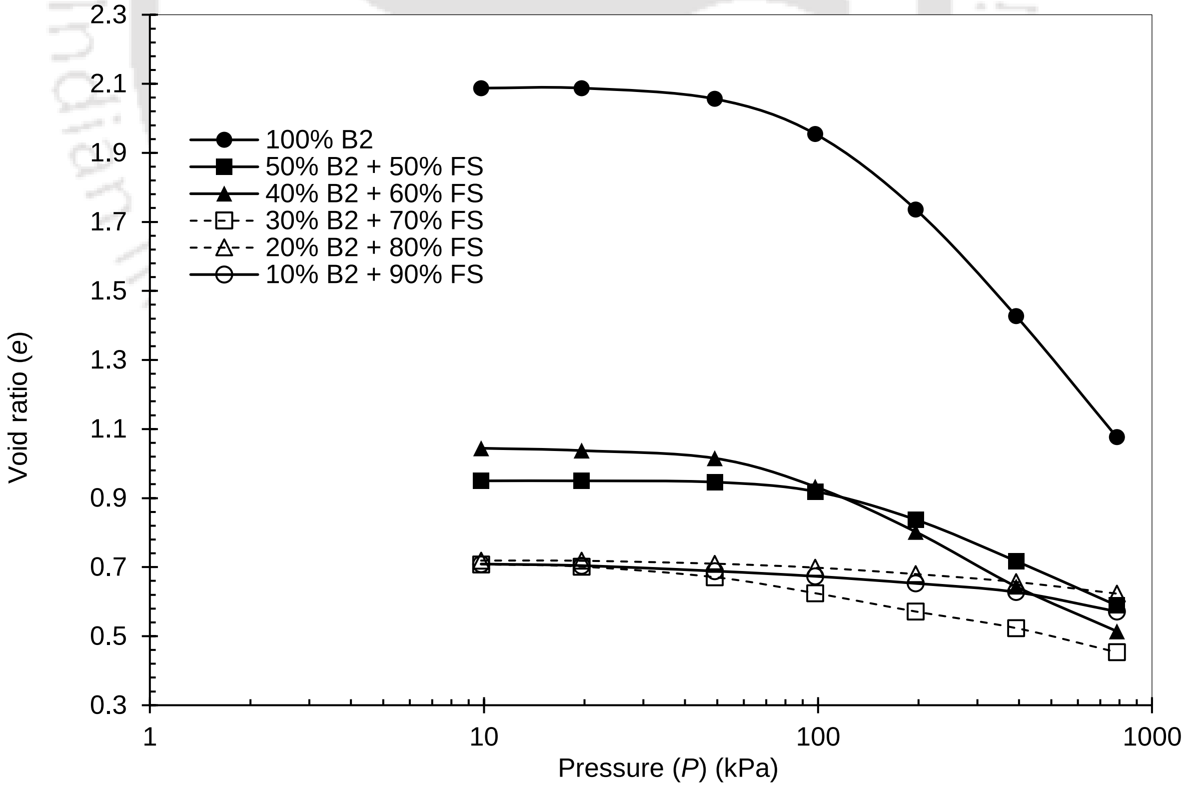


Figure 4.36 Effect of bentonite content on *e*-log *P* for FS-B2 samples compacted at 5% wet of OMC-MDD

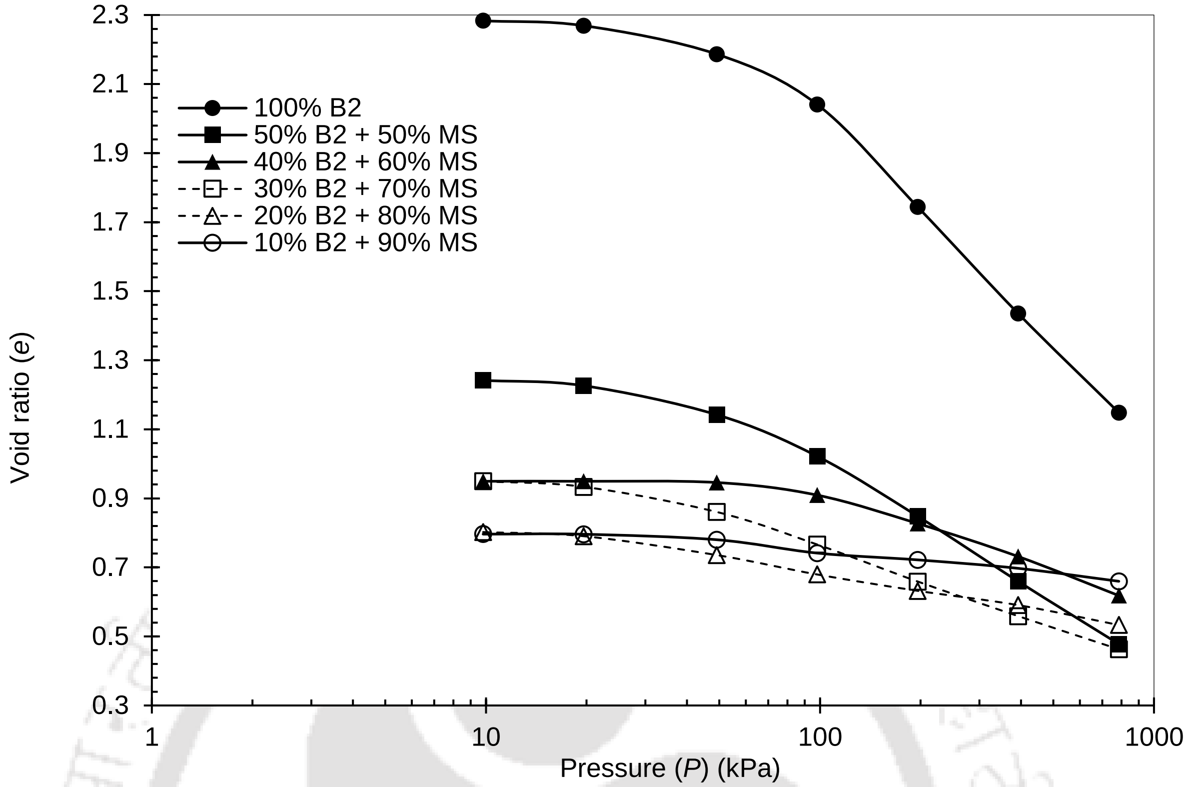


Figure 4.37 Effect of bentonite content on *e*-log *P* for MS-B2 samples compacted at 5% dry of OMC-MDD

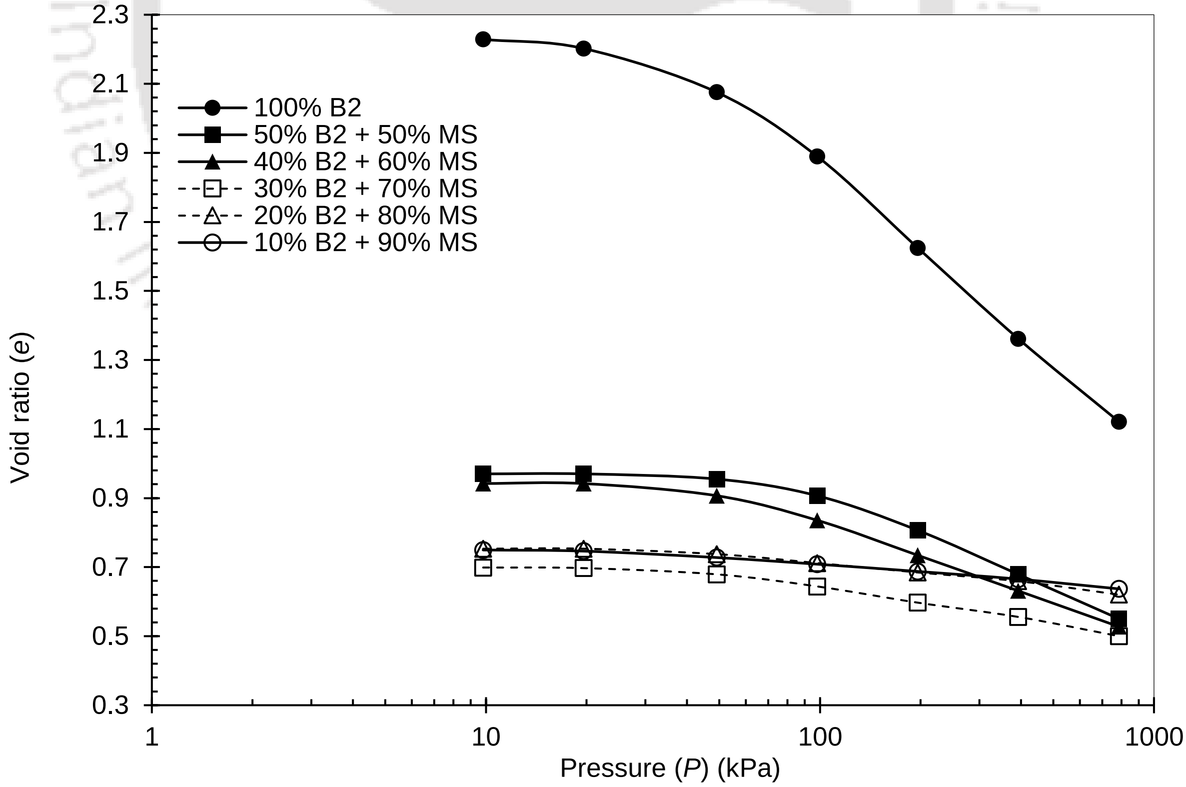


Figure 4.38 Effect of bentonite content on *e*-log *P* for MS-B2 samples compacted at OMC-MDD

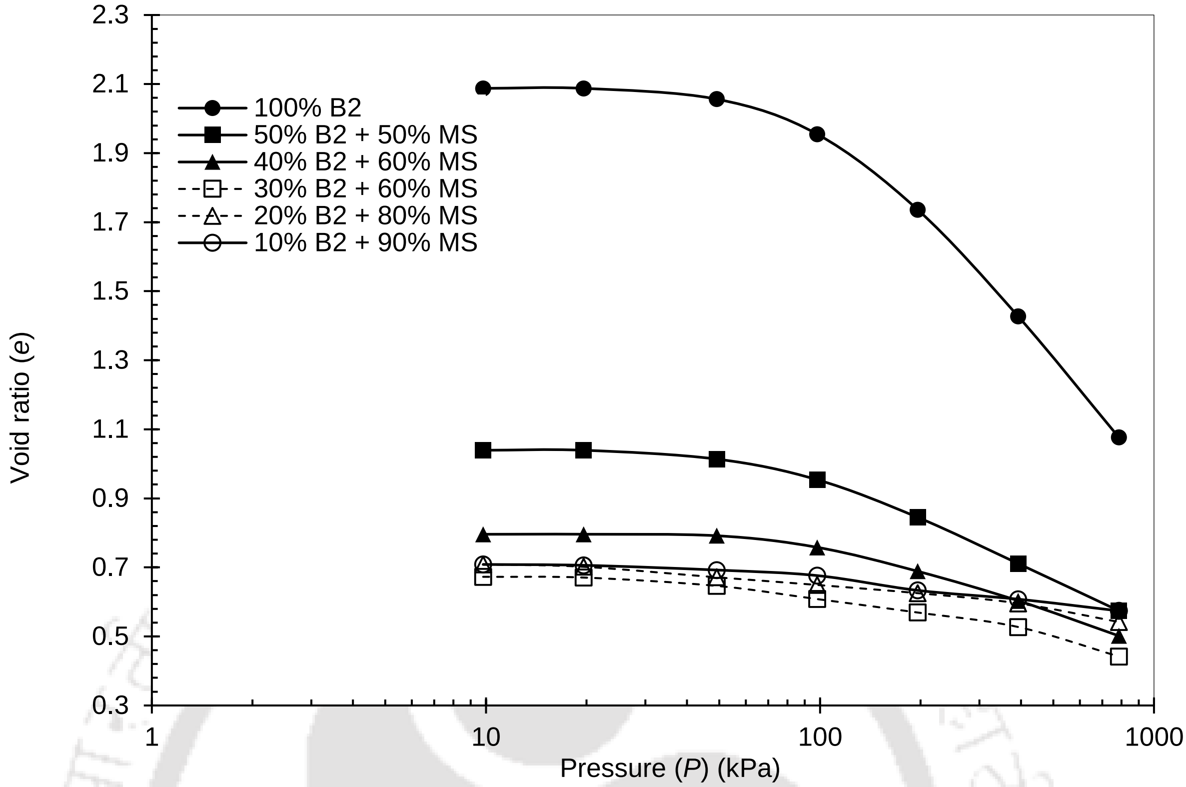


Figure 4.39 Effect of bentonite content on *e*-log *P* for MS-B2 samples compacted at 5% wet of OMC-MDD

4.1.3.6 Effect of bentonite content and initial compaction conditions on Coefficient of consolidation (c_v)-Pressure relationship for sand-bentonite mixes

Coefficient of consolidation is essentially an indicator of the rate of consolidation of soil sample and is dependent on the rate at which water can get out of the compacted sample for a given load increment. A higher value of c_v indicates a faster rate of consolidation. Coefficient of consolidation values were calculated using time for 90% consolidation for the subsequent pressure increments, i.e. 49 to 98, 98 to 196.1 kPa etc.

4.1.3.6.1 Effect of bentonite content and initial compaction conditions on c_v-Pressure relationship for FS-B1 and MS-B1 mixes

Coefficient of consolidation (c_v) - Pressure relationship exhibited by various FS-B1 mixes compacted at three different compaction conditions are represented in Figs. 4.40 through Figs. 4.42. Mixes with 50% bentonite content exhibited c_v values in the range of 5.2×10^{-8} to 3.3×10^{-9} m^2/s. Mixes with 40% bentonite content exhibited c_v values in the range of 2.1×10^{-7} to 7.3×10^{-9} m^2/s. Mixes with 30% bentonite content exhibited c_v values in the range of 1.0×10^{-6} to 2.9×10^{-8} m^2/s. Mixes with 20% bentonite content exhibited c_v values in the range of 1.4×10^{-6} to 3.3×10^{-7} m^2/s. Mixes with 10% bentonite content exhibited c_v values in the range of 7.8x10^{-6} to 5.9x10^{-6} m^2/s. With load increments c_v values were found to be fairly constant in case of mixtures with B1 content less than 20% and were found to be decreasing with load increment for mixtures with bentonite content more than 20%. With the increasing load, the voids and pathways in the compacted sample tend to collapse leading to a lower c_v value. When restricted by a surcharge pressure, bentonite particles in the FS-B1 mixture swell upon access to water resulting in blocking or partial blocking of pathways, which would result in a reduced flow rate. As bentonite content in the mixtures increases, the possibility of blocking the pathways also increases leading to much slower flow rates and the same is reflected as reduced c_v value with increasing bentonite content in the mixture. Effectiveness of compactive effort employed in making a compacted sample improves with increment in the initial mixing water content, as the clay particles in the mixture transform from flocculated structure to dispersed structure with increasing water content. As the effectiveness of compactive effort improves, voids and pathways formed in the compacted sample drastically reduce leading to a slower flow rate. It can be seen from the figures, FS-B1 mixtures compacted at 5% dry of OMC-MDD possess a flocculated structure and exhibited relatively higher c_v values, while mixtures compacted at 5% wet of OMC-MDD possessing a dispersed structure exhibited a relatively lower c_v values with those compacted at OMC-MDD being intermittent.

Coefficient of consolidation-Pressure relationship exhibited by various MS-B1 mixes compacted at three different compaction conditions are represented in Figs. 4.43 through Figs. 4.45. Mixes with 50% bentonite content exhibited c_v values in the range of 8.4x10^{-8} to 4.7x10^{-9} m^2/s. Mixes with 40% bentonite content exhibited c_v values in the range of 3.0x10^{-7} to 1.0x10^{-8} m^2/s. Mixes with 30% bentonite content exhibited c_v values in the range of 8.0x10^{-7} to 2.0x10^{-7} m^2/s. Mixes with 20% bentonite content exhibited c_v values in the range of 6.0x10^{-6} to 3.7x10^{-6} m^2/s. Mixes with 10% bentonite content exhibited c_v values in the range of 4.6x10^{-5} to 3.5x10^{-5} m^2/s. Trends similar to those observed with FS-B1 mixtures were observed. Medium sand with its relatively larger particle size is capable of forming larger void spaces and pathways, which the B1 in the mixtures occupies. Even though the voids deform and collapse under surcharge loading, the pathways available for flow to take place are relatively higher as compared to FS-B1 mixtures and hence, the c_v values exhibited are also relatively higher in case of MS-B1 mixtures.

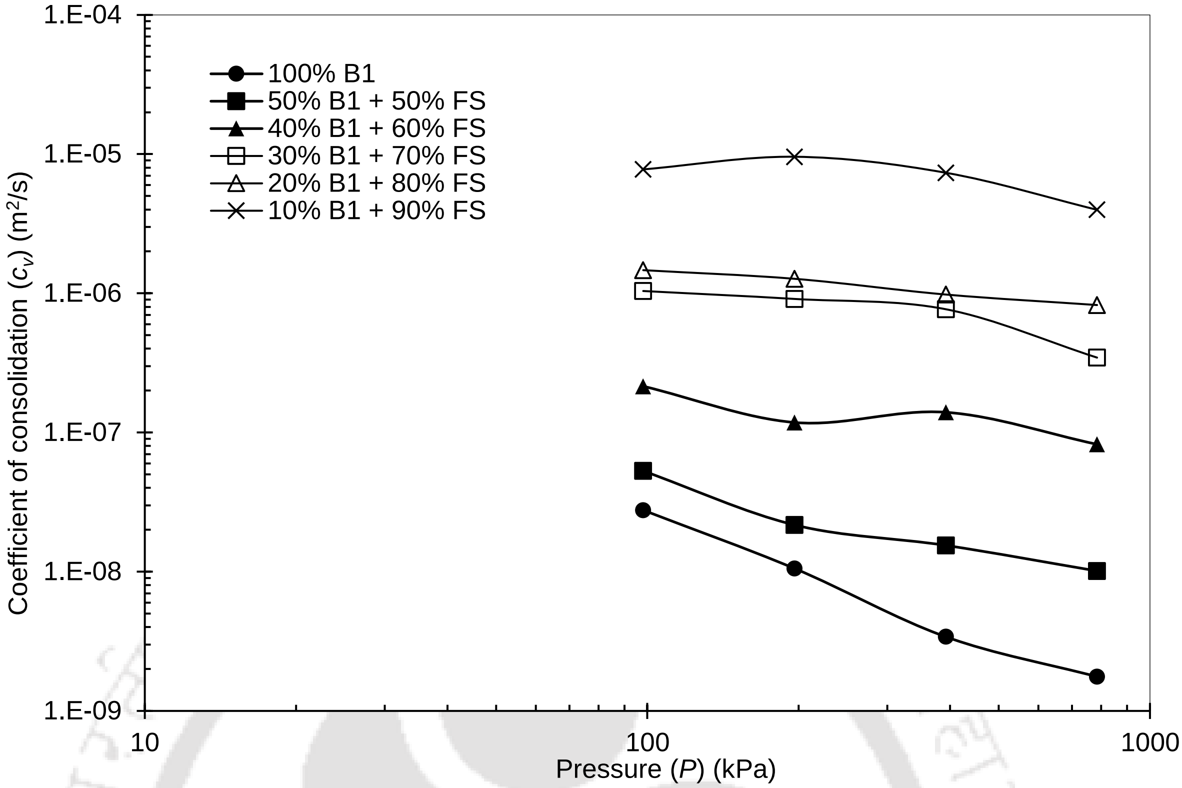


Figure 4.40 Effect of bentonite content on c_V-Pressure for FS-B1 samples compacted at 5% dry of OMC-MDD

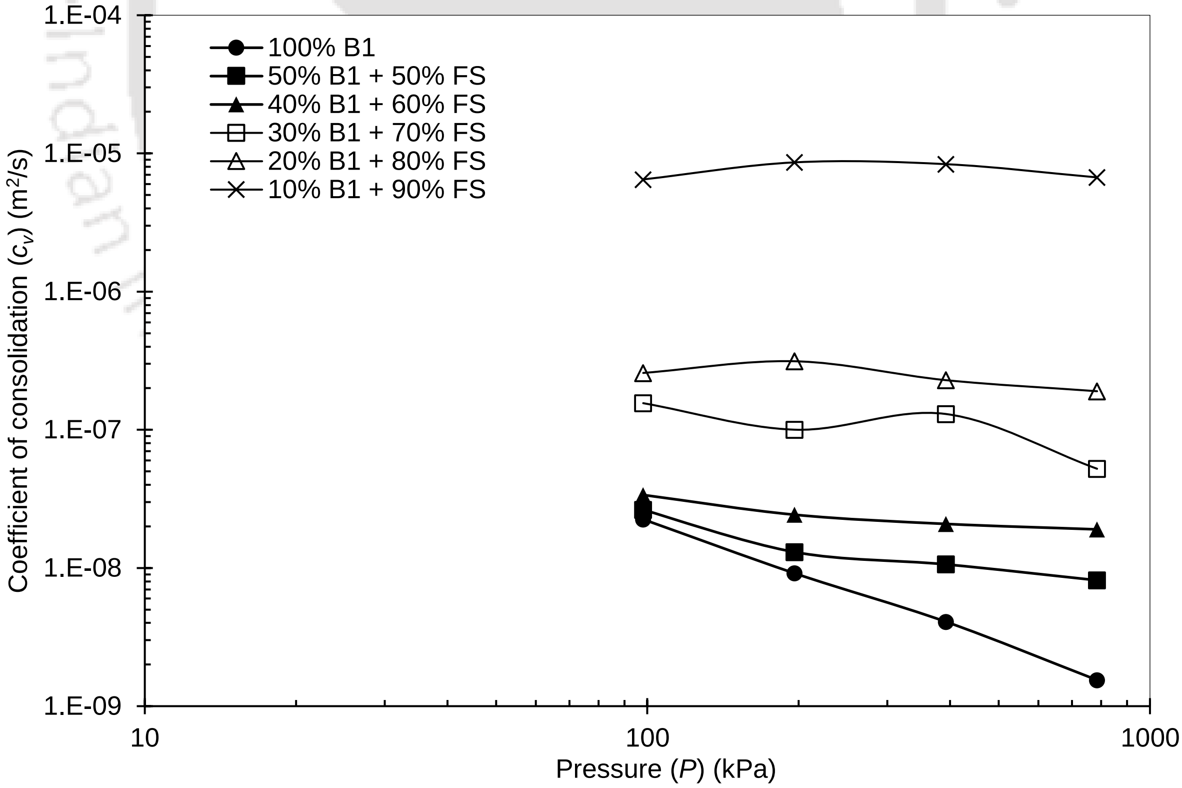


Figure 4.41 Effect of bentonite content on c_V-Pressure for FS-B1 samples compacted at OMC-MDD

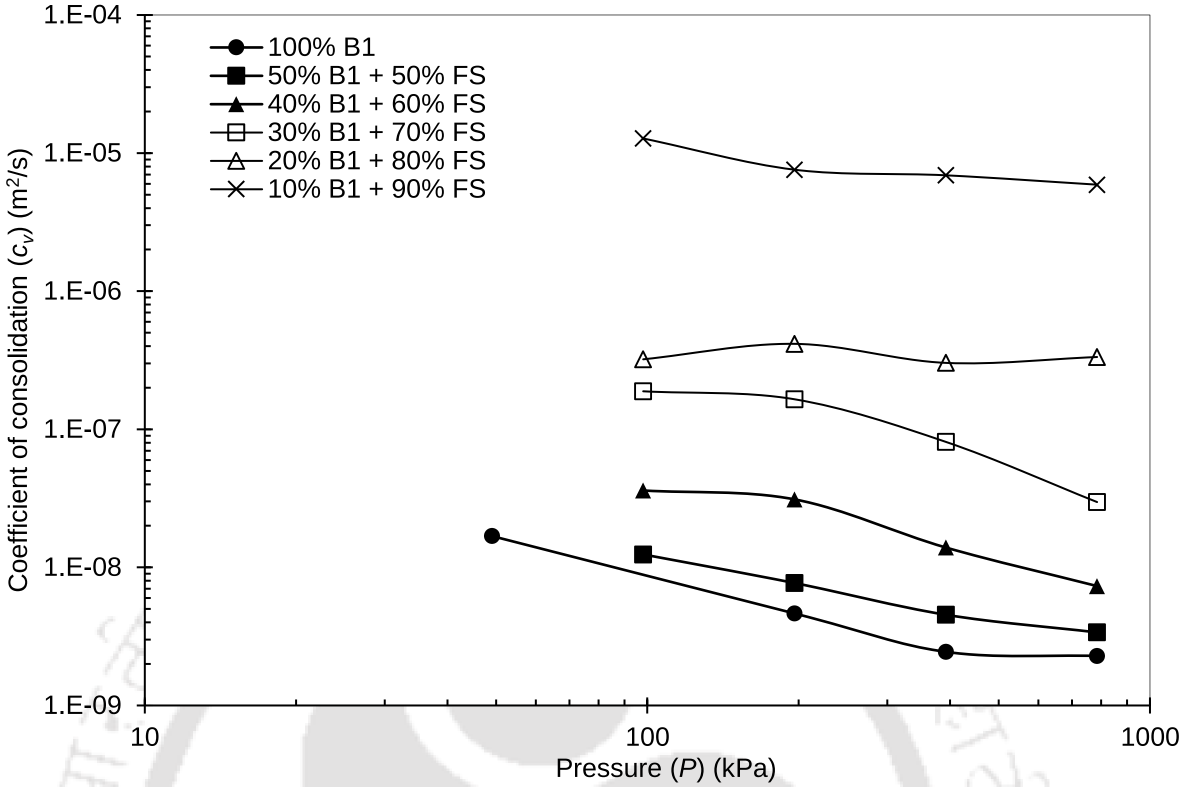


Figure 4.42 Effect of bentonite content on c_v-Pressure for FS-B1 samples compacted at 5% wet of OMC-MDD

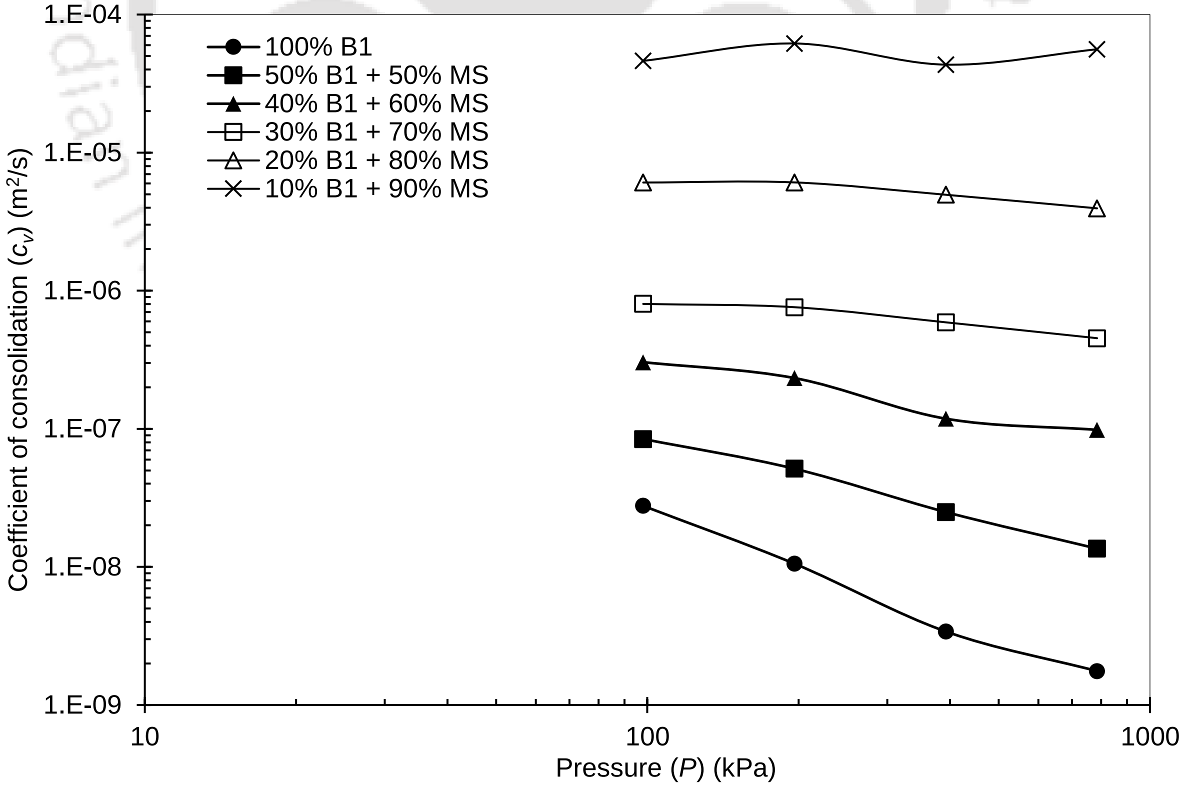


Figure 4.43 Effect of bentonite content on c_v-Pressure for MS-B1 samples compacted at 5% dry of OMC-MDD

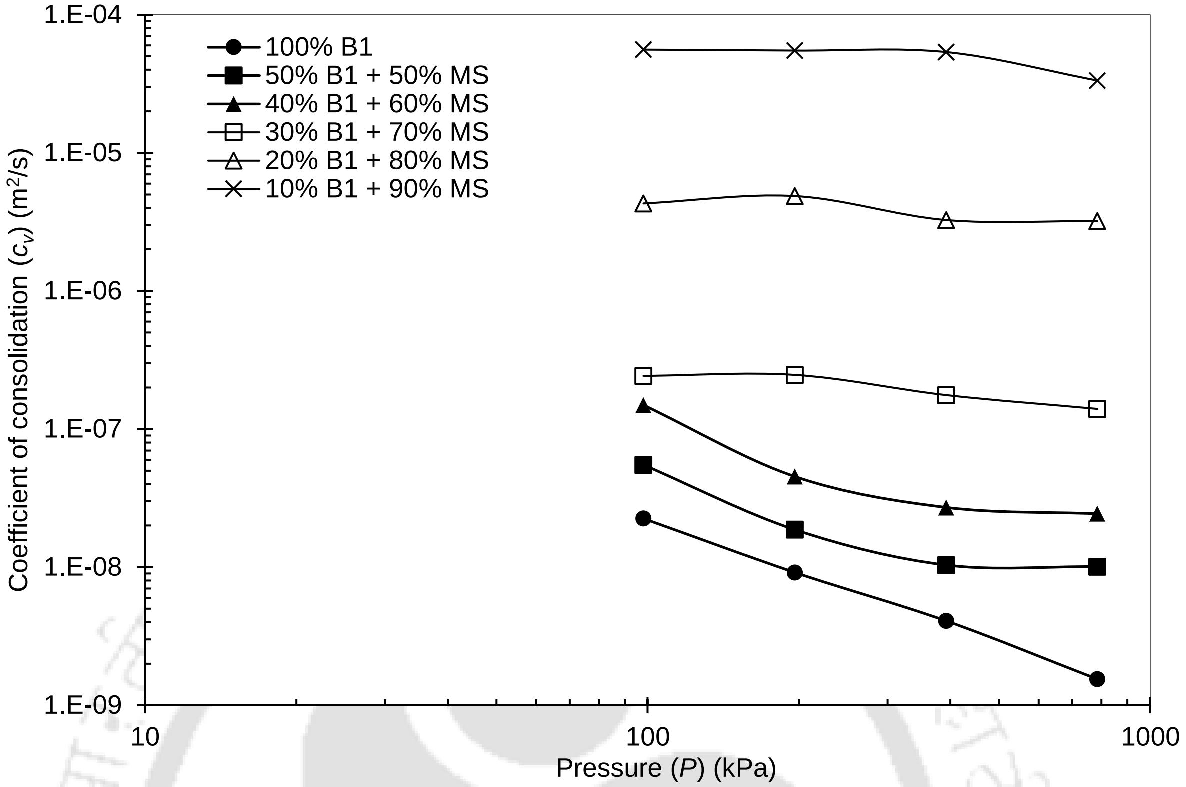


Figure 4.44 Effect of bentonite content on c_v-Pressure for MS-B1 samples compacted at OMC-MDD

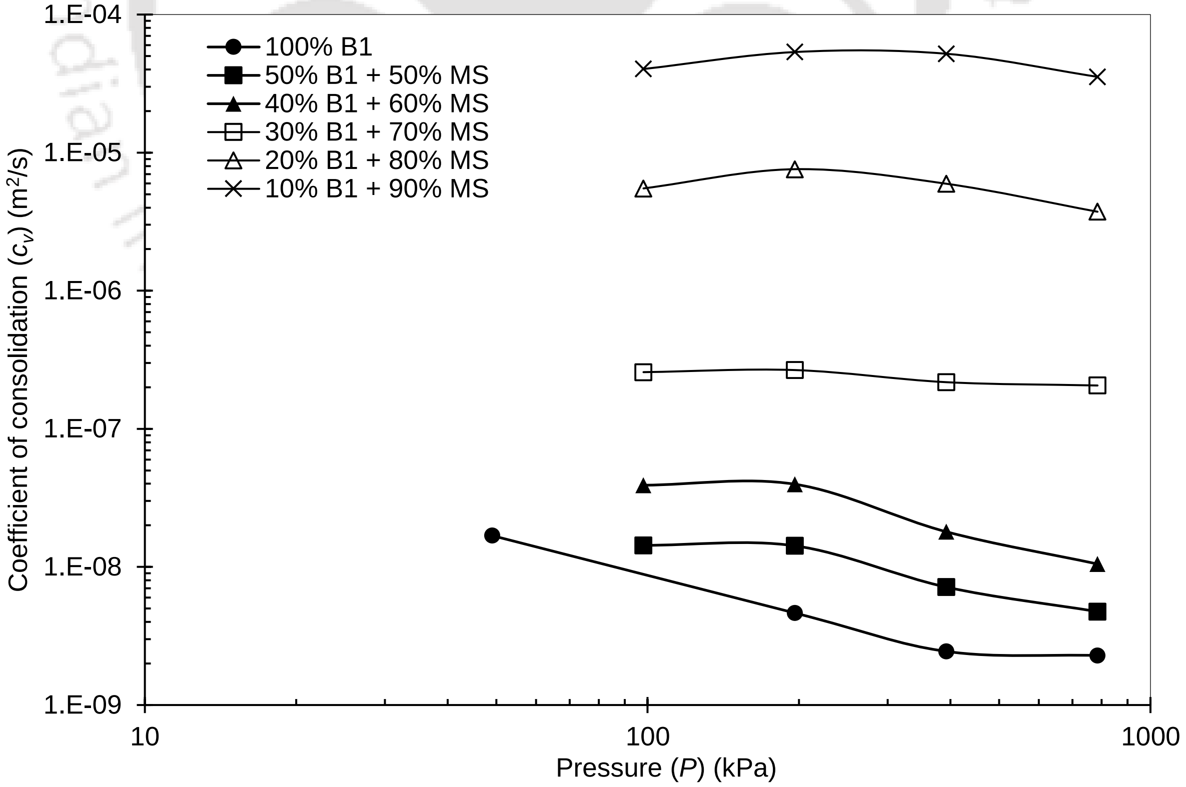


Figure 4.45 Effect of bentonite content on c_v-Pressure for MS-B1 samples compacted at 5% wet of OMC-MDD

Mixes with 100% B1 exhibited lower c_v values compared to other sand-bentonite proportions. Mixes with 100% bentonite content exhibited c_v values in the range of 2.8×10^{-8} to 1.5×10^{-9} m^2/s. Availability of relatively higher amounts of swelling clay minerals combined with relatively smaller particle sizes and associated voids are the possible reasons for relatively lower c_v values.

4.1.3.6.2 Effect of bentonite content and initial compaction conditions on c_v-Pressure relationship for FS-B2 and MS-B2 mixes

Coefficient of consolidation - Pressure relationship exhibited by different FS-B2 mixes and MS-B2 mixes compacted at three different compaction conditions are represented in Figs. 4.46 through Figs. 4.51. Fine sand mixes with 50% bentonite content exhibited c_v values in the range of 8.5×10^{-9} to 1.3×10^{-9} m^2/s. Fine sand mixes with 40% bentonite content exhibited c_v values in the range of 2.0×10^{-8} to 2.8×10^{-9} m^2/s. Fine sand mixes with 30% bentonite content exhibited c_v values in the range of 4.4×10^{-8} to 6.5×10^{-9} m^2/s. Fine sand mixes with 20% bentonite content exhibited c_v values in the range of 8.1×10^{-8} to 4.3×10^{-8} m^2/s. Fine sand mixes with 10% bentonite content exhibited c_v values in the range of 4.6×10^{-6} to 2.1×10^{-6} m^2/s.

Medium sand mixes with 50% bentonite content exhibited c_v values in the range of 4.8×10^{-9} to 1.9×10^{-9} m^2/s. Medium sand mixes with 40% bentonite content exhibited c_v values in the range of 1.8×10^{-8} to 2.9×10^{-9} m^2/s. Medium sand mixes with 30% bentonite content exhibited c_v values in the range of 4.1×10^{-8} to 7.7×10^{-9} m^2/s. Medium sand mixes with 20% bentonite content exhibited c_v values in the range of 1.5×10^{-7} to 6.0×10^{-8} m^2/s. Medium sand mixes with 10% bentonite content exhibited c_v values in the range of 4.8×10^{-6} to 3.0×10^{-6} m^2/s. Upon comparing the influence of bentonite content and initial compaction conditions on coefficient of consolidation-pressure relationship, trends exhibited by sand-bentonite-2 mixtures was observed to be similar to those of sand-bentonite-1 mixtures. The higher swelling nature of B2 present in FS-B2 and MS-B2 mixtures helps in filling the voids in a much efficient manner compared to B1. The better filling of voids is in turn reflected as reduced pathways for water flow to take place leading to a relatively lower c_v values.

Mixes with 100% B2 exhibited lower c_v values compared to other sand-bentonite proportions for all compaction conditions. Mixes with 100% bentonite content exhibited c_v values in the range of 3.4×10^{-9} to 1.0×10^{-9} m^2/s. Influence of relatively higher swelling nature of B2 as compared to B1 is reflected in the much lower c_v values.

An attempt was made to highlight the role and the extent to which particle size of sand could influence the coefficient of consolidation of sand-bentonite mixtures, while doing so, influence of a host of other parameters (namely compaction condition, bentonite proportion and quality) on coefficient of consolidation is also verified and the same can be seen in Figs. 4.52 through Figs. 4.57. Influence of sand type can be seen in mixtures with B1 content less than 30%, with FS-B1 mixes exhibiting lower c_v values for all compaction conditions and both pressure increments. As the B1 content increased from 30% to 50%, the difference in c_v values became nominal. In case of FS-B2 and MS-B2 mixes, mixes exhibited almost similar trends for all compaction conditions and both pressure increments, relative difference in c_v values observed can be considered as negligible for all practical purposes. Upon comparing FS-B1, MS-B1, FS-B2 and MS-B2 mixes with different compaction conditions and bentonite proportions, it can be concluded that the influence of sand particle size was observed in mixes with low swelling bentonite and that too in the mixes with lower bentonite contents.

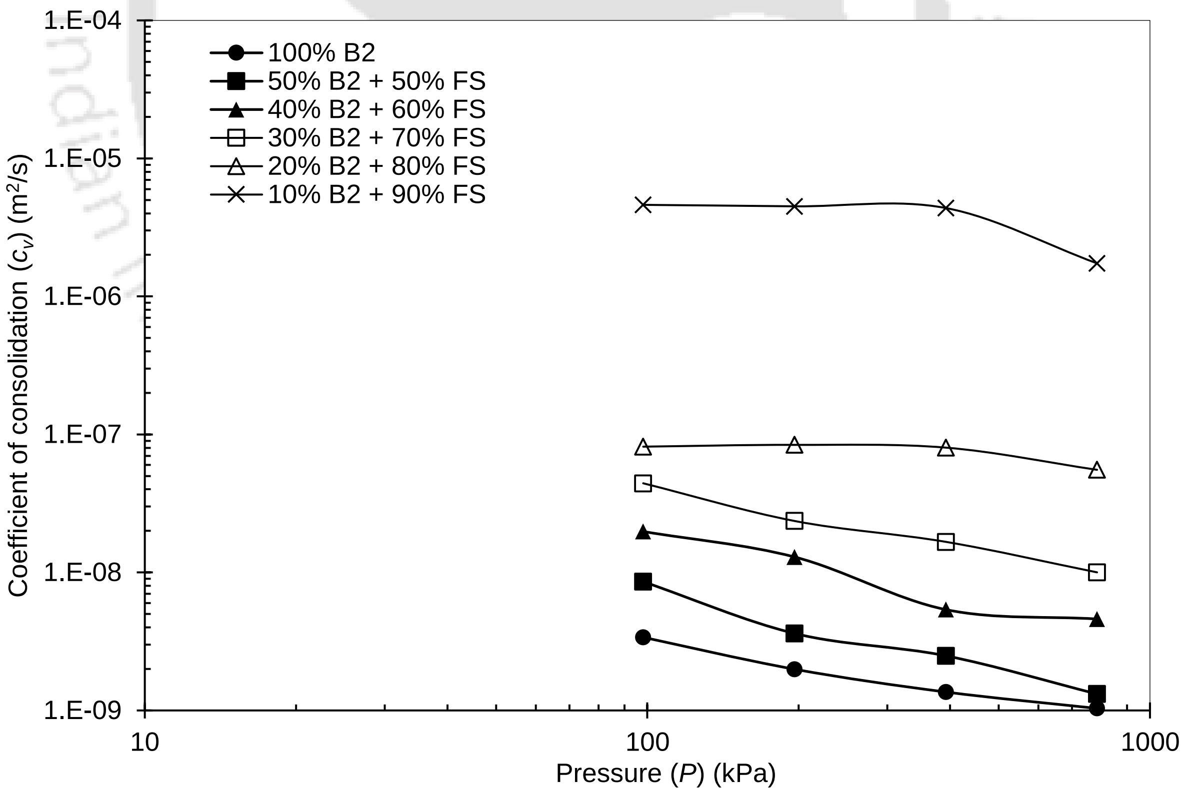


Figure 4.46 Effect of bentonite content on c_v-Pressure for FS-B2 samples compacted at 5% dry of OMC-MDD

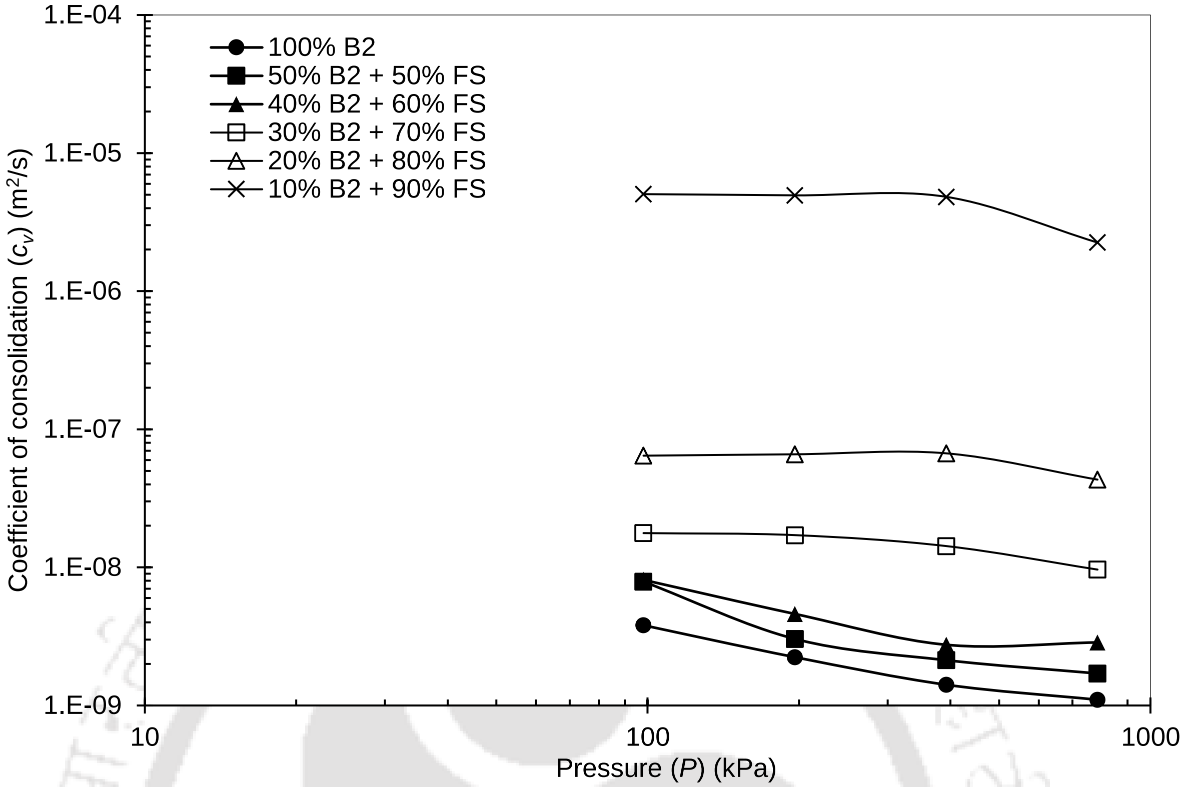


Figure 4.47 Effect of bentonite content on c_V-Pressure for FS-B2 samples compacted at OMC-MDD

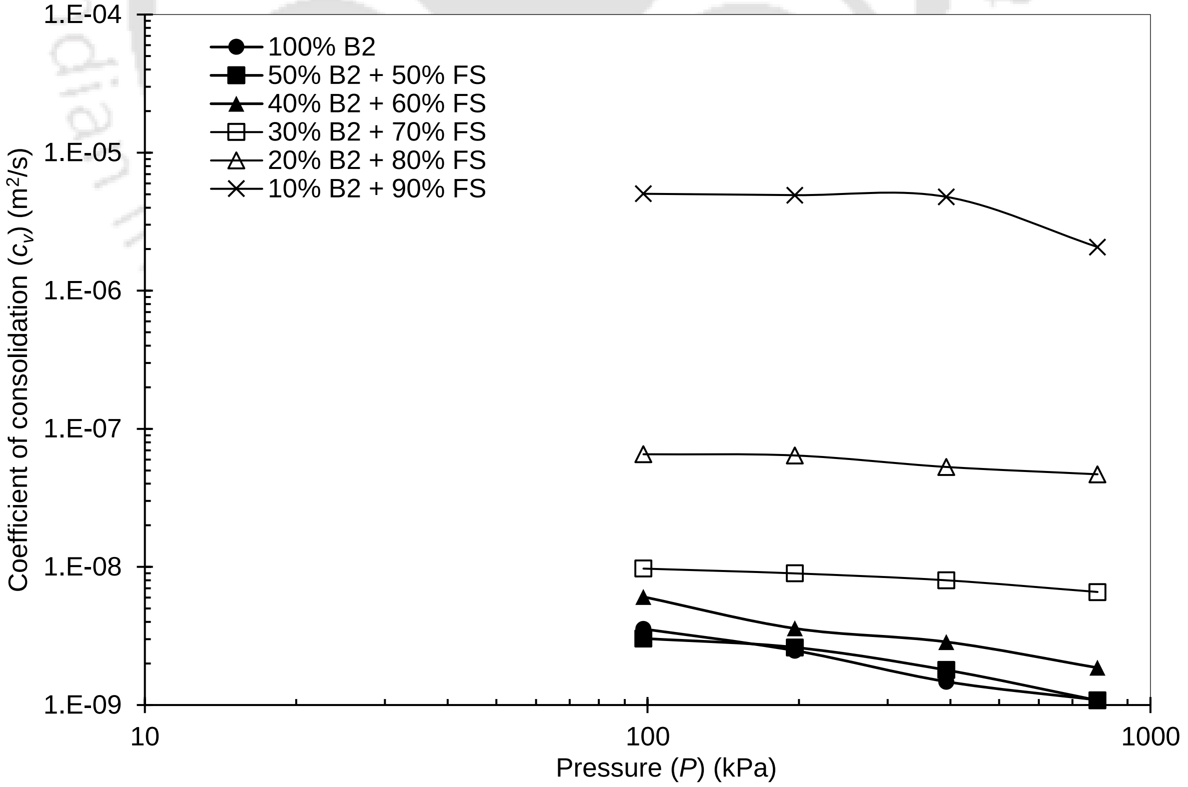


Figure 4.48 Effect of bentonite content on c_V-Pressure for FS-B2 samples compacted at 5% wet of OMC-MDD

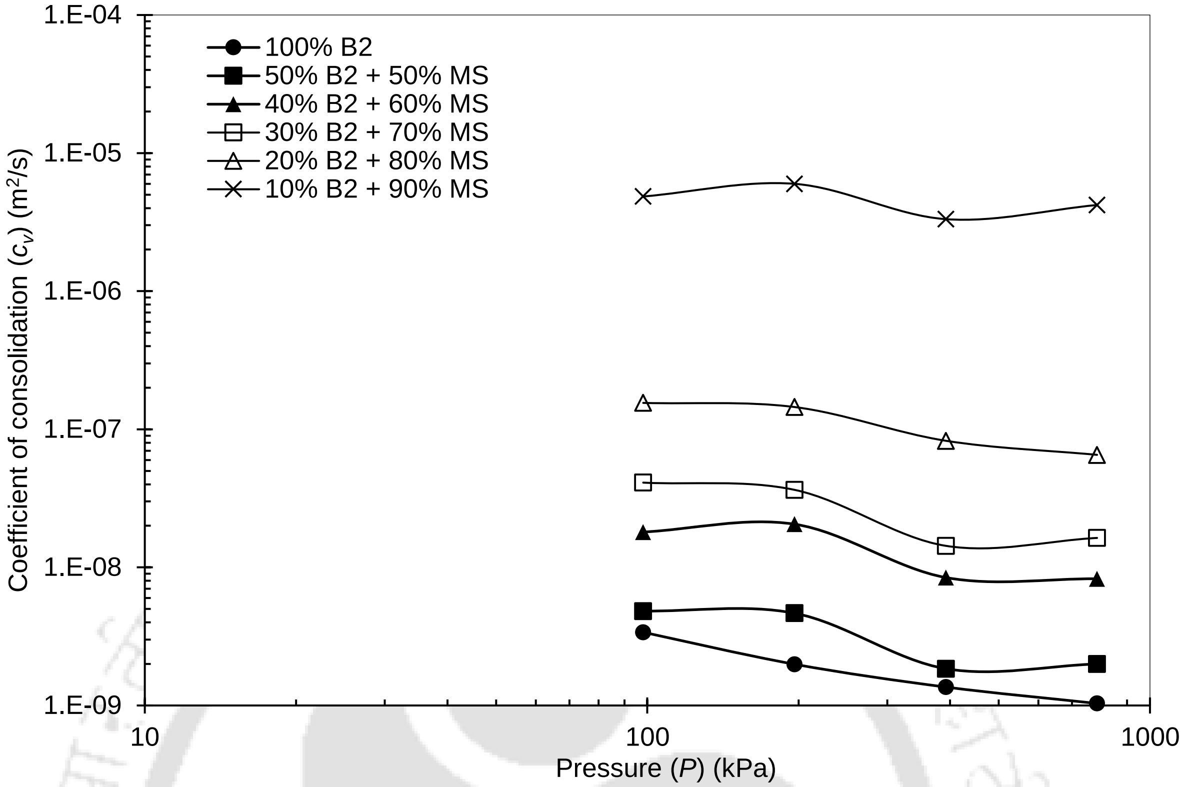


Figure 4.49 Effect of bentonite content on c_v-Pressure for MS-B2 samples compacted at 5% dry of OMC-MDD

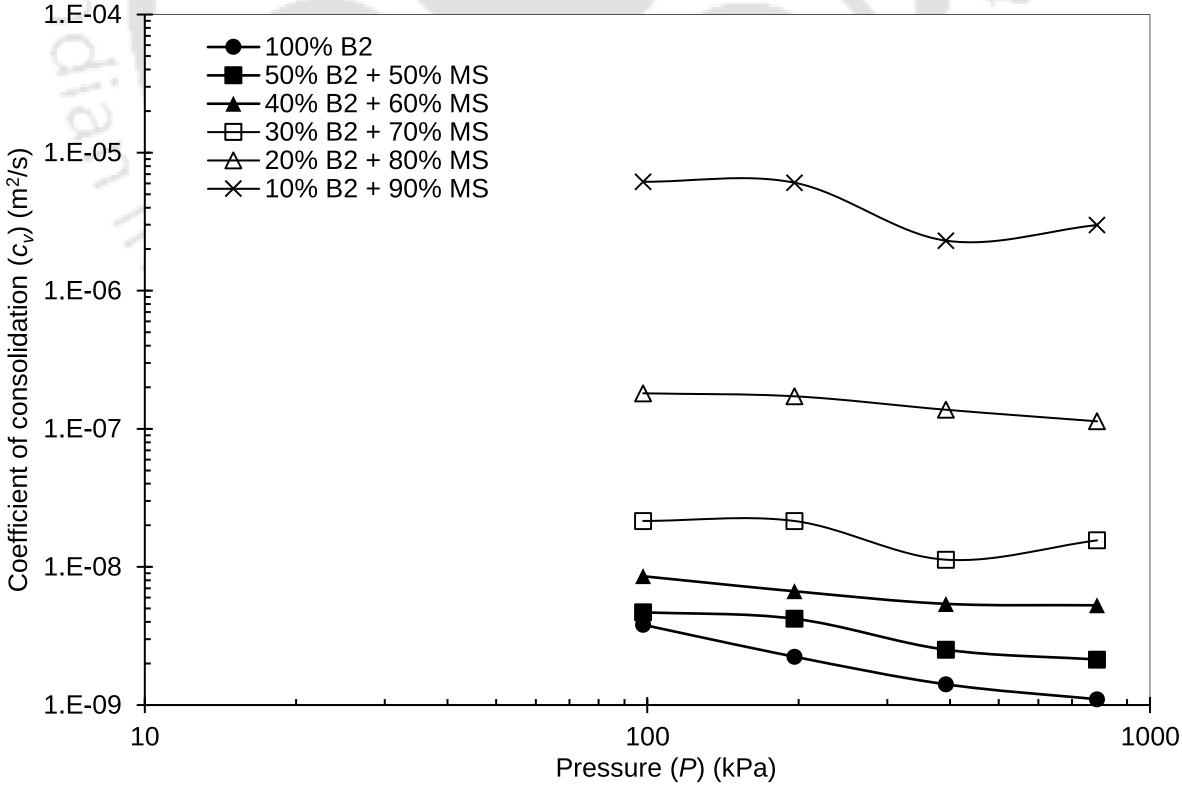


Figure 4.50 Effect of bentonite content on c_v-Pressure for MS-B2 samples compacted at OMC-MDD

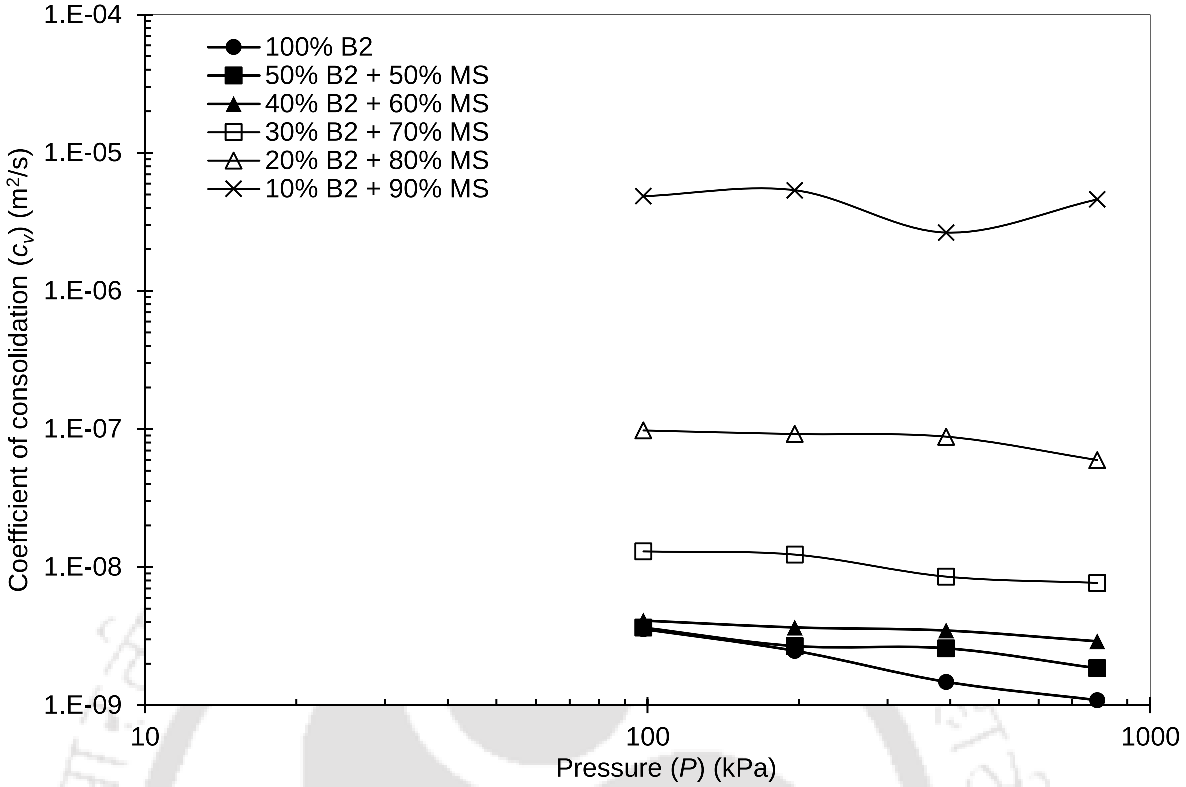


Figure 4.51 Effect of bentonite content on c_v-Pressure for MS-B2 samples compacted at 5% wet of OMC-MDD

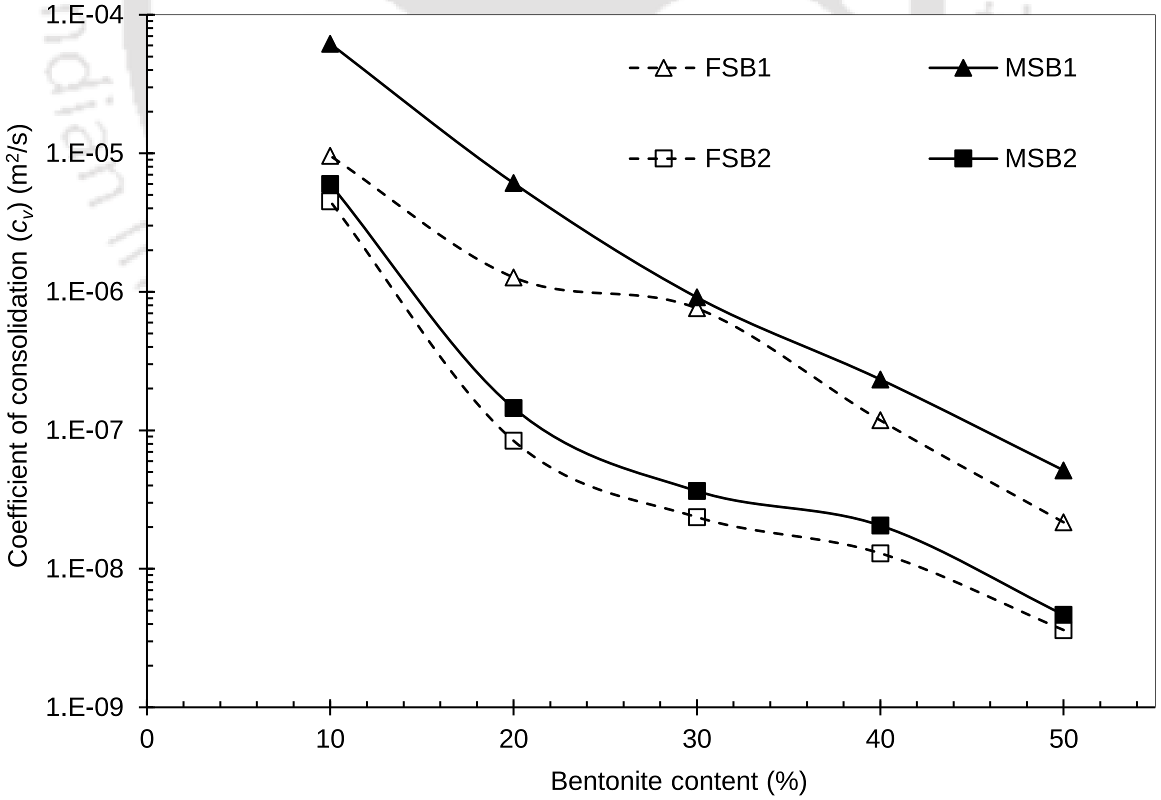


Figure 4.52 Effect of bentonite content on Coefficient of consolidation for sand-bentonite mixtures compacted at 5% dry of OMC-MDD, under a load of 196.2 kPa

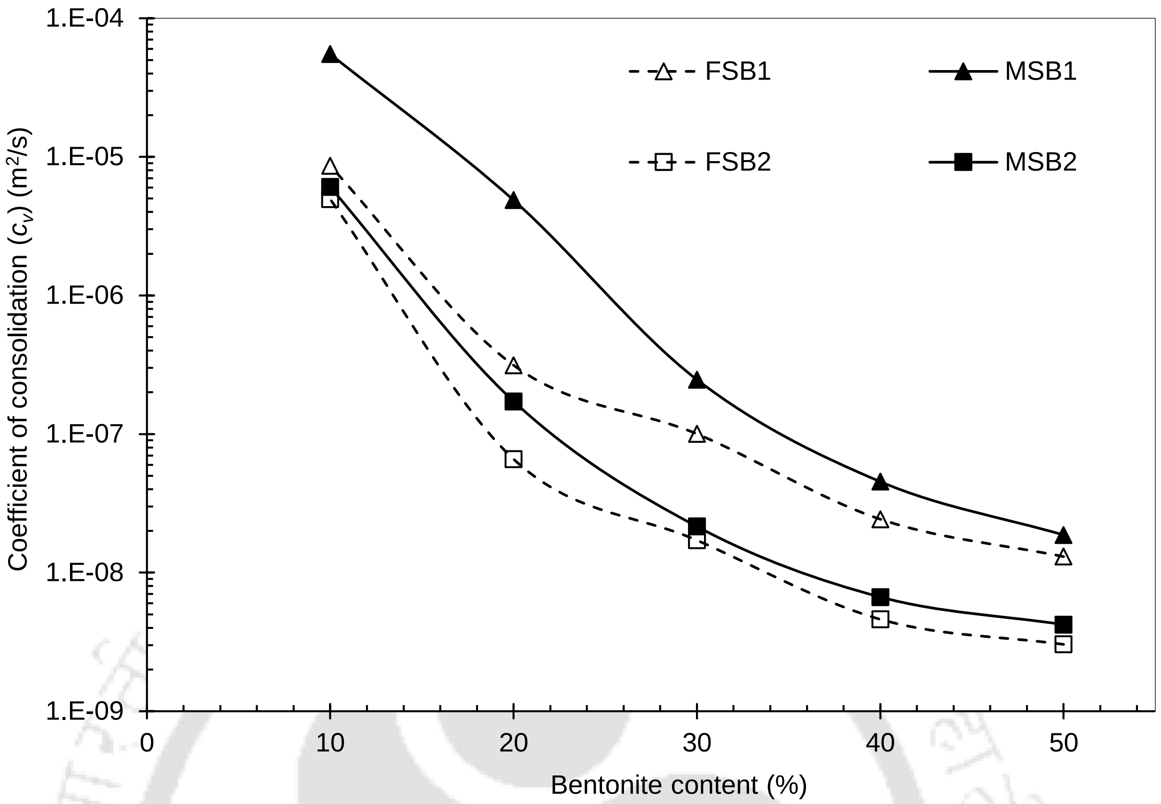


Figure 4.53 Effect of bentonite content on coefficient of consolidation for sand-bentonite mixtures compacted at OMC-MDD, under a load of 196.2 kPa

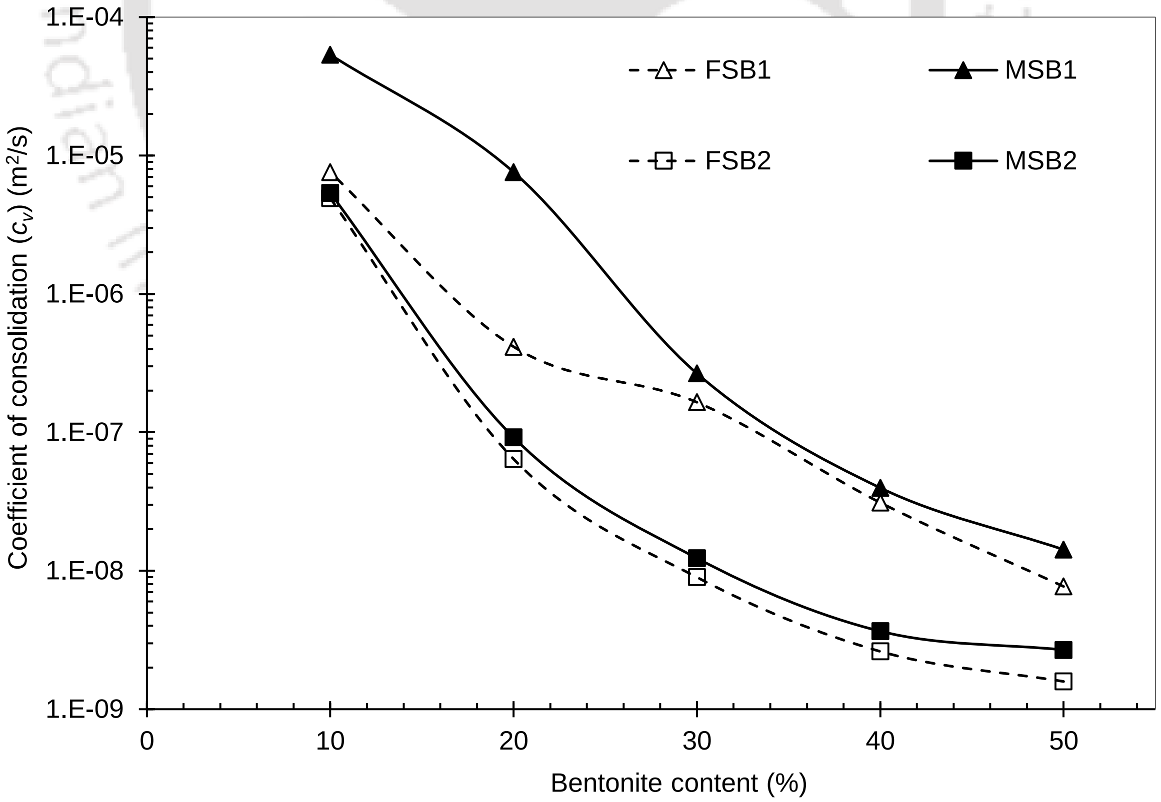


Figure 4.54 Effect of bentonite content on coefficient of consolidation for sand-bentonite mixtures compacted at 5% wet of OMC-MDD, under a load of 196.2 kPa

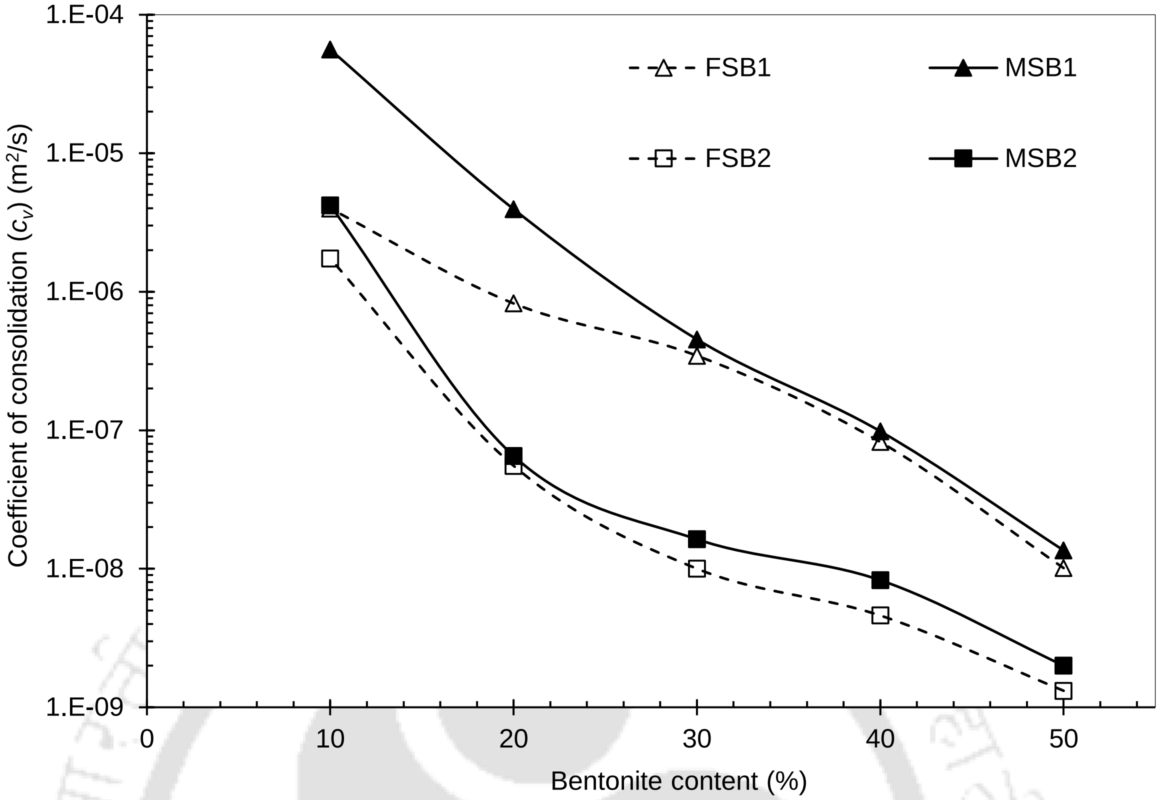


Figure 4.55 Effect of bentonite content on coefficient of consolidation for sand-bentonite mixtures compacted at 5% dry of OMC-MDD, under a load of 784.8 kPa

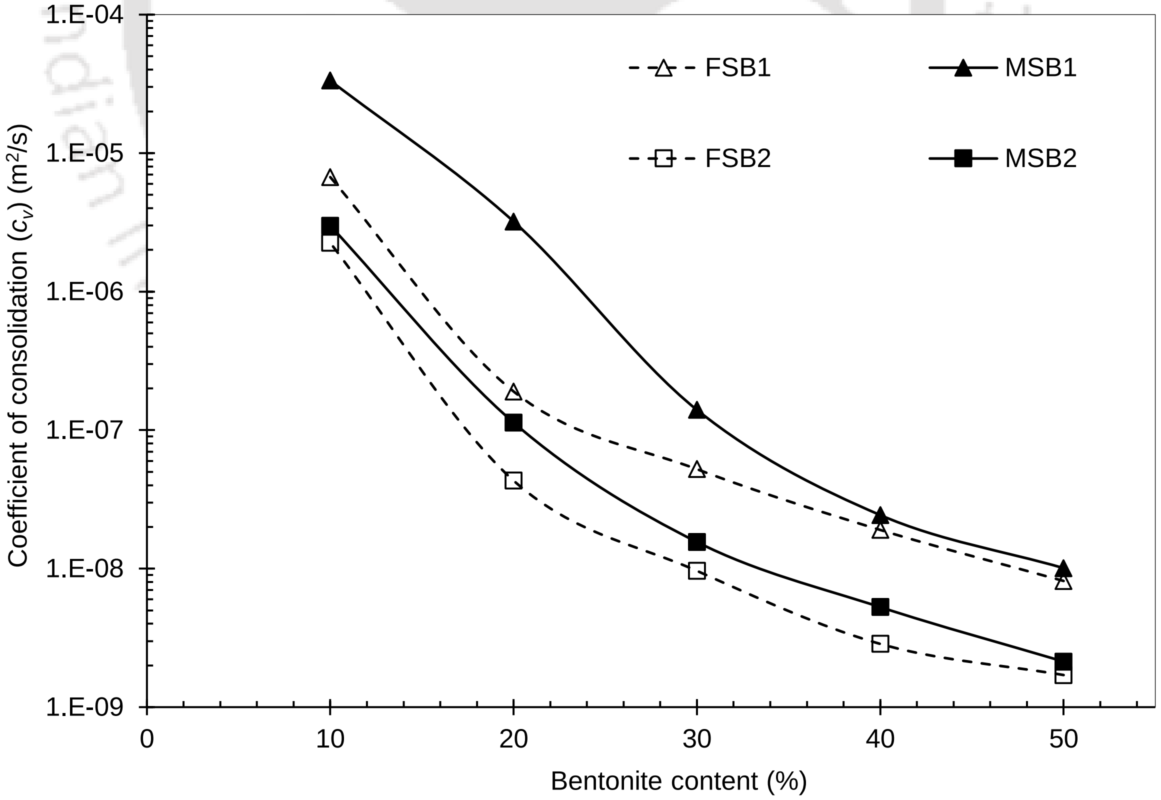


Figure 4.56 Effect of bentonite content on coefficient of consolidation for sand-bentonite mixtures compacted at OMC-MDD, under a load of 784.8 kPa

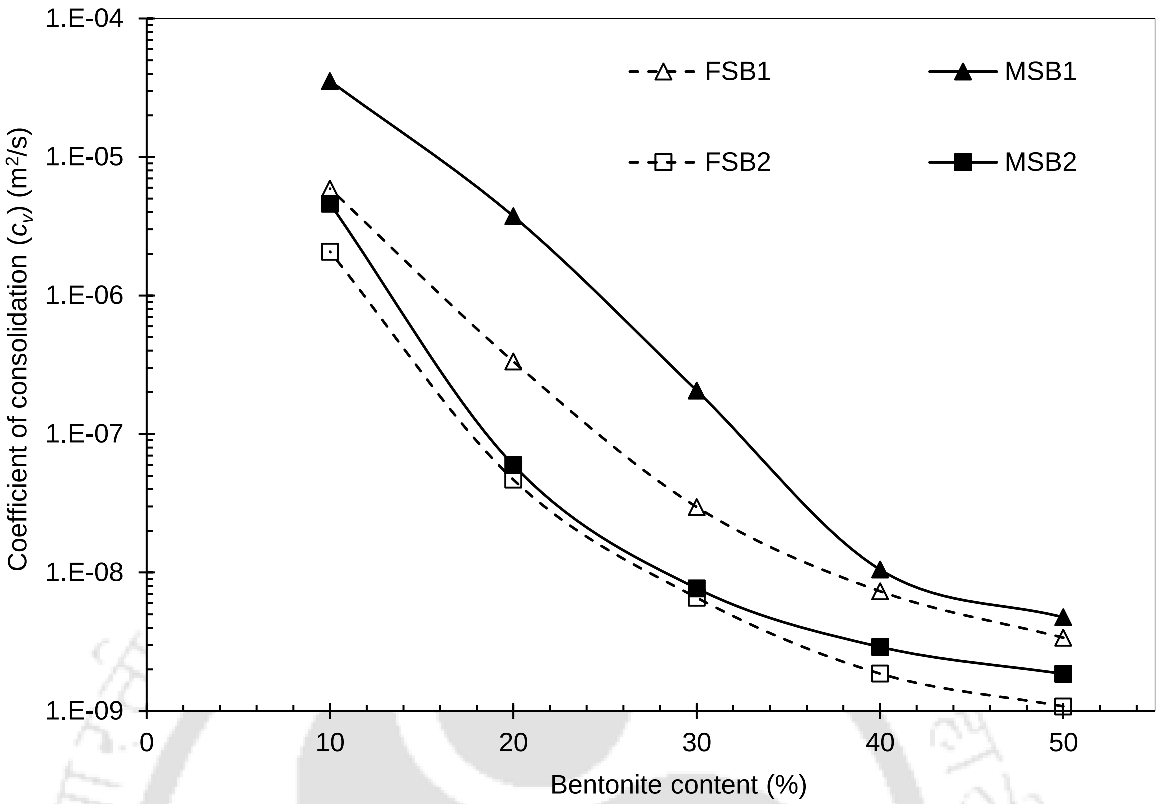


Figure 4.57 Effect of bentonite content on coefficient of consolidation for sand-bentonite mixtures compacted at 5% wet of OMC-MDD, under a load of 784.8 kPa

4.1.3.7 Effect of bentonite content and initial compaction conditions on Coefficient of volume change (m_v)-Pressure relationship for various sand-bentonite mixes

4.1.3.7.1 Effect of bentonite content and initial compaction conditions on m_v-Pressure relationship for FS-B1 and MS-B1 mixes

Coefficient of volume change (m_v) is defined as the volume change per unit volume per unit increase in load and it depends on the range of stress over which it is determined. Influence of bentonite content, initial compaction conditions, sand type on the compressibility behavior of FS-B1 and MS-B1 mixes is presented in Figs. 4.58 through Figs. 4.63. Irrespective of initial compaction conditions, sand type and content used in the mixture, with load increment, the m_v were seen to be decreasing with increasing overburden pressure. For a given load increment, as the bentonite content of mixture is increasing m_v values were seen to be increasing. For both FS-B1 and MS-B1 mixtures, mixtures with B1 content less than or equal to 30% exhibited a much lower m_v values compared to mixes with 40% and 50% indicating a shift in load carrying mechanism.

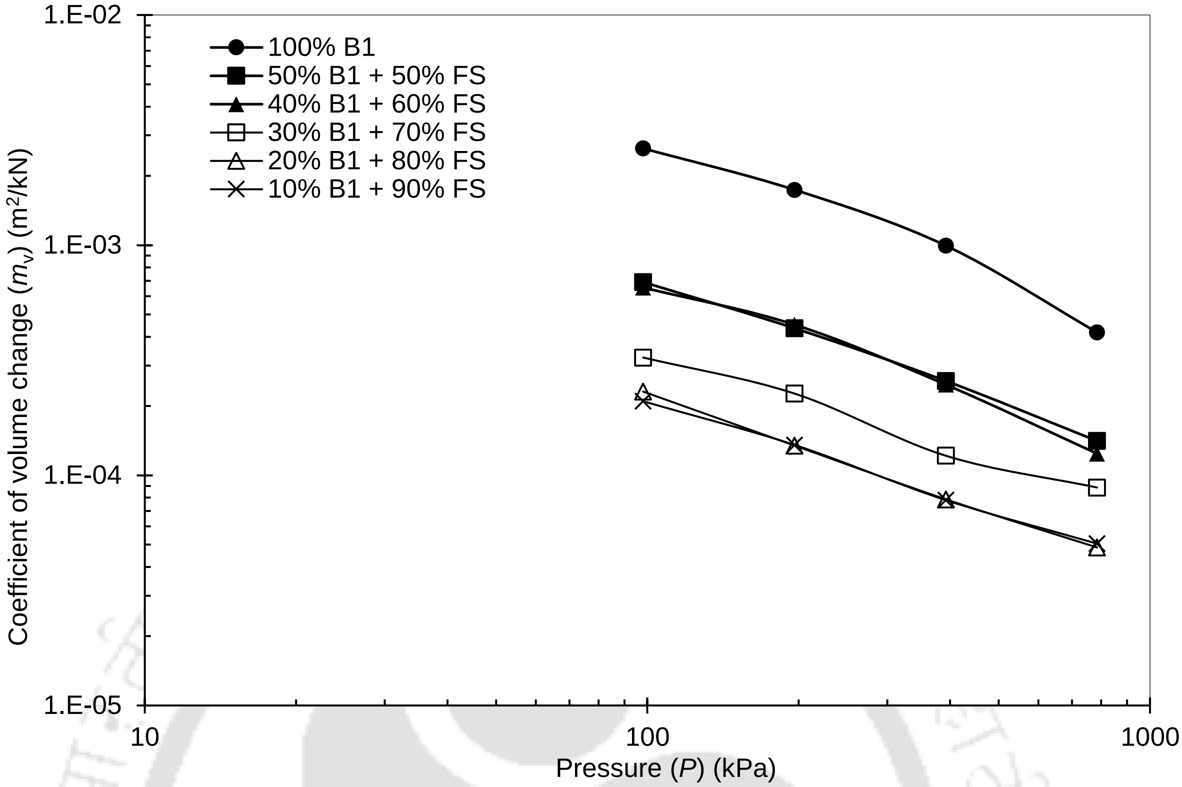


Figure 4.58 Effect of bentonite content on m_v-Pressure for FS-B1 samples compacted at 5% dry of OMC-MDD

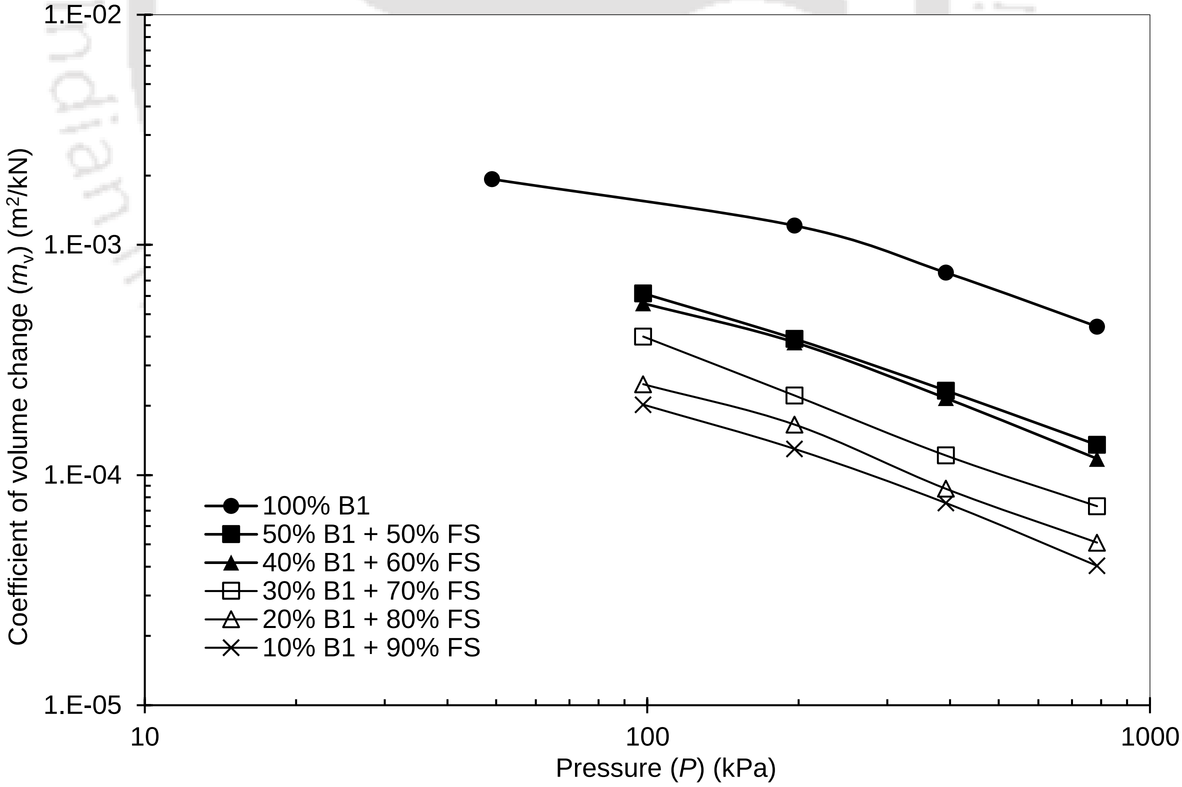


Figure 4.59 Effect of bentonite content on m_v-Pressure for FS-B1 samples compacted at OMC-MDD

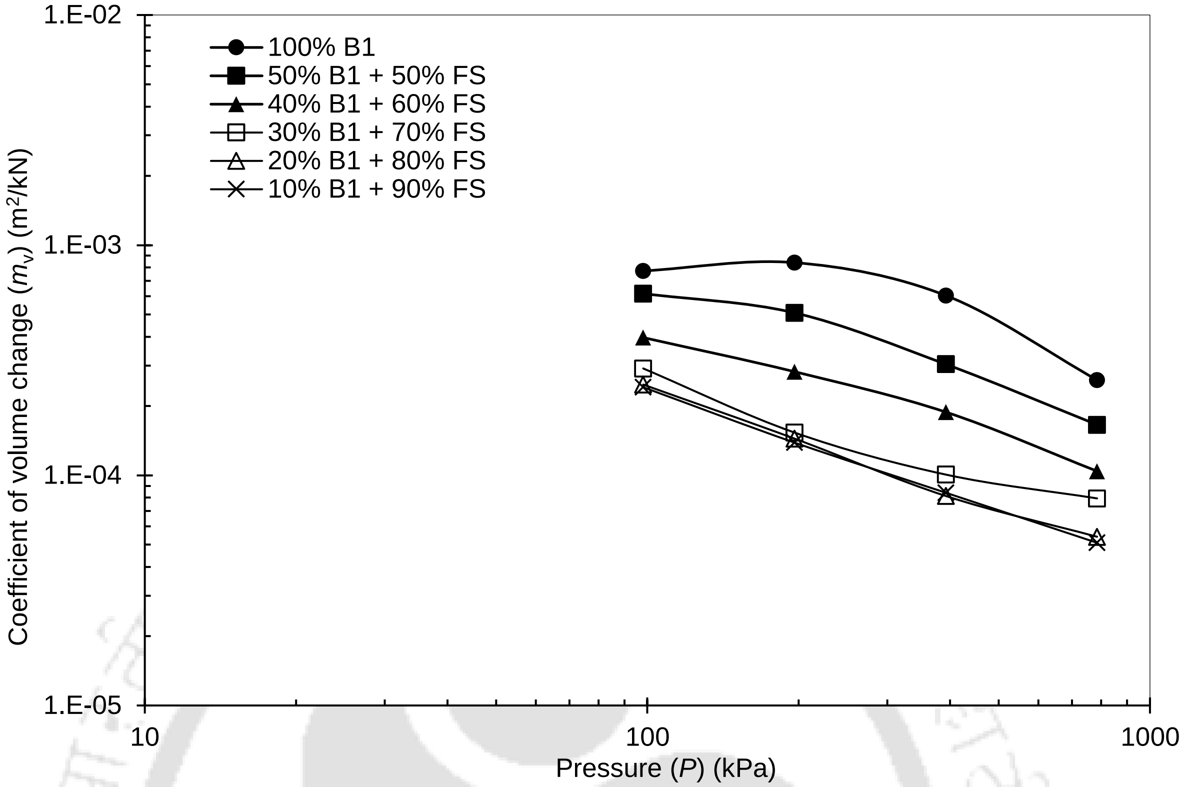


Figure 4.60 Effect of bentonite content on m_v-Pressure for FS-B1 samples compacted at 5% wet of OMC-MDD

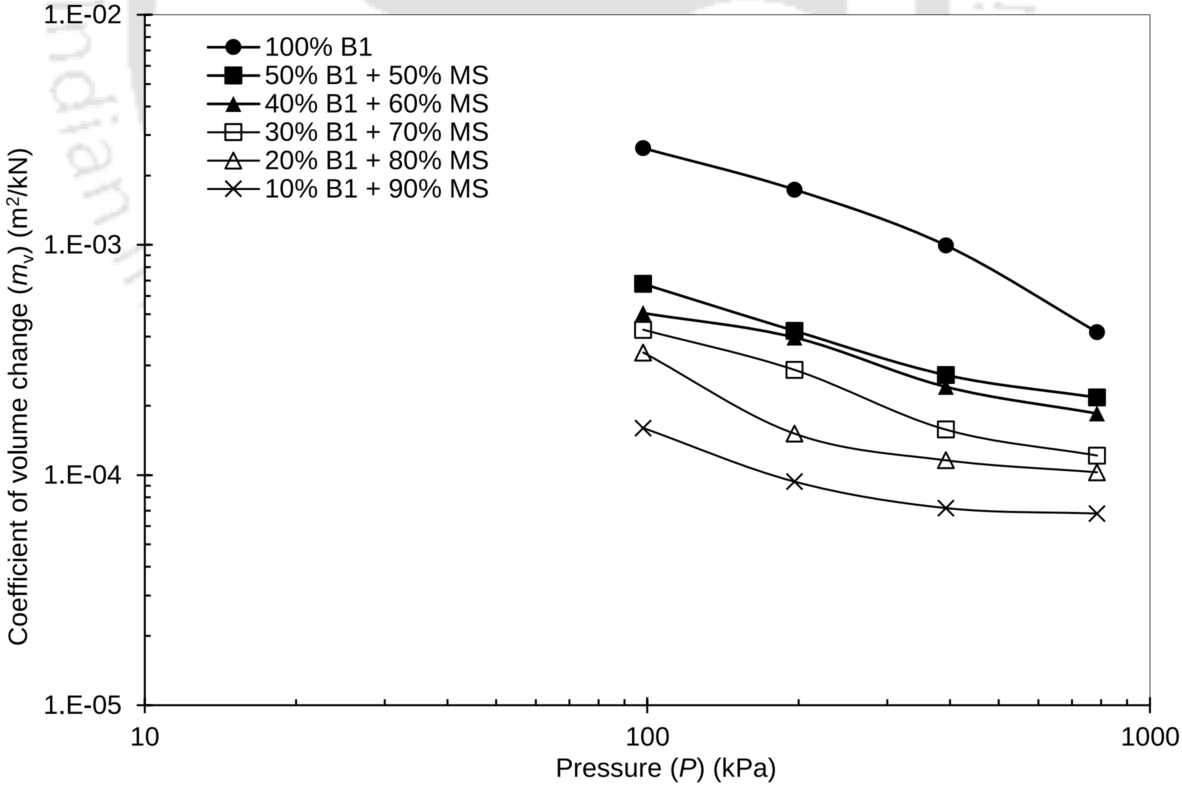


Figure 4.61 Effect of bentonite content on m_v-Pressure for MS-B1 samples compacted at 5% dry of OMC-MDD

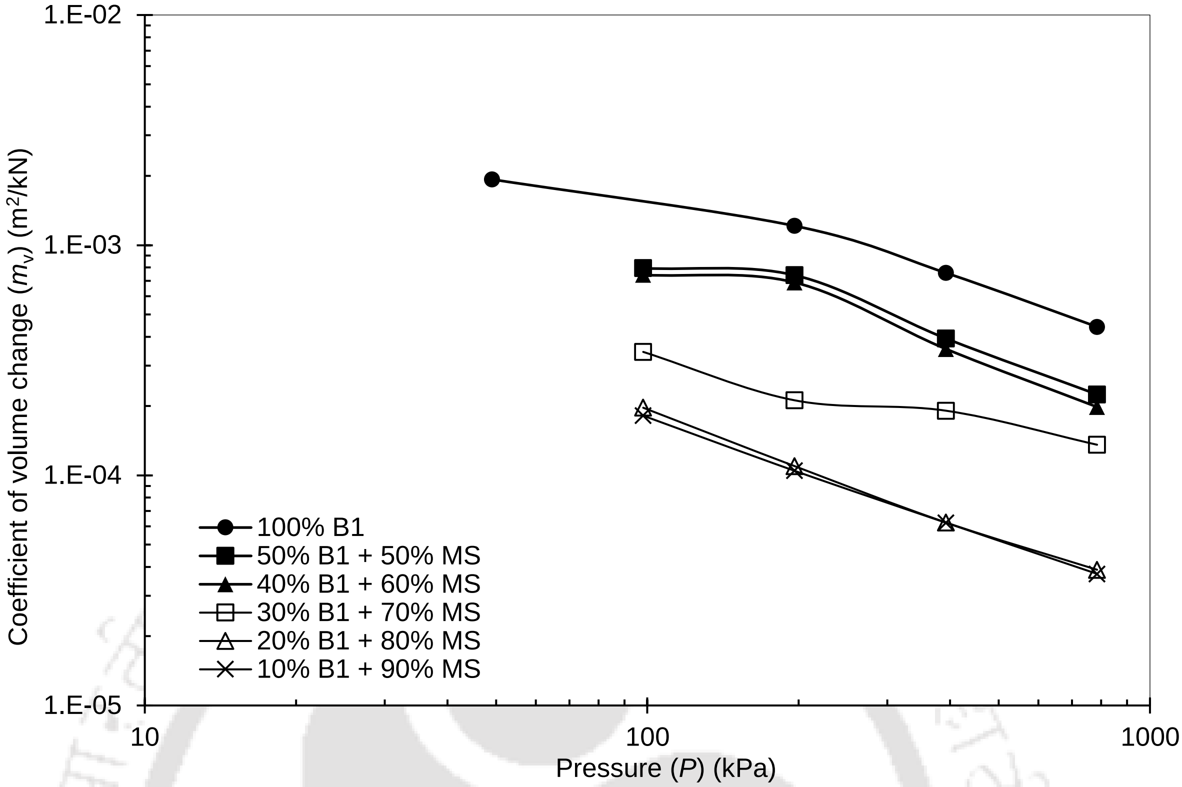


Figure 4.62 Effect of bentonite content on m_v-Pressure for MS-B1 samples compacted at OMC-MDD

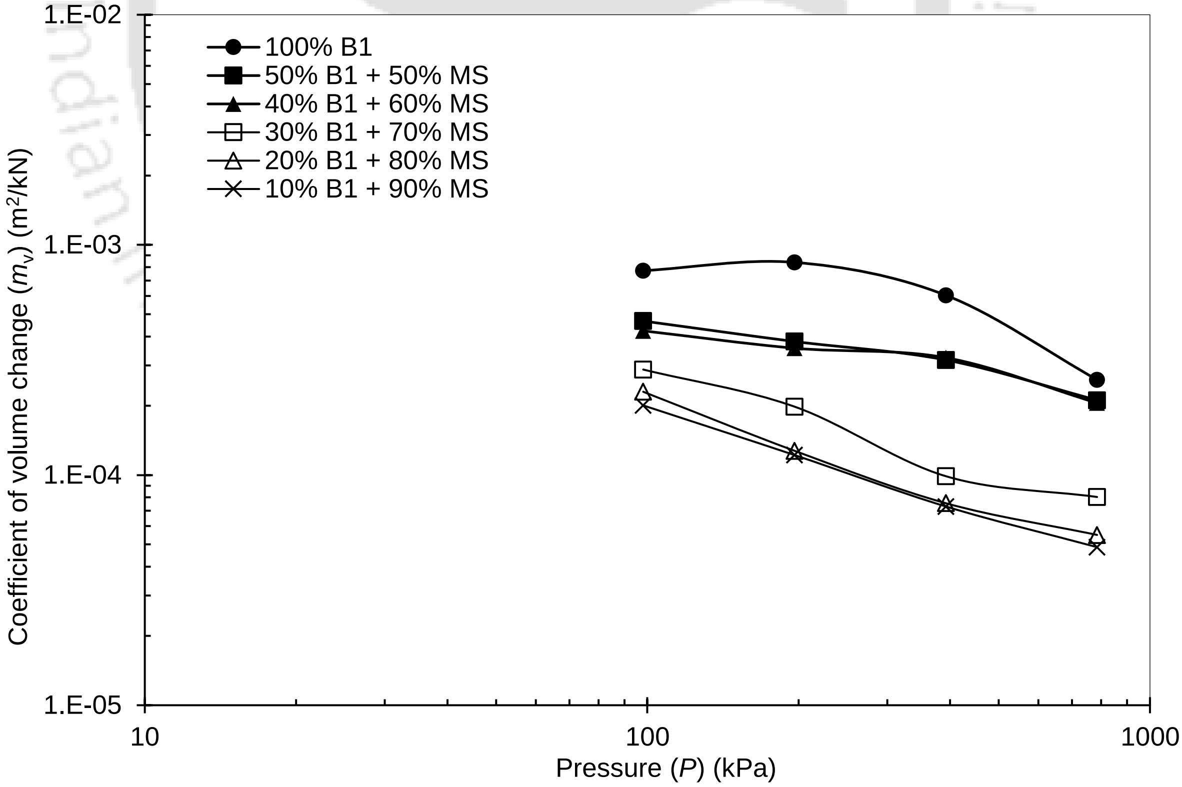


Figure 4.63 Effect of bentonite content on m_v-Pressure for MS-B1 samples compacted at 5% wet of OMC-MDD

Compared to other compacted sand-bentonite mixtures, 100% B1 mixtures exhibited higher m_v values irrespective of the initial compaction condition. When a compacted mixture made up of 100% B1 is subjected to incremental loading, the swollen bentonite with fully developed diffuse double layers is readily available for compression; load transfer mechanism starts by compressing the diffuse double layers leading to expulsion of water resulting in change in volume of soil mass. When the same load increment is applied to a compacted sand-bentonite mixture, load is shared by sand skeleton and diffuse double layer of swollen bentonite and coming to the load transfer mechanism, sand skeleton carries a partial load while a portion of the applied load is transferred via compression of diffuse double layers of bentonite occupying the sand skeleton. This difference in load carrying mechanisms is the prime reason for different m_v values for different bentonite proportions in the mixtures.

4.1.3.7.2 Effect of bentonite content and initial compaction conditions on m_v-Pressure relationship of FS-B2 and MS-B2 mixes

Compressibility behavior exhibited by FS-B2 and MS-B2 mixtures is presented in Figs. 4.64 through Figs. 4.69.

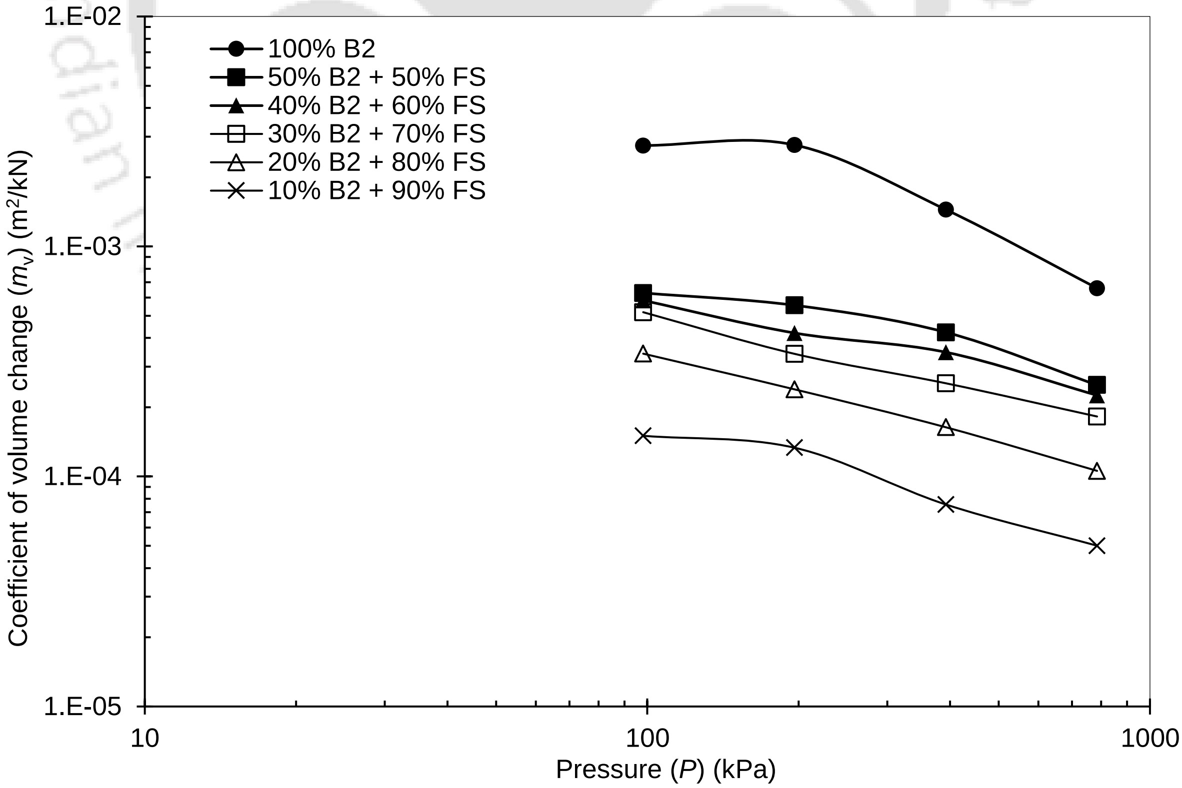


Figure 4.64 Effect of bentonite content on m_v-Pressure for FS-B2 samples compacted at 5% dry of OMC-MDD

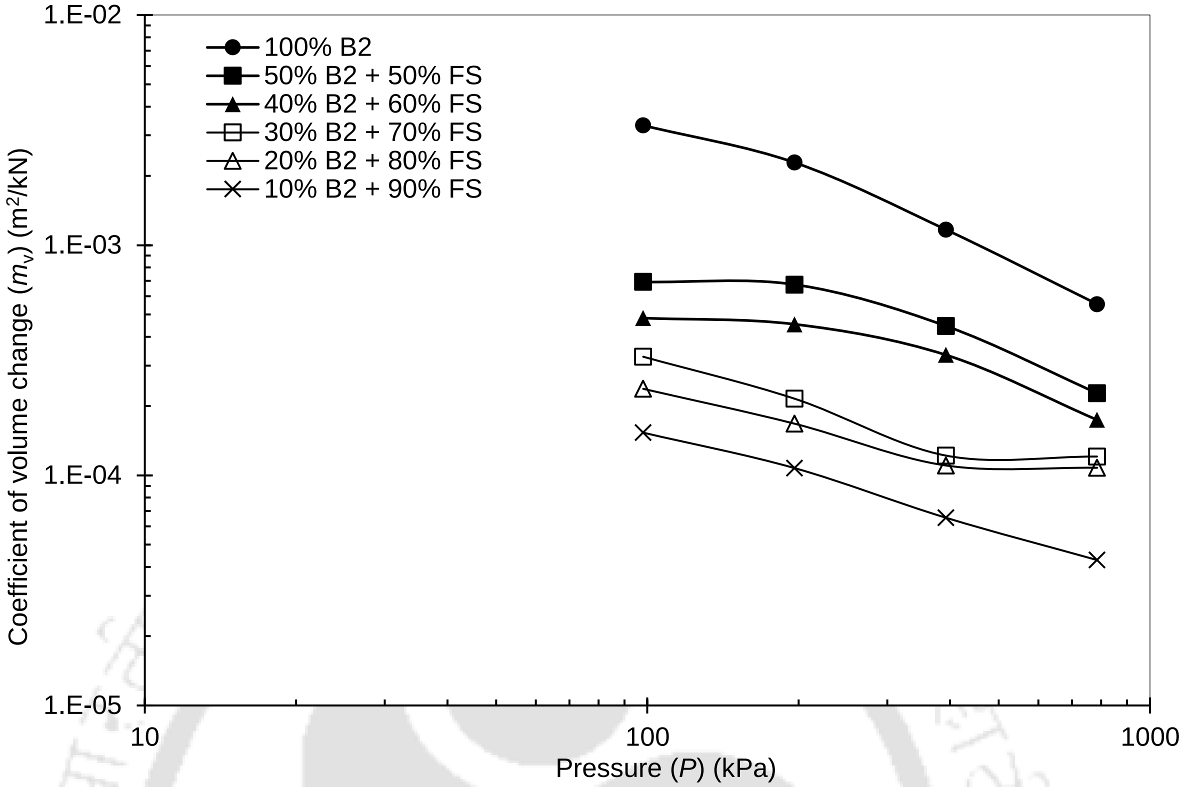


Figure 4.65 Effect of bentonite content on m_v-Pressure for FS-B2 samples compacted at OMC-MDD

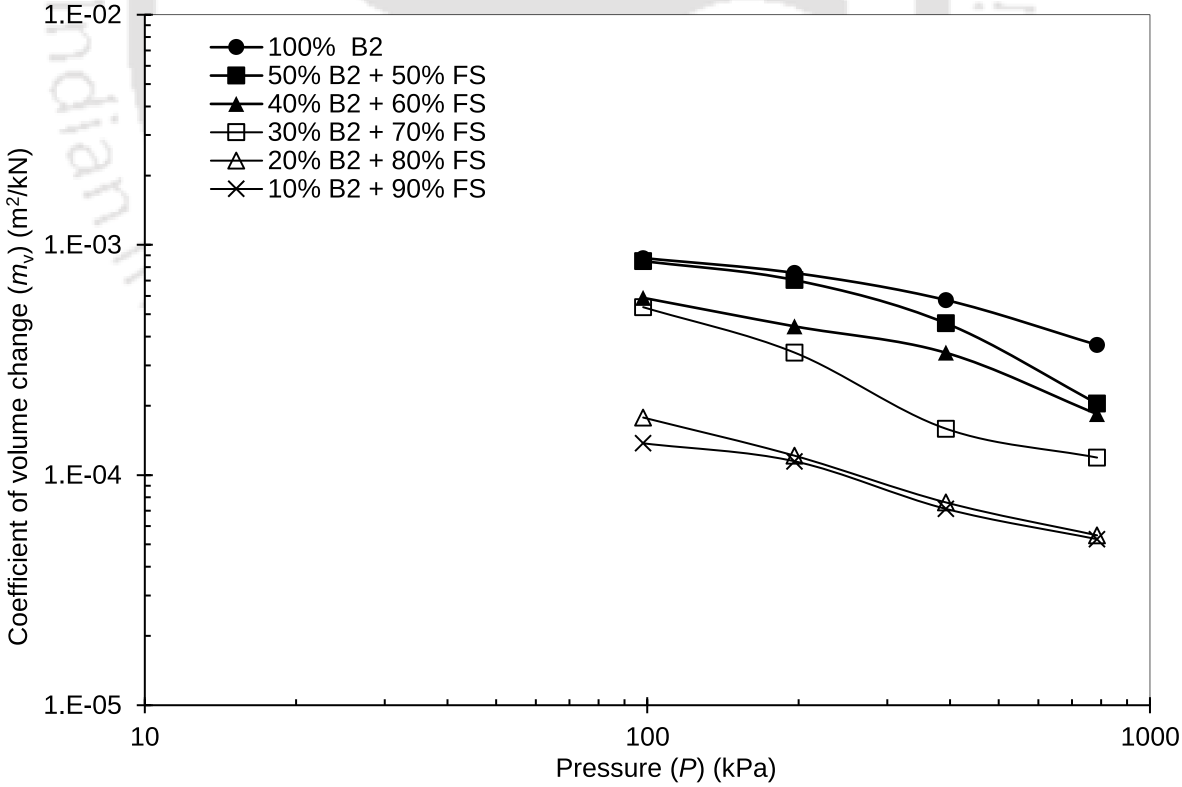


Figure 4.66 Effect of bentonite content on m_v-Pressure for FS-B2 samples compacted at 5% wet of OMC-MDD

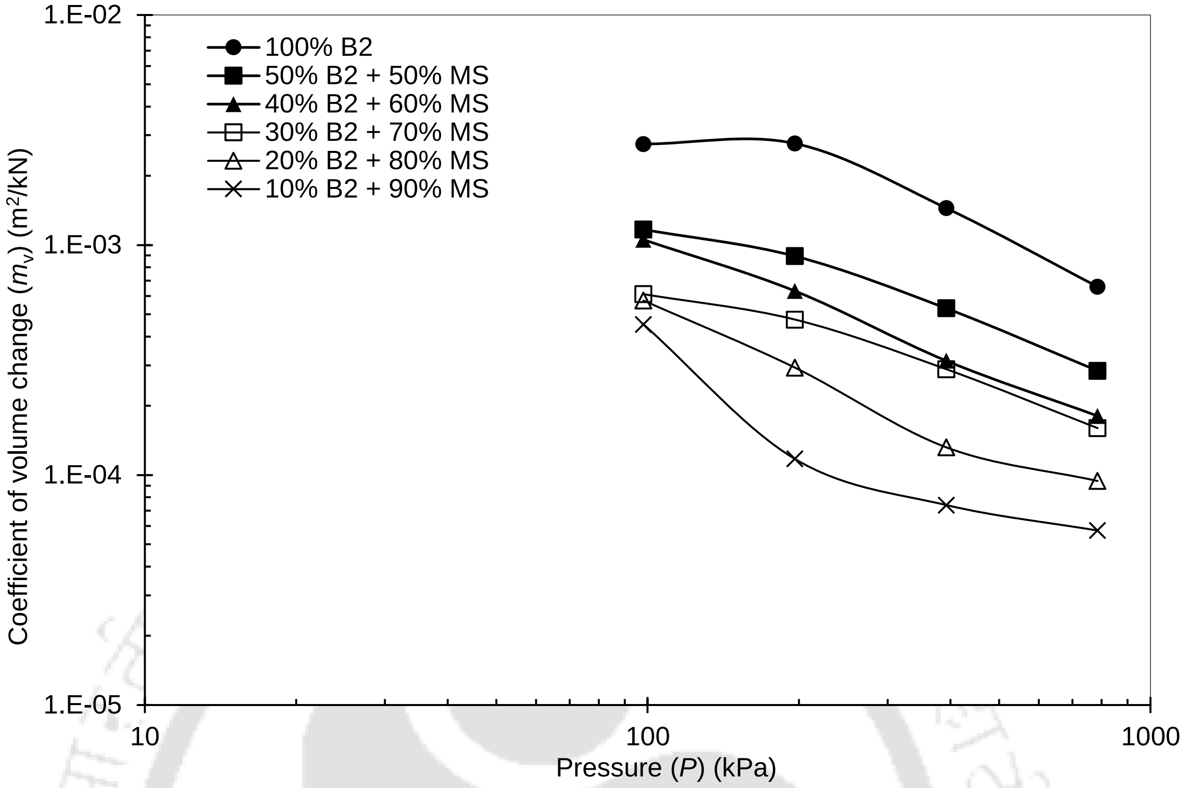


Figure 4.67 Effect of bentonite content on m_v-Pressure for MS-B2 samples compacted at 5% dry of OMC-MDD

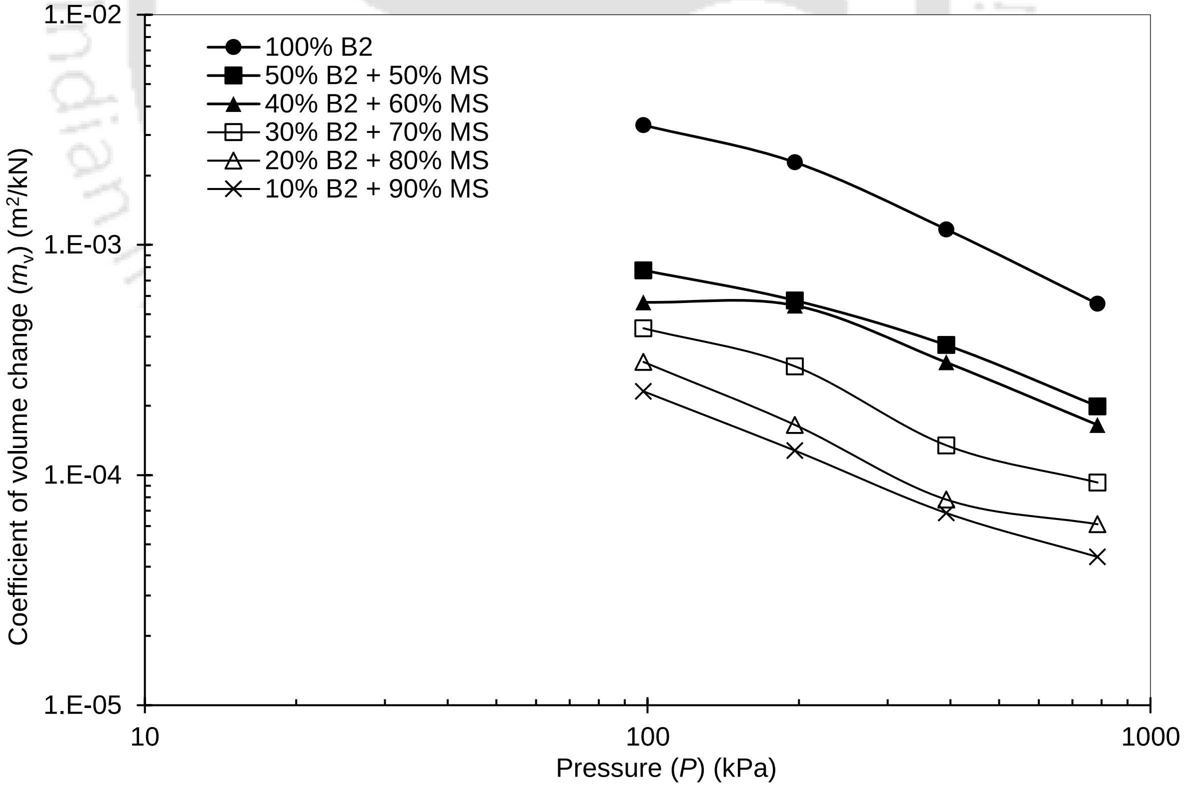


Figure 4.68 Effect of bentonite content on m_v-Pressure for MS-B2 samples compacted at OMC-MDD

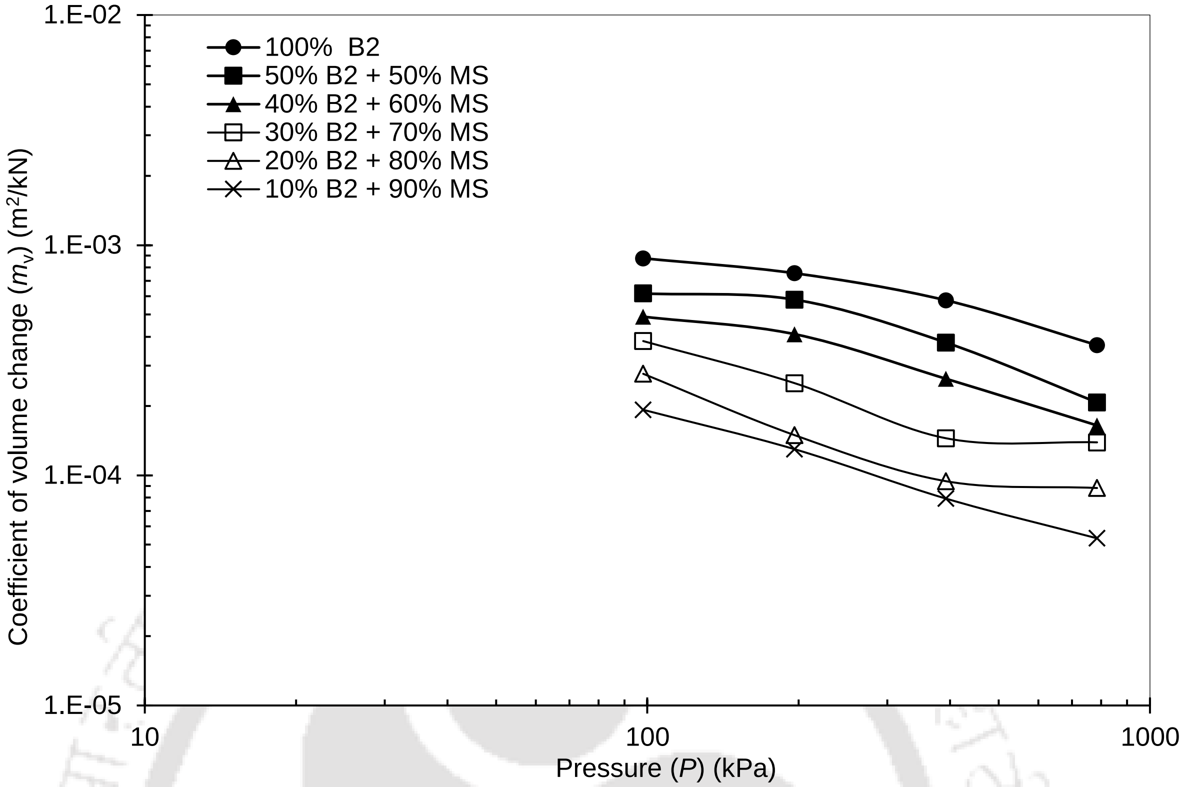


Figure 4.69 Effect of bentonite content on m_v-Pressure for MS-B2 samples compacted at 5% wet of OMC-MDD

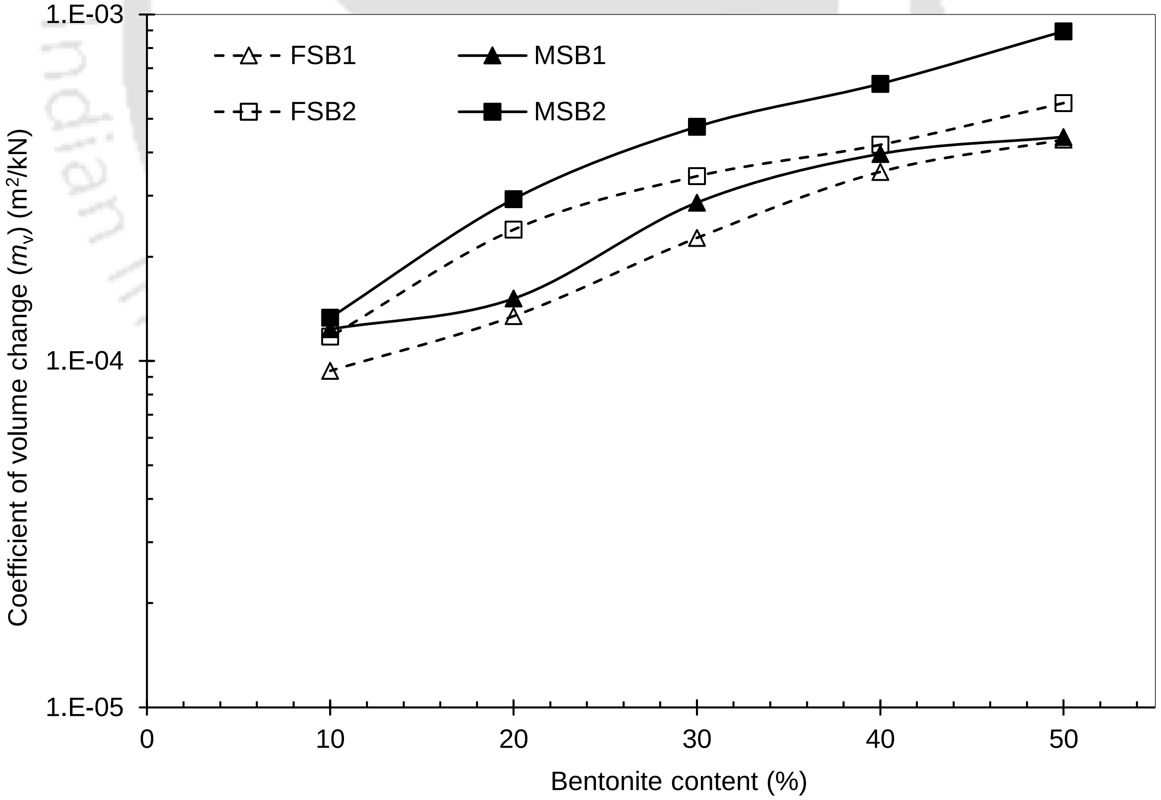


Figure 4.70 Effect of bentonite content on coefficient of volume change for sand-bentonite mixtures compacted at 5% dry of OMC-MDD, under a load of 196.2 kPa

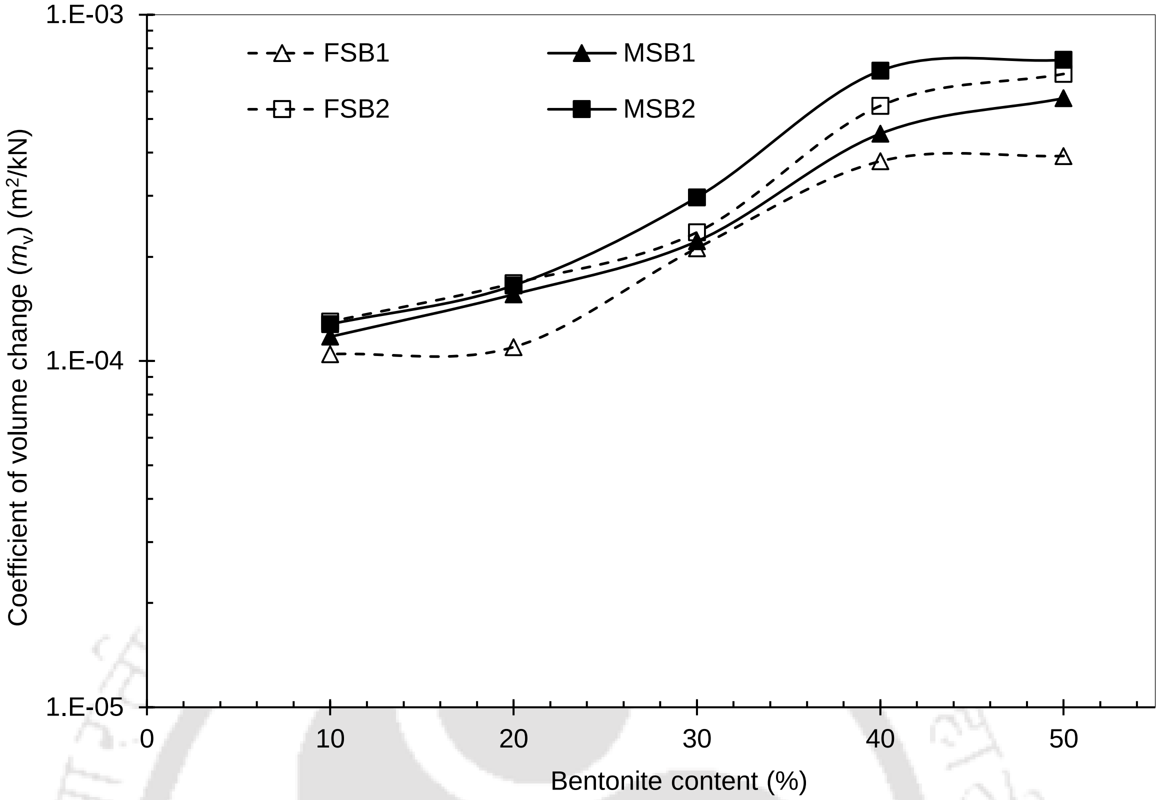


Figure 4.71 Effect of bentonite content on coefficient of volume change for sand-bentonite mixtures compacted at OMC-MDD, under a load of 196.2 kPa

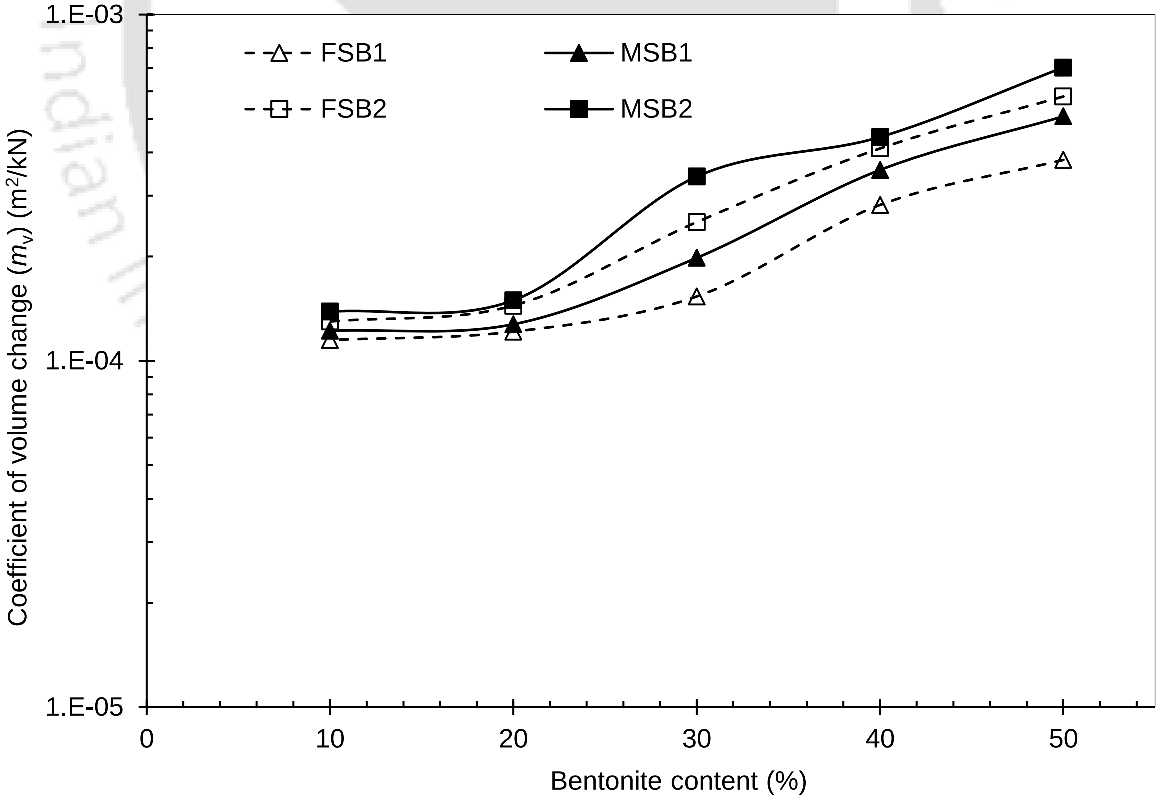


Figure 4.72 Effect of bentonite content on coefficient of volume change for sand-bentonite mixtures compacted at 5% wet of OMC-MDD, under a load of 196.2 kPa

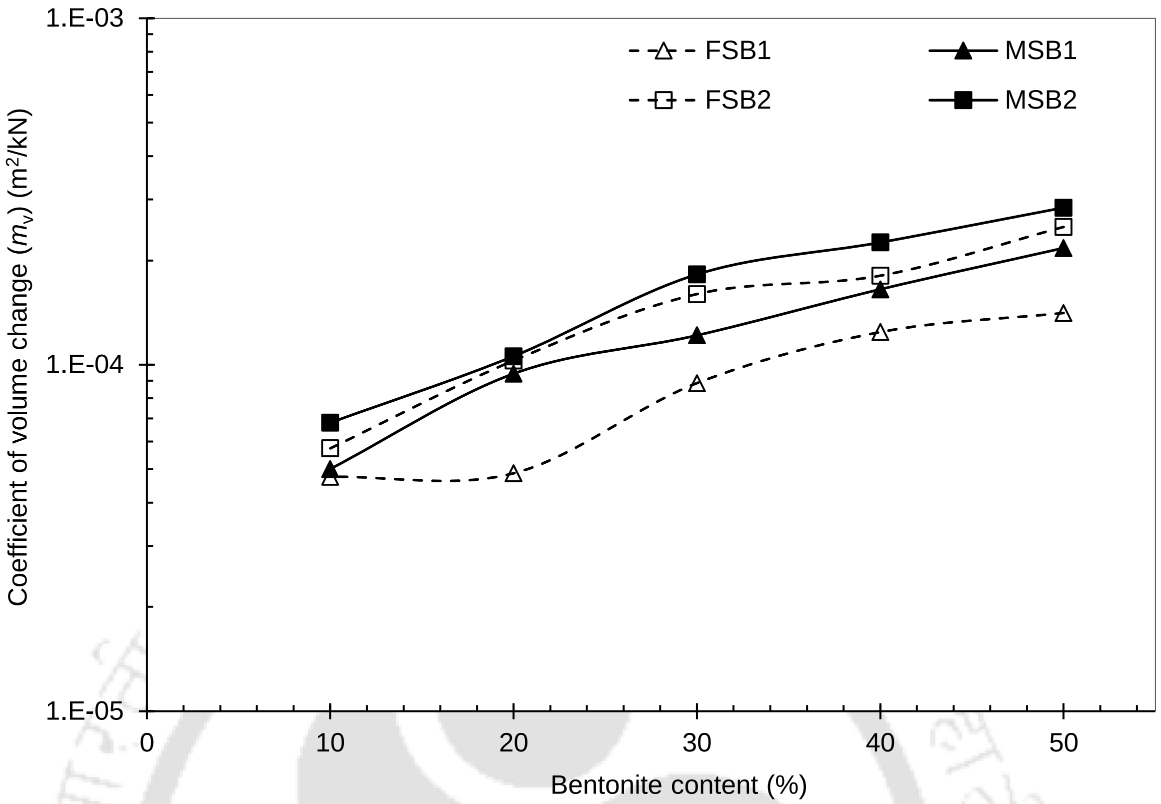


Figure 4.73 Effect of bentonite content on coefficient of volume change for sand-bentonite mixtures compacted at 5% dry of OMC-MDD, under a load of 784.8 kPa

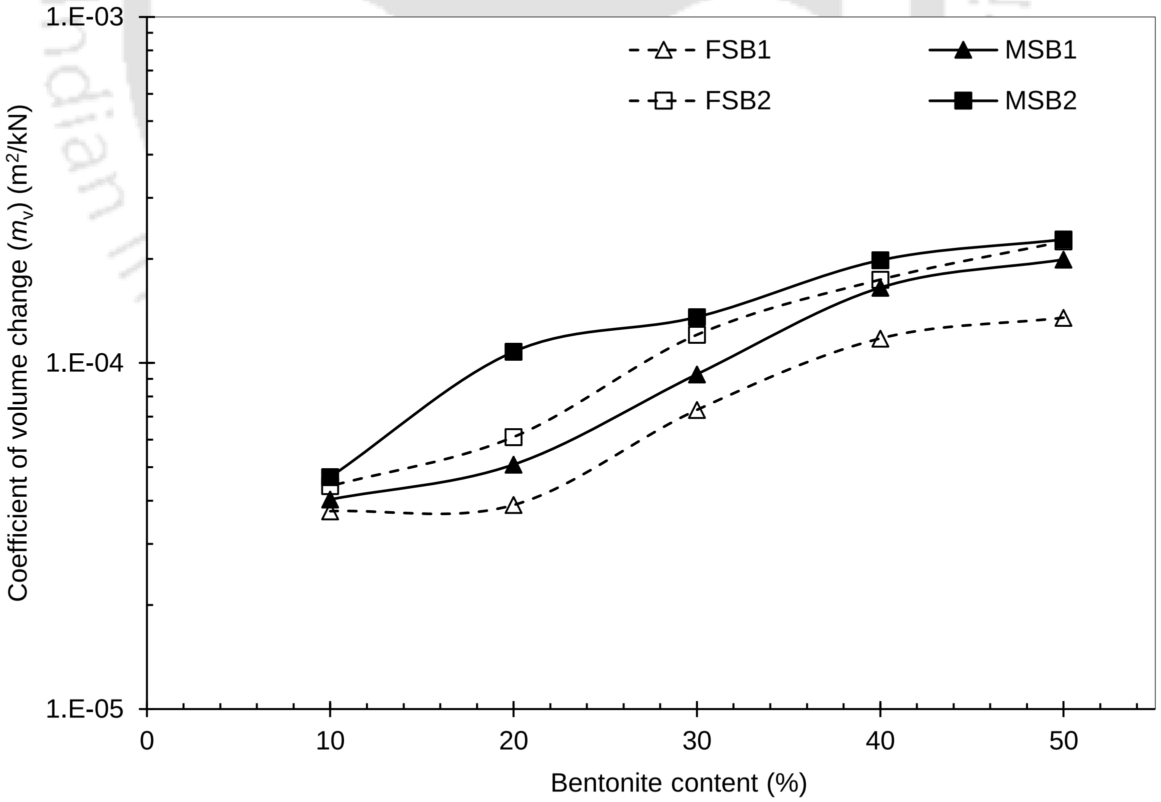


Figure 4.74 Effect of bentonite content on coefficient of volume change for sand-bentonite mixtures compacted at OMC-MDD, under a load of 784.8 kPa

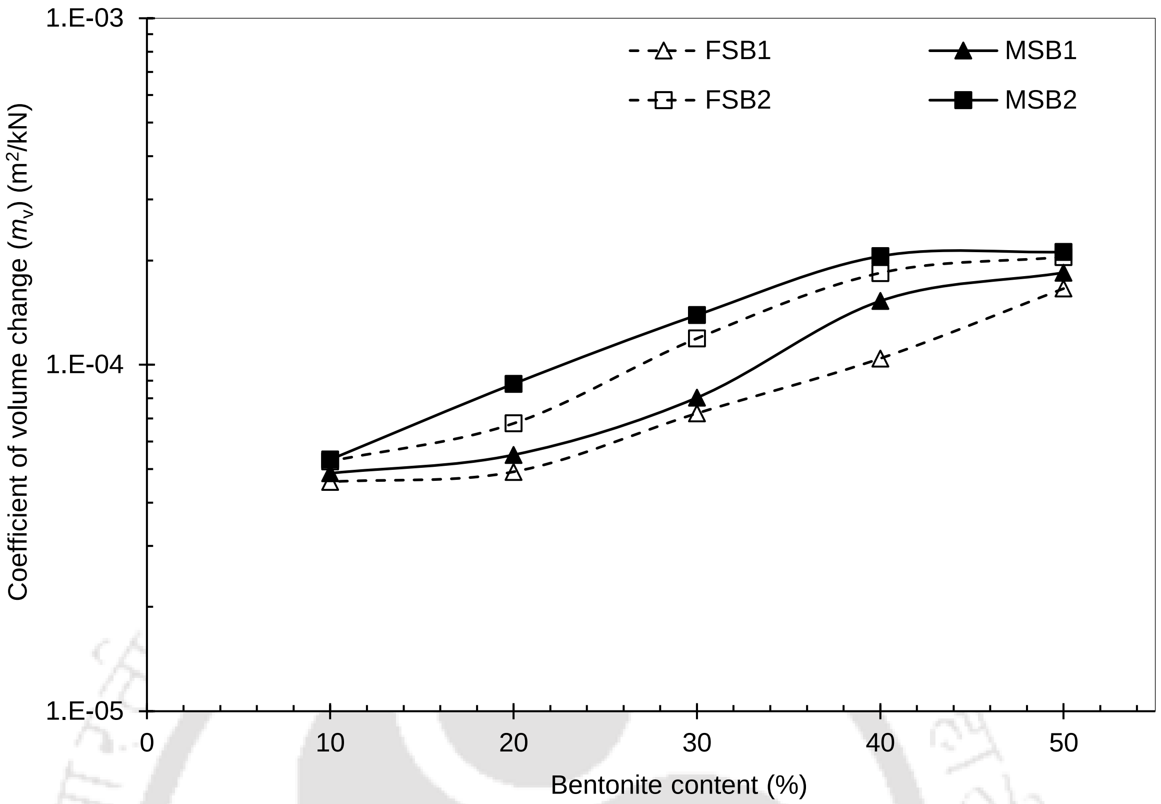


Figure 4.75 Effect of bentonite content on coefficient of volume change for sand-bentonite mixtures compacted at 5% wet of OMC-MDD, under a load of 784.8 kPa

In terms of their behavior with respect to initial compaction condition, bentonite content and sand type used in the mixture, a trend similar to those observed in case of FS-B1 and MS-B1 has been noticed.

Comparing compressibility behavior of FS-B1, MS-B1, FS-B2 and MS-B2 mixtures subjected to different consolidation pressures has shown an increase in m_v values with increasing bentonite content and decreasing with increasing consolidation pressure as can be seen in Figs. 4.70 through Figs. 4.75.

4.1.3.8 Effect of bentonite content and initial compaction conditions on time required for 90% consolidation (t_{90})-Pressure relationship of sand-bentonite mixes

4.1.3.8.1 Effect of bentonite content and initial compaction conditions on t_{90}-Pressure relationship of FS-B1 and MS-B1 mixes

Influence of bentonite content, initial compaction conditions, consolidation pressure and sand type on the time required for the completion of 90% consolidation (t_{90}) of FS-B1 and MS-B1 mixtures is as shown in Figs. 4.76 through Figs. 4.81. It can be seen that t_{90} increases with increasing consolidation pressure for all mixtures. Upon comparison, a very clear distinction can be noticed in the exhibited t_{90} values indicating that B1 content in the mixtures plays a major role in consolidation phenomenon. As the B1 content in the mixture is decreasing, t_{90} was found to be decreasing. For any FS-B1 or MS-B1 mixture, t_{90} values were found to be increasing with initial mixing water content. FS-B1 mixtures exhibited relatively higher t_{90} values for all mix proportions and compaction conditions. As the bentonite content in the mixture increases, voids in the sand skeleton are filled more effectively leading to a lower hydraulic conductivity, which in turn reflects in higher t_{90} values. With the increasing consolidation pressure, the voids and pathways that were available for flow to take place earlier are destroyed leading to a lower hydraulic conductivity and resulting in an increase in the duration needed for 90% consolidation. The voids present in FS-B1 mixtures being relatively smaller in size compared to MS-B1 mixtures and less permeable, exhibiting relatively higher t_{90} values. For all compaction conditions, with their lowest hydraulic conductivities, 100% B1 mixtures exhibited highest t_{90} values compared to all sand-bentonite-1 mixtures.

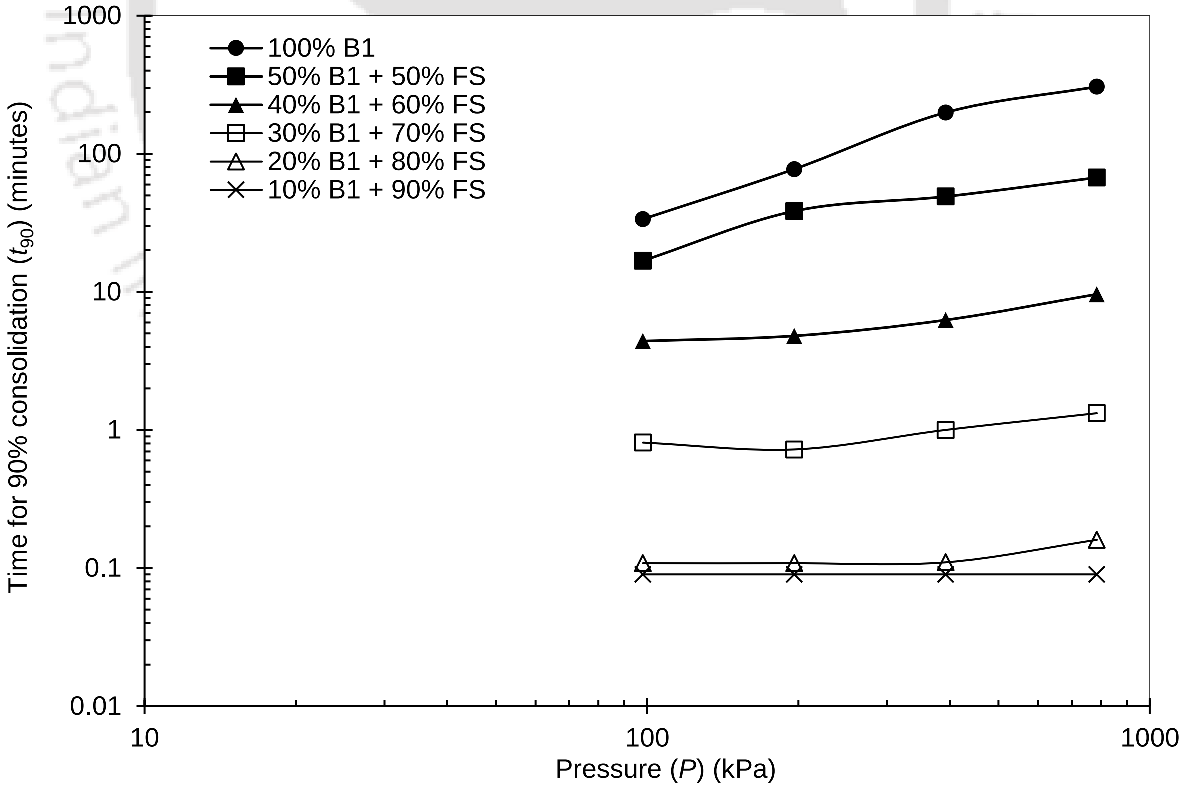


Figure 4.76 Effect of bentonite content on t_{90}-Pressure for FS-B1 samples compacted at 5% dry of OMC-MDD

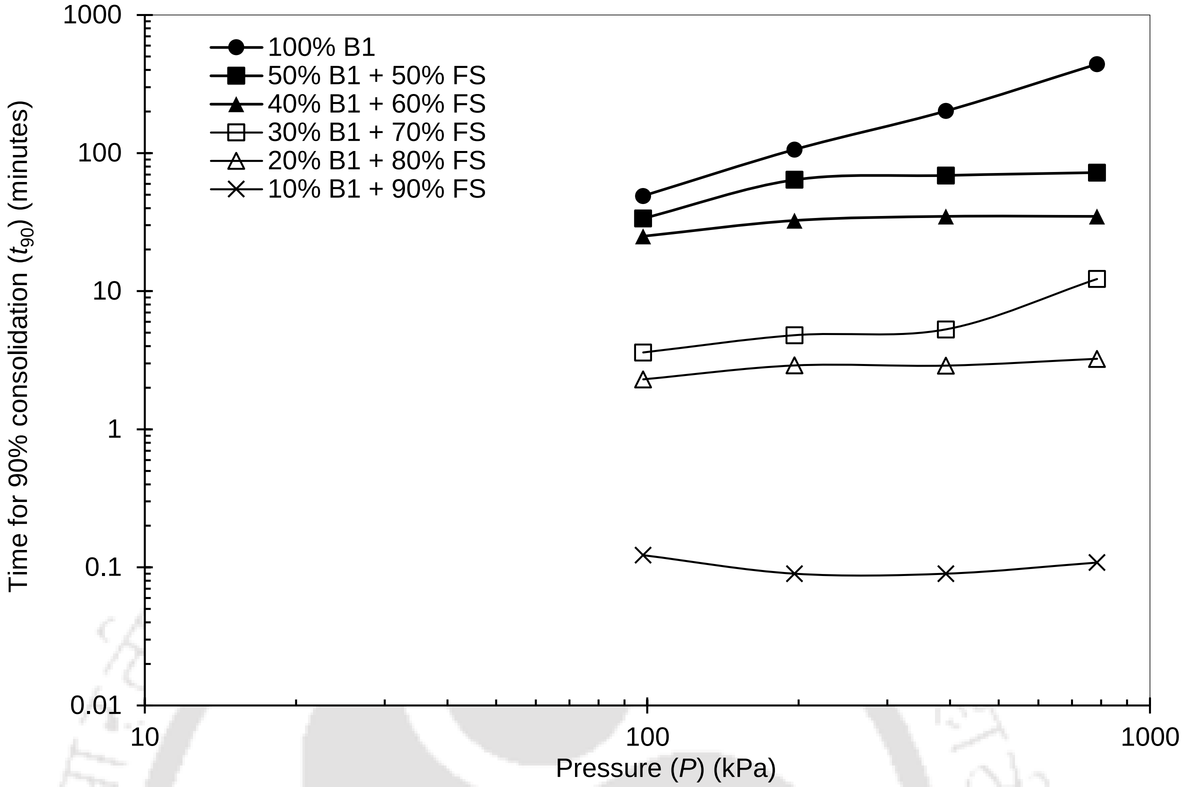


Figure 4.77 Effect of bentonite content on t_{90}-Pressure for FS-B1 samples compacted at OMC-MDD

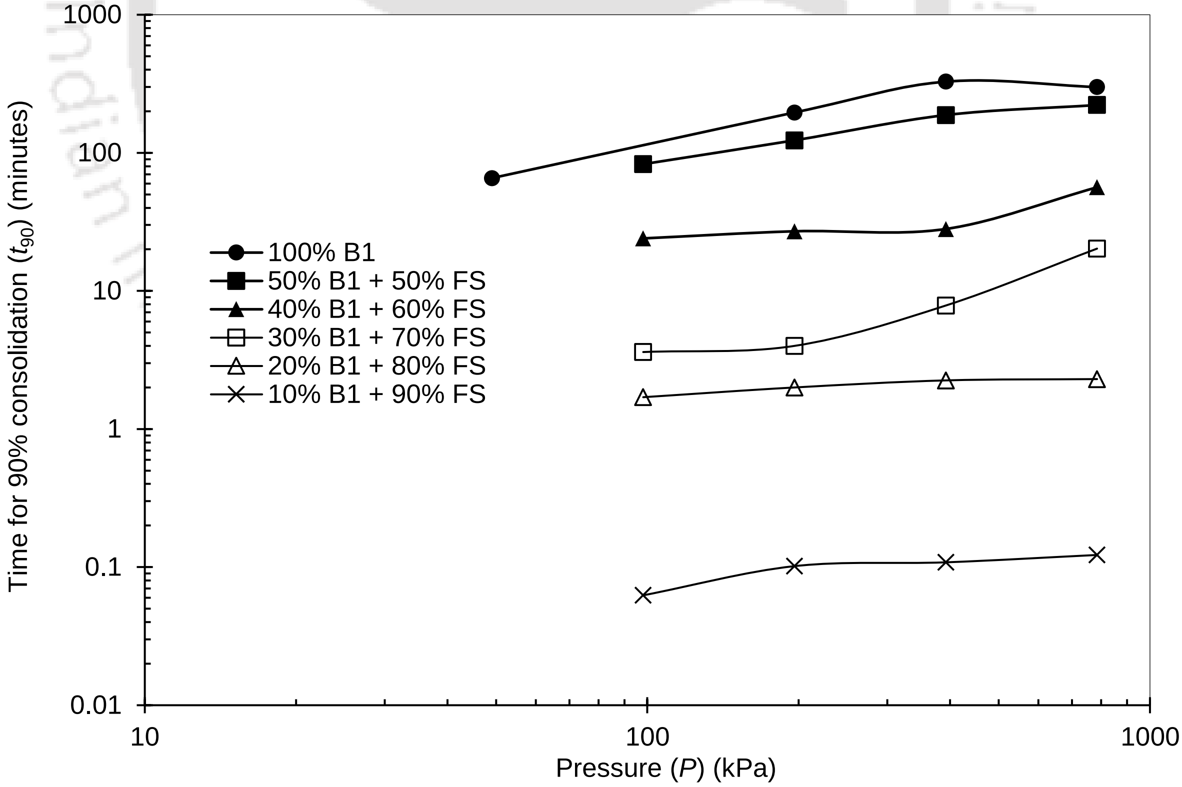


Figure 4.78 Effect of bentonite content on t_{90}-Pressure for FS-B1 samples compacted at 5% wet of OMC-MDD

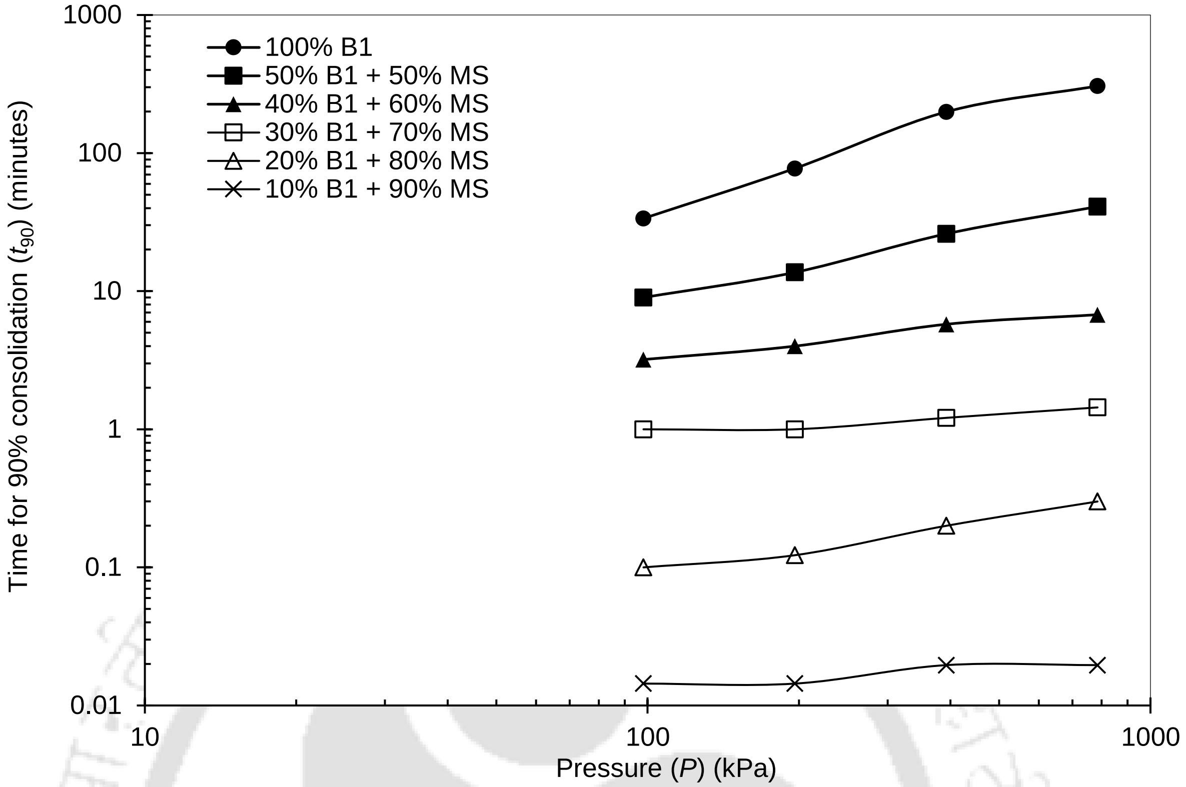


Figure 4.79 Effect of bentonite content on t_{90}-Pressure for MS-B1 samples compacted at 5% dry of OMC-MDD

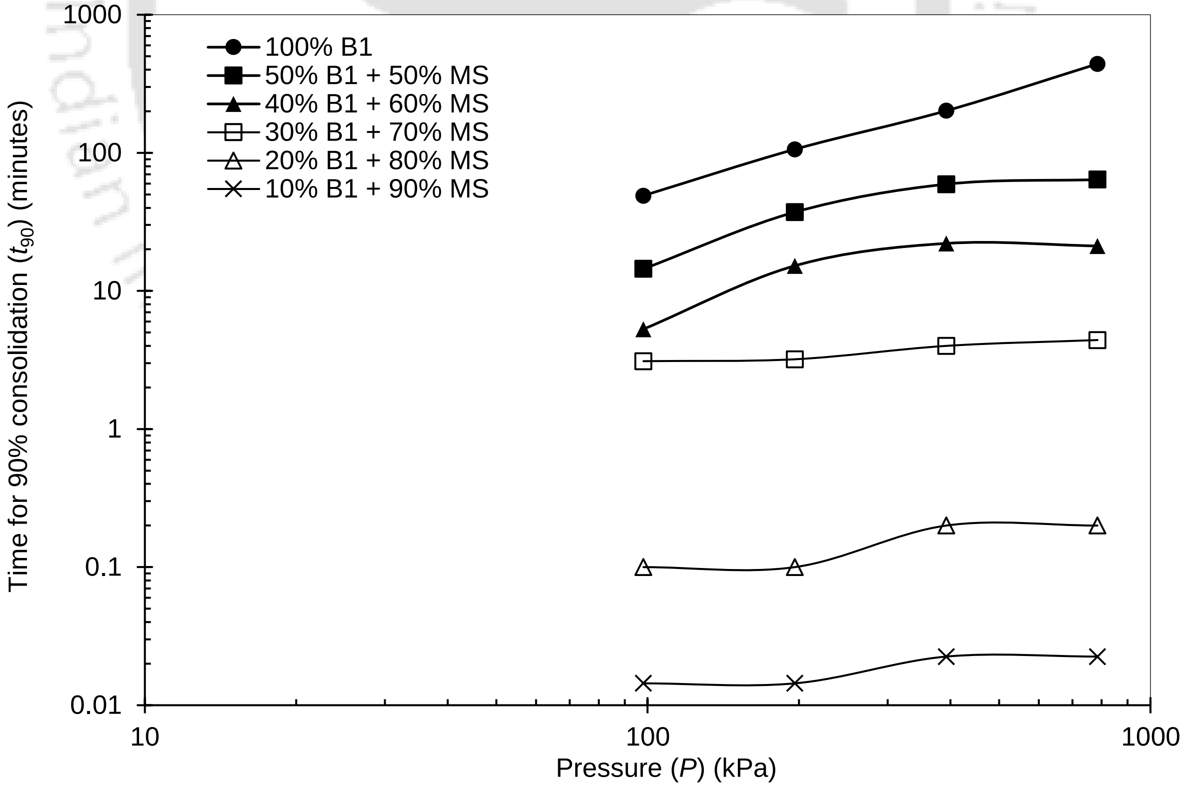


Figure 4.80 Effect of bentonite content on t_{90}-Pressure for MS-B1 samples compacted at OMC-MDD

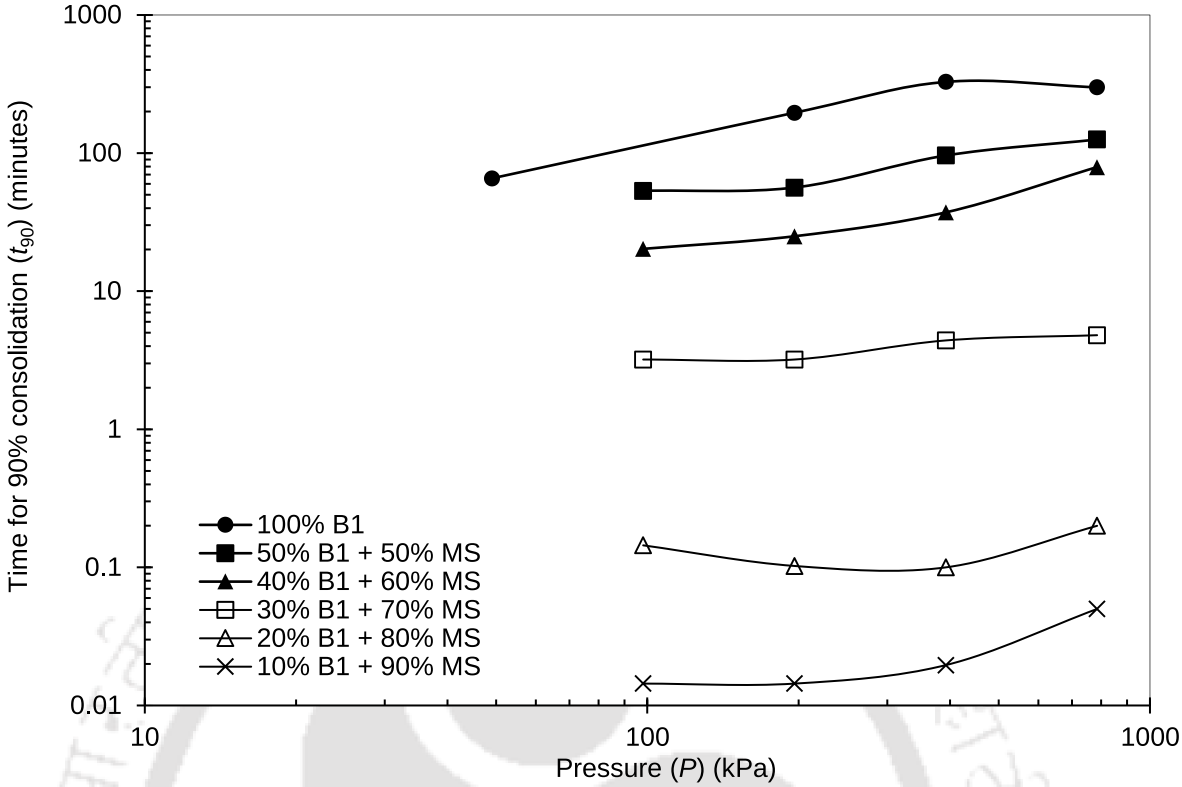


Figure 4.81 Effect of bentonite content on t_{90}-Pressure for MS-B1 samples compacted at 5% wet of OMC-MDD

4.1.3.8.2 Effect of bentonite content and compaction conditions on t_{90}-Pressure relationship of FS-B2 and MS-B2 mixes

Influence of bentonite content, initial compaction conditions, consolidation pressure and sand type on the t_{90} of FS-B2 and MS-B2 mixtures is shown in Figs. 4.82 through Figs. 4.87. Trend similar to those exhibited by FS-B1 and MS-B1 mixtures were seen in the case of FS-B2 and MS-B2 mixtures. A clear influence of high swelling nature of B2 can be seen in the relatively higher t_{90} values exhibited by FS-B2 and MS-B2 mixtures for all compaction conditions.

Effect of bentonite content, compaction conditions, sand type and consolidation pressure on time for 90% consolidation (t_{90}) can be seen in the Figs. 4.88 through Figs. 4.93. For all the compaction states and bentonite contents, mixtures with B2 exhibited higher t_{90} values some times as high as 10 times those demonstrated by B1 mixtures. Comparison of factors influencing t_{90} indicated that quality of bentonite has the most effect followed by bentonite content in the mixture. Influence of sand type on t_{90} can be seen in the mixtures with bentonite contents less than 30%, though very little.

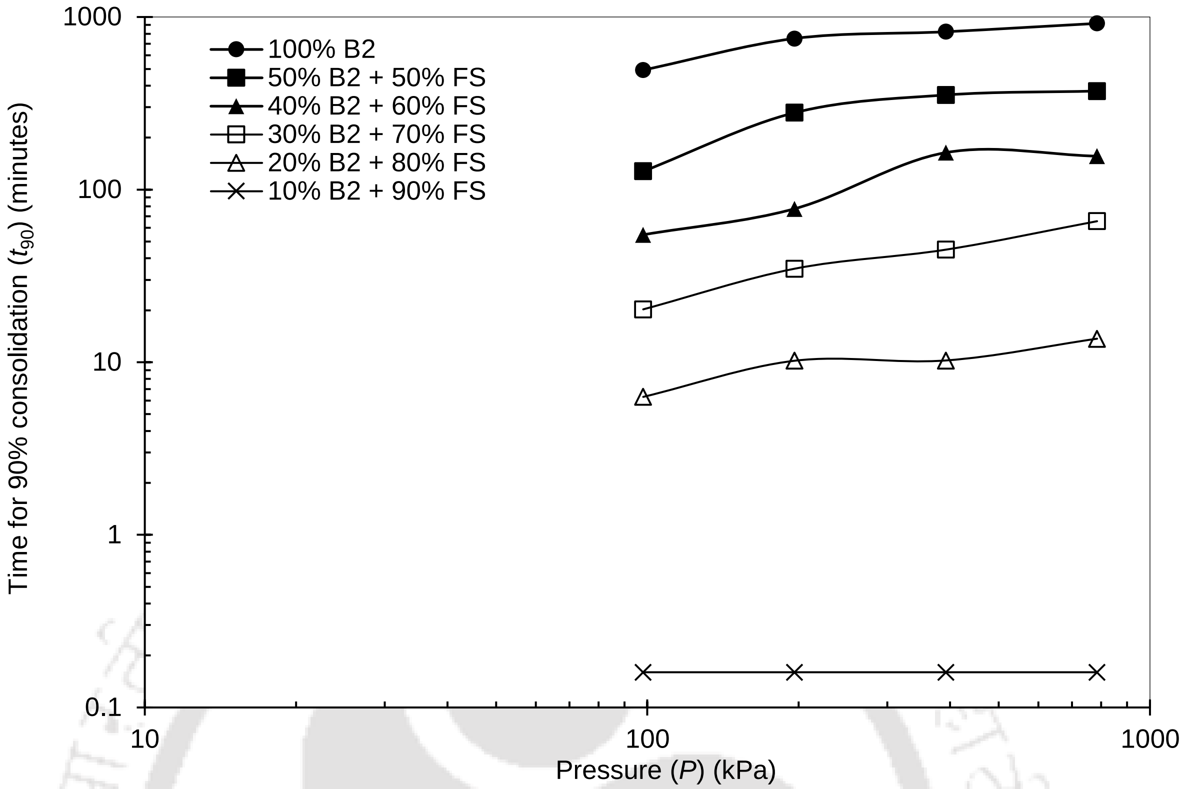


Figure 4.82 Effect of bentonite content on t_{90}-Pressure for FS-B2 samples compacted at 5% dry of OMC-MDD

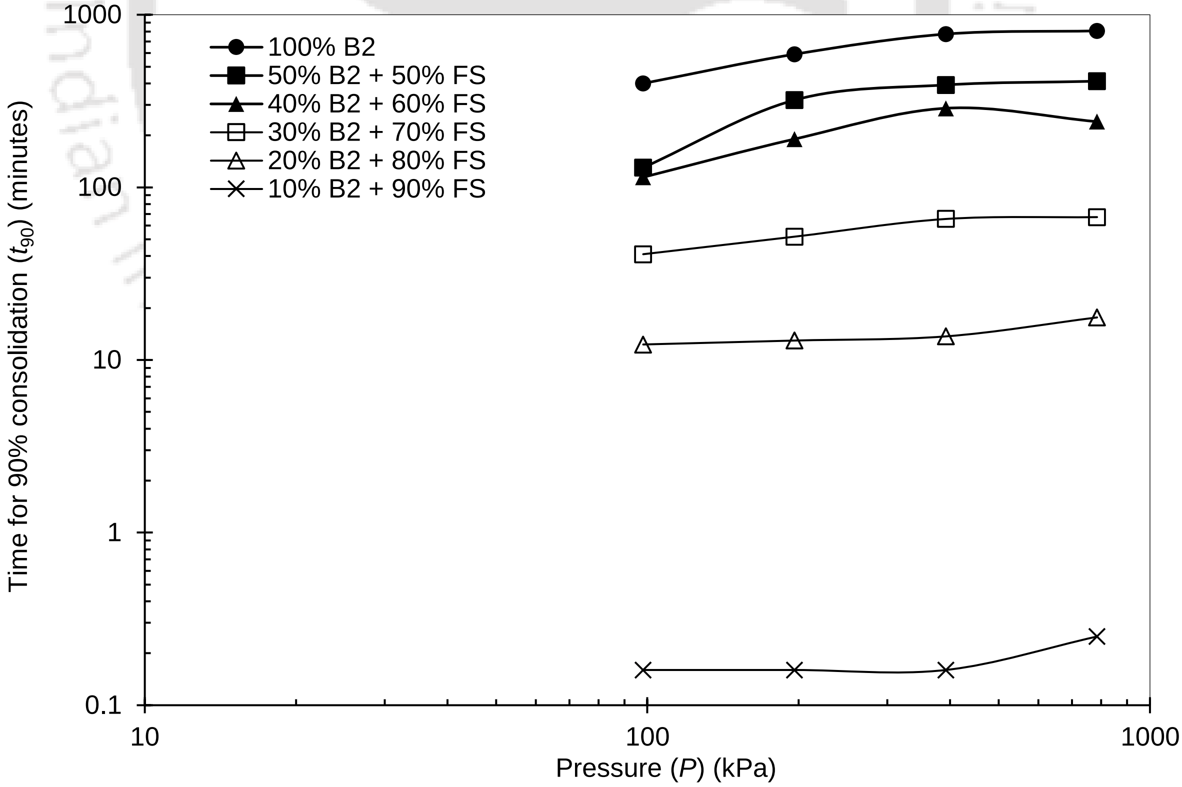


Figure 4.83 Effect of bentonite content on t_{90}-Pressure for FS-B2 samples compacted at OMC-MDD

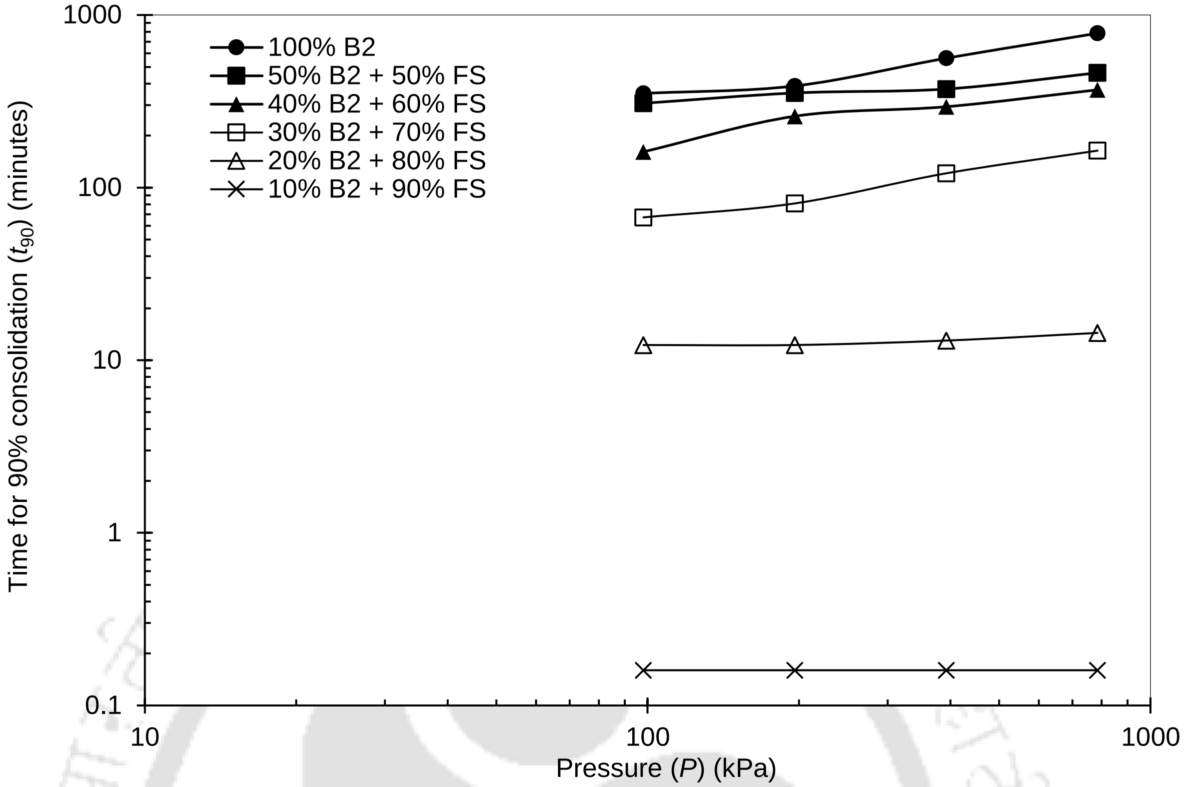


Figure 4.84 Effect of bentonite content on t_{90}-Pressure for FS-B2 samples compacted at 5% wet of OMC-MDD

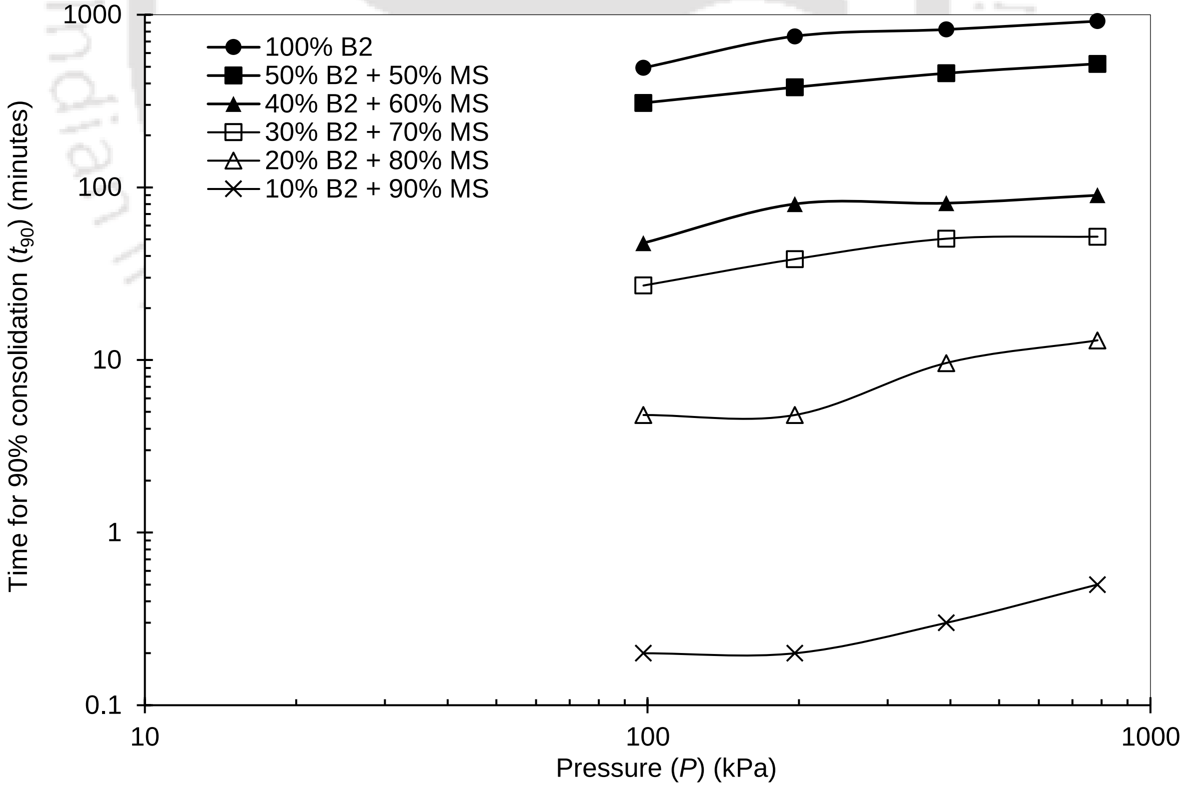


Figure 4.85 Effect of bentonite content on t_{90}-Pressure for MS-B2 samples compacted at 5% dry of OMC-MDD

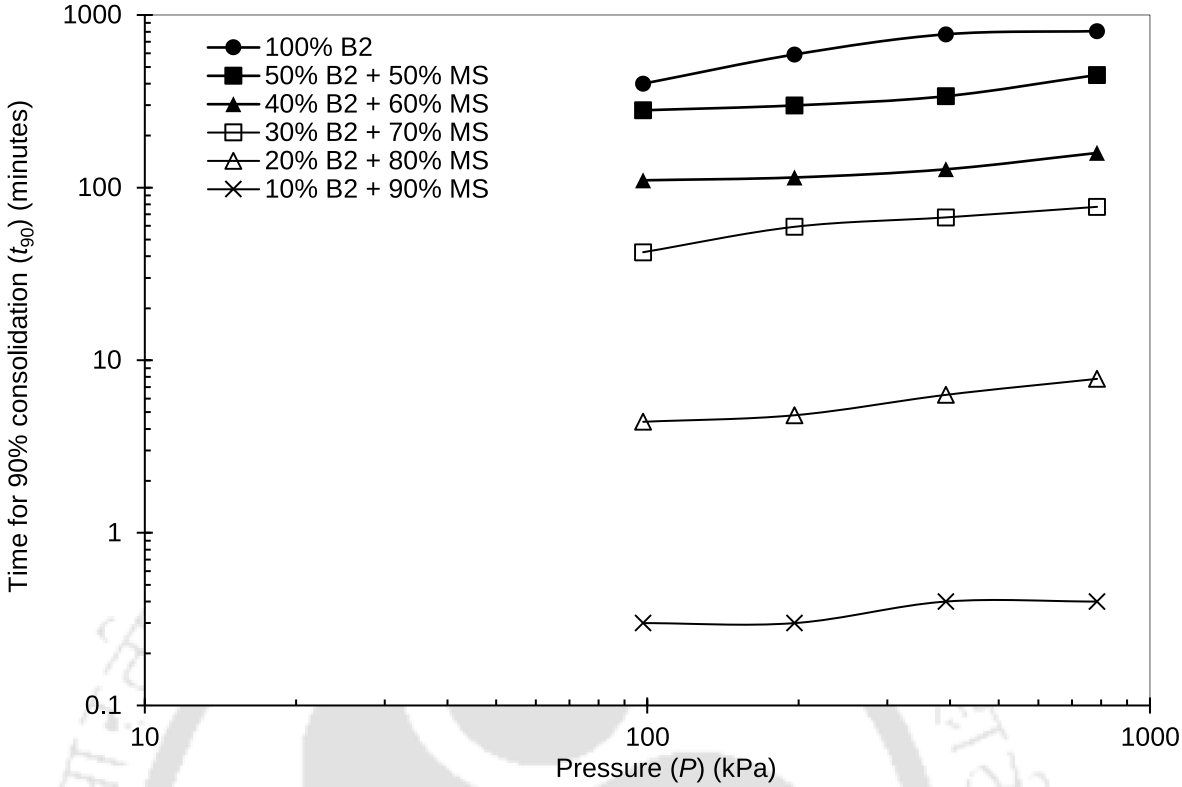


Figure 4.86 Effect of bentonite content on t_{90}-Pressure for MS-B2 samples compacted at OMC-MDD

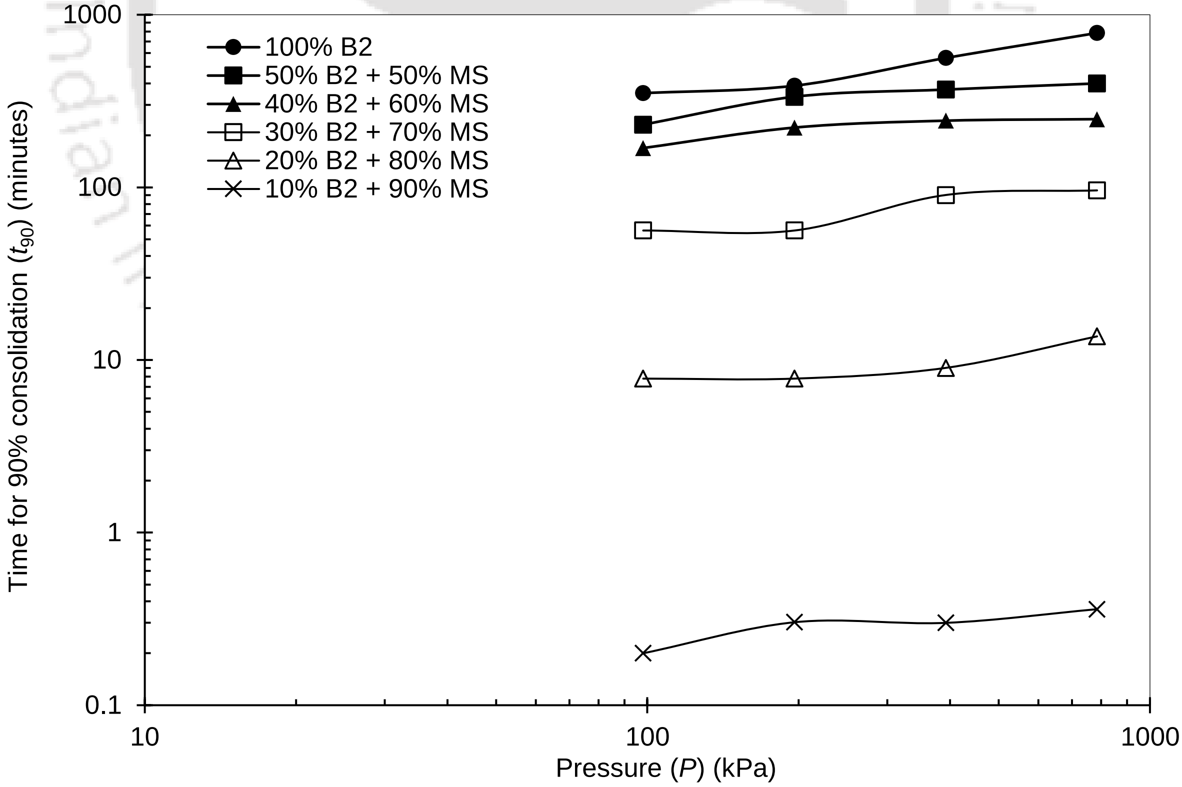


Figure 4.87 Effect of bentonite content on t_{90}-Pressure for MS-B2 samples compacted at 5% wet of OMC-MDD

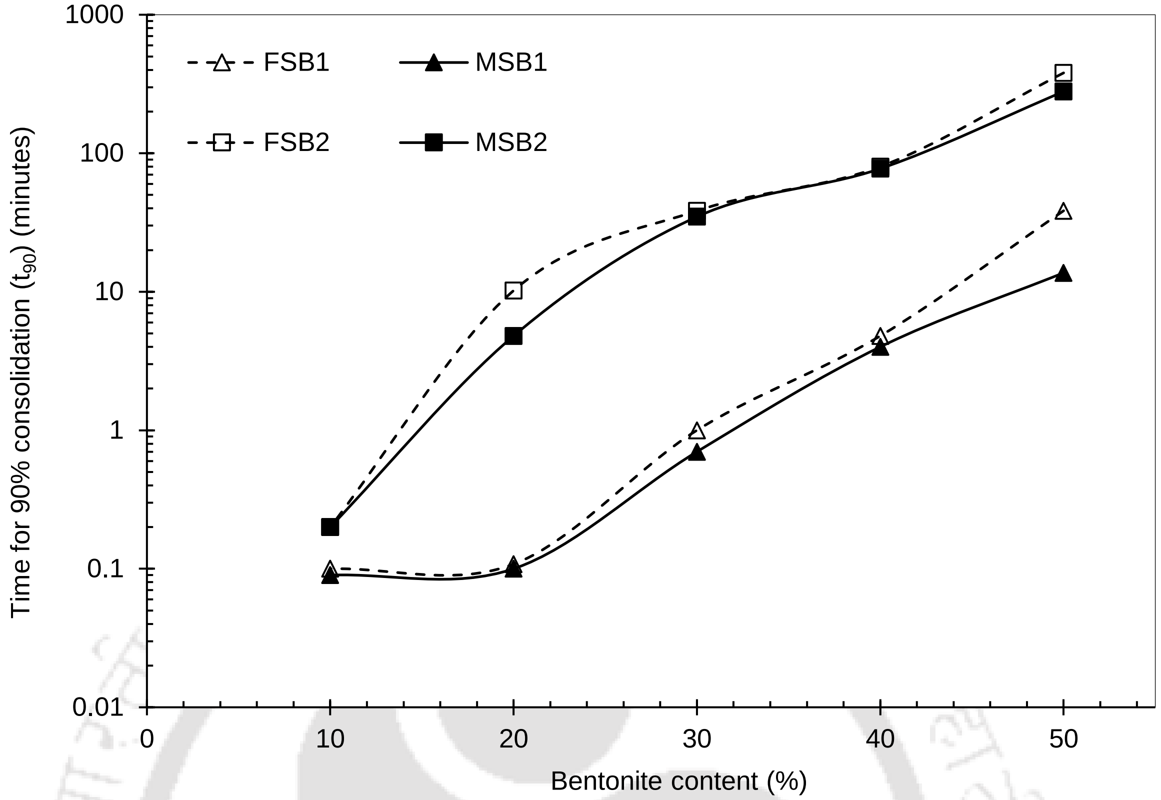


Figure 4.88 Effect of bentonite content on t_{90} of sand-bentonite mixtures compacted at 5% dry of OMC-MDD, under a load of 196.2 kPa

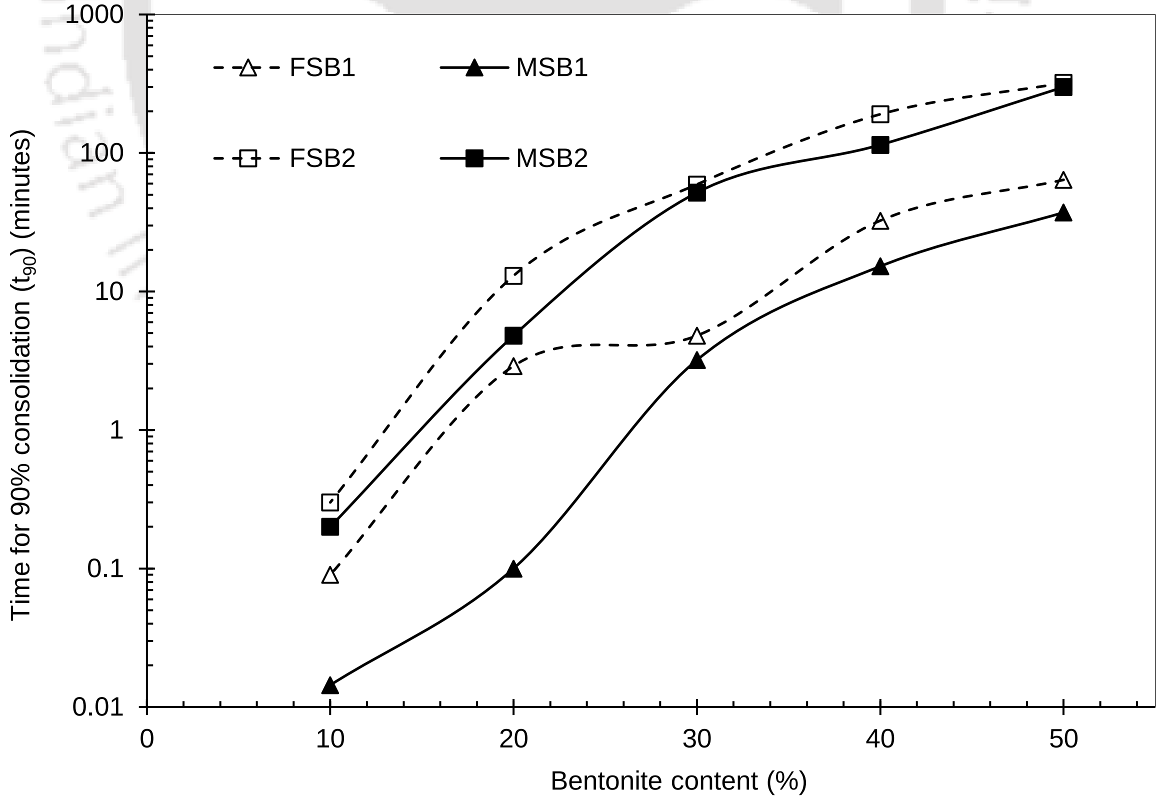


Figure 4.89 Effect of bentonite content on t_{90} of sand-bentonite mixtures compacted at OMC-MDD, under a load of 196.2 kPa

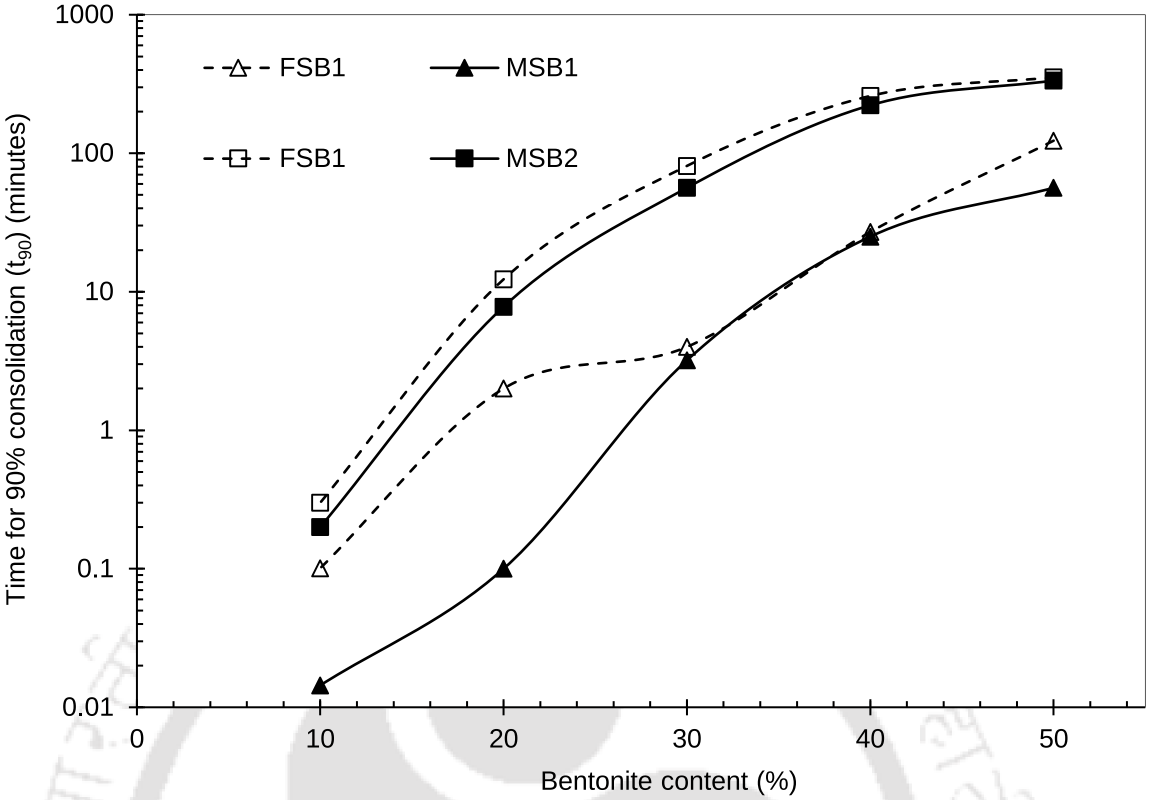


Figure 4.90 Effect of bentonite content on t_{90} of sand-bentonite mixtures compacted at 5% wet of OMC-MDD, under a load of 196.2 kPa

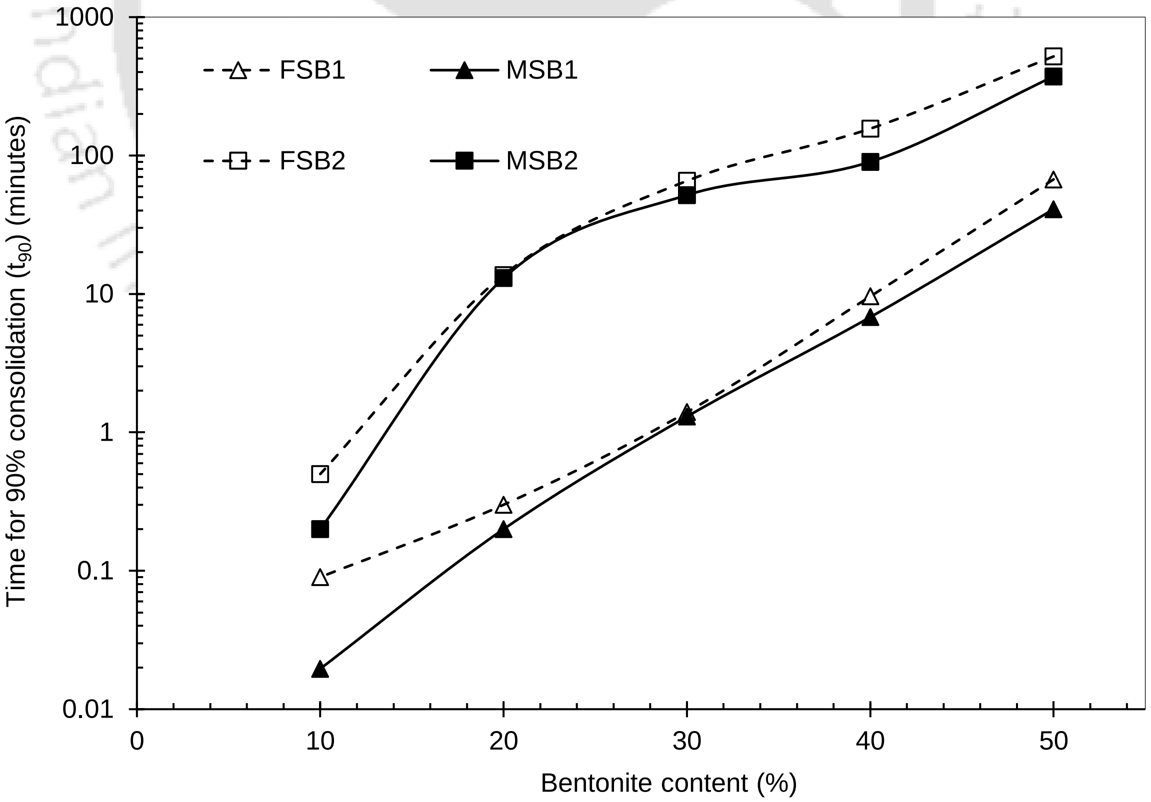


Figure 4.91 Effect of bentonite content on t_{90} of sand-bentonite mixtures compacted at 5% dry of OMC-MDD, under a load of 784.8 kPa

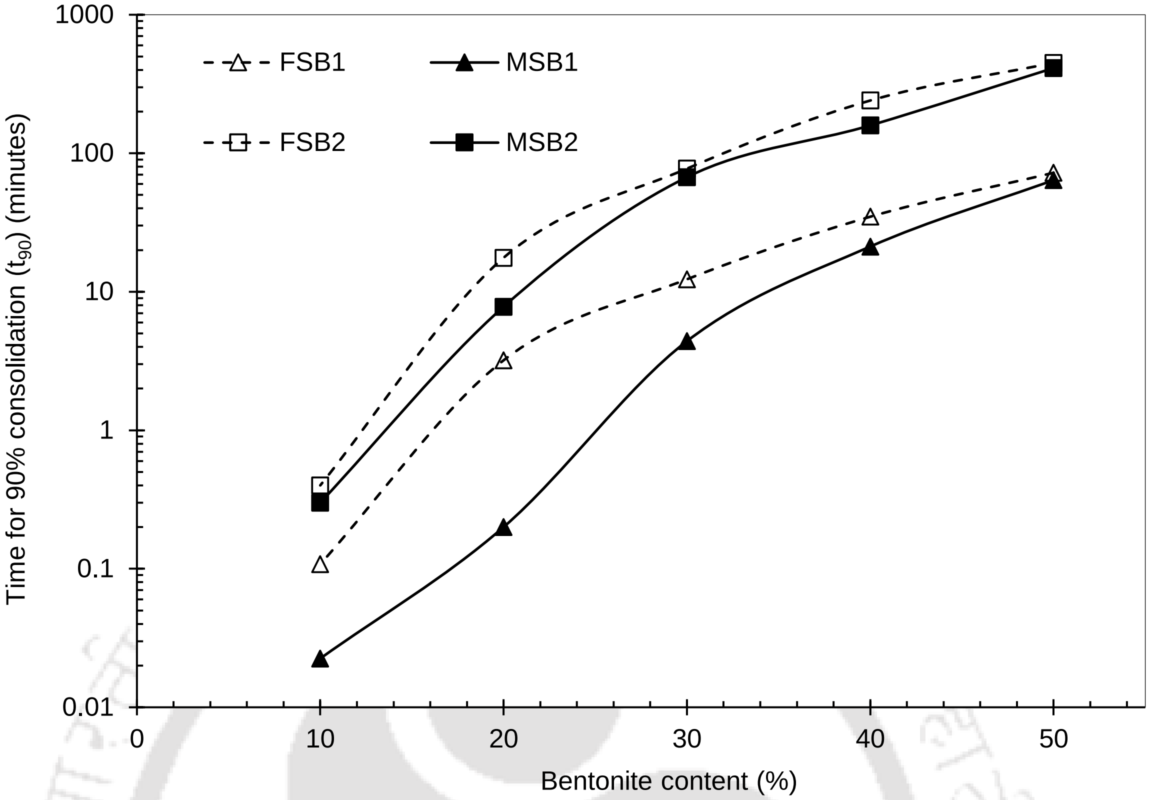


Figure 4.92 Effect of bentonite content on t_{90} of sand-bentonite mixtures compacted at OMC-MDD, under a load of 784.8 kPa

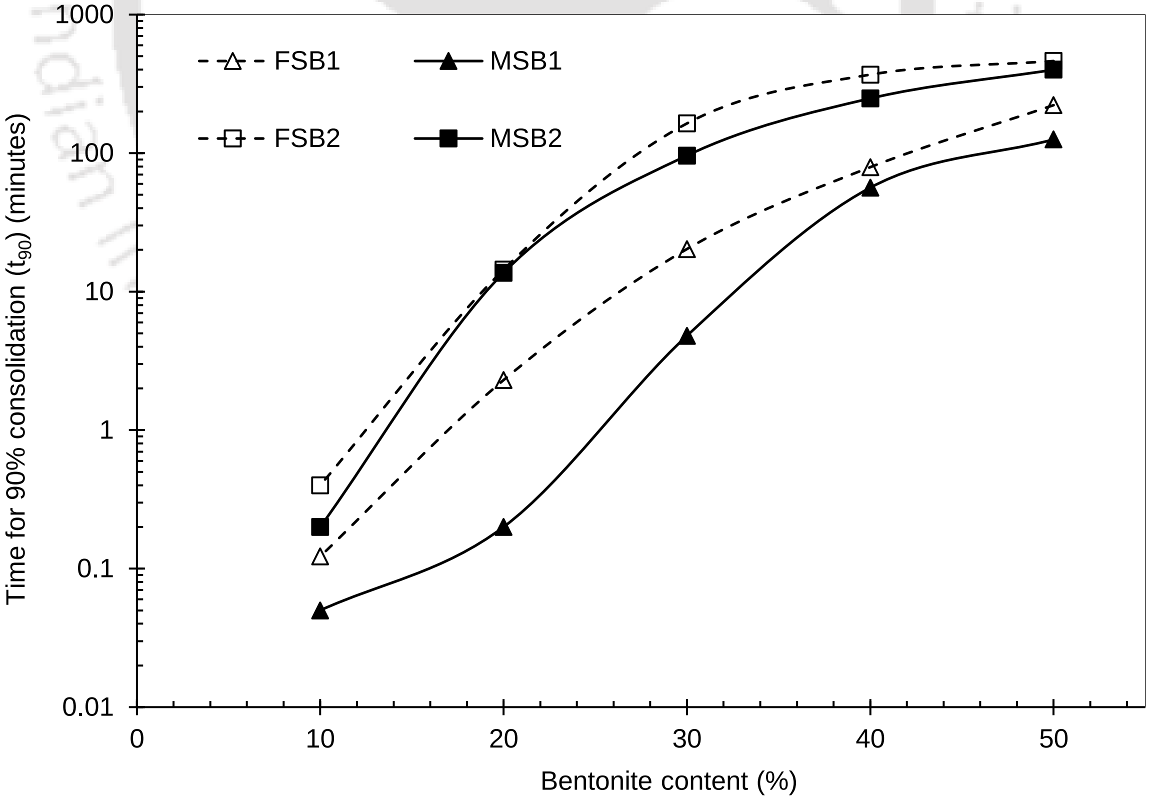


Figure 4.93 Effect of bentonite content on t_{90} of sand-bentonite mixtures compacted at 5% wet of OMC-MDD, under a load of 784.8 kPa

Compressibility characteristics exhibited by FS-B1 and MS-B1 mixtures are summarized in Table 4.7. Compression index (c_c) is defined as the slope of the virgin compression line in the *e*-log *P* curve. Compression index represents the ease of volume change when acted upon by a surcharge load. Observations indicated that compression index is increasing with bentonite content and the reason being the physical compression of diffuse double layers, formed around the bentonite particles upon hydration, is more in case of mixtures with high bentonite content when acted upon by increased surcharge load. Mixes made using medium sand exhibited relatively higher c_c values indicating the ease of breakdown of relatively larger voids in the medium sand skeleton. The compressibility characteristics exhibited by sand-bentonite-2 mixtures are summarized in Table 4.8. Bentonite-2 being a high expansive soil resulted in relatively higher c_c values.

Table 4.7 Summary of compression index results of FS-B1 and MS-B1 mixtures

	Mix proportion (S:B)	**Compression index (c_c)**		
		Compaction condition		
		OMC	**5% dry of OMC**	**5% wet of OMC**
Medium Sand (MS)	0:100	0.506	0.326	0.380
	50:50	0.400	0.235	0.365
	60:40	0.385	0.273	0.356
	70:30	0.093	0.143	0.093
	80:20	0.057	0.089	0.060
	90:10	0.064	0.136	0.065
Fine Sand (FS)	0:100	0.506	0.326	0.380
	50:50	0.235	0.256	0.308
	60:40	0.222	0.269	0.145
	70:30	0.108	0.119	0.066
	80:20	0.165	0.087	0.073
	90:10	0.073	0.066	0.073

Table 4.8 Summary of compression index results of FS-B2 and MS-B2 mixtures

	Mix proportion (S:B)	**Compression index (c_c)**		
		Compaction condition		
		OMC	**5% dry of OMC**	**5% wet of OMC**
Medium Sand (MS)	**0:100**	0.670	0.729	0.576
	50:50	0.435	0.629	0.46
	60:40	0.345	0.348	0.312
	70:30	0.147	0.326	0.134
	80:20	0.087	0.148	0.089
	90:10	0.071	0.073	0.098
Fine Sand (FS)	**0:100**	0.670	0.729	0.576
	50:50	0.515	0.502	0.419
	60:40	0.371	0.522	0.483
	70:30	0.120	0.264	0.167
	80:20	0.106	0.179	0.068
	90:10	0.064	0.073	0.073

4.1.4 FIELD EMISSION SCANNING ELECTRON MICROSCOPE (FESEM) IMAGES OF COMPACTED SAND-BENTONITE MIXES

Field emission scanning electron microscope (FESEM) images of a few selected compacted sand-bentonite mixes were obtained and can be seen in Figs. 4.94 through Figs. 4.105. The purpose of this part of the study was to understand, microscopically, the effect of bentonite content, sand particle size and bentonite quality on the formation of voids and their effective filling in a compacted sand-bentonite mixture. Compacted sample of FS-B1, MS-B1, FS-B2 and MS-B2 mixtures with 50%, 30% and 10% bentonite content were made with initial mixing water content to their respective OMC and compacted to their MDD. Comparison confirmed that fine sand mixtures possessed a large number of small voids while medium sand mixtures exhibited a few but relatively bigger voids. With the reducing bentonite content in the mixtures, size and the number of voids were found to be increasing. A closer look at FS-B2 mixes indicated that B2 virtually filled all the voids in the sand skeleton. Comparing sand-bentonite-1 and sand-bentonite-2 mixtures indicated that voids in FS-B2 and MS-B2 mixes were filled to a relatively larger extent unlike the FS-B1, MS-B1 mixes at respective MDD.

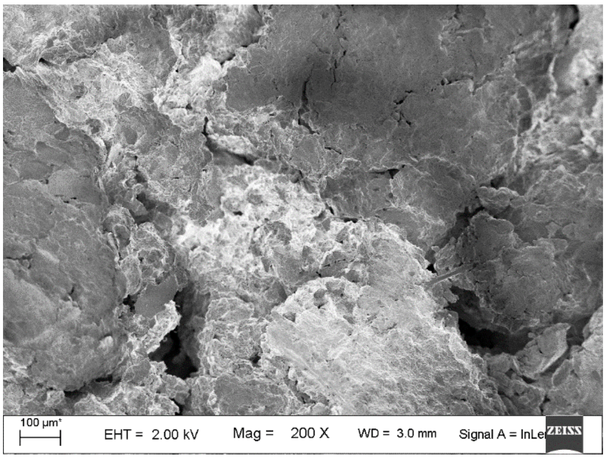


Figure 4.94 MS-B1 50-50 at OMC-MDD

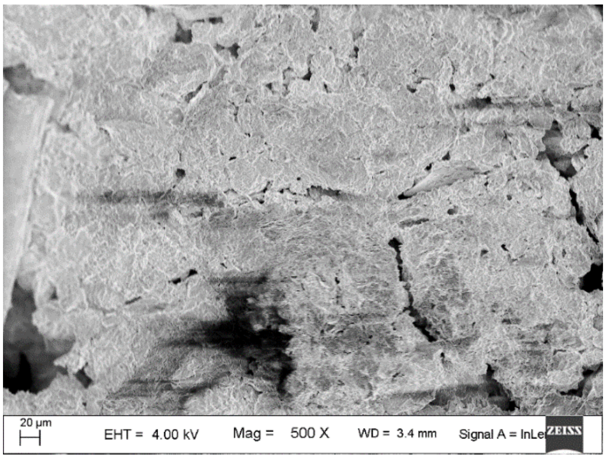


Figure 4.95 FS-B1 50-50 at OMC-MDD

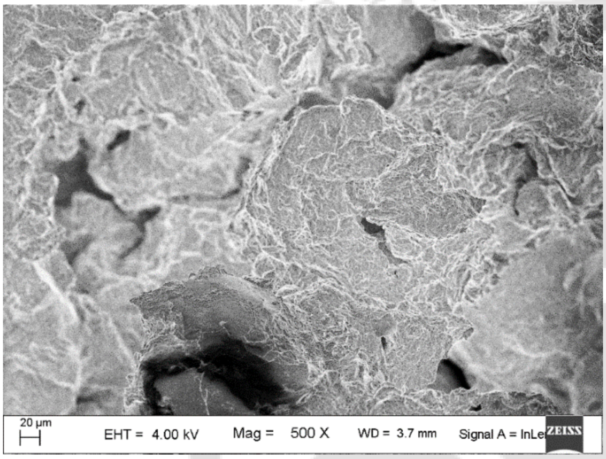


Figure 4.96 MS-B1 70-30 at OMC-MDD

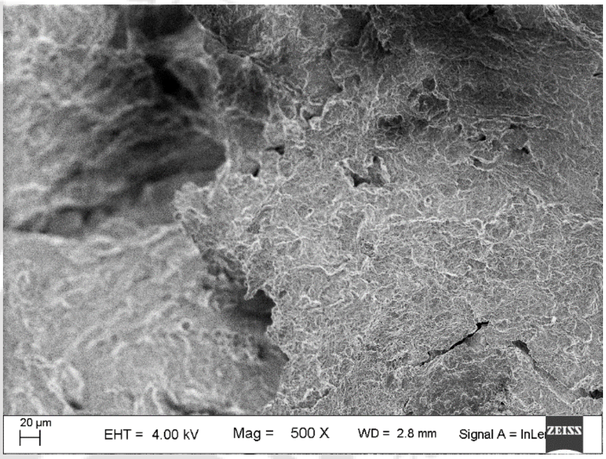


Figure 4.97 FS-B1 70-30 at OMC-MDD

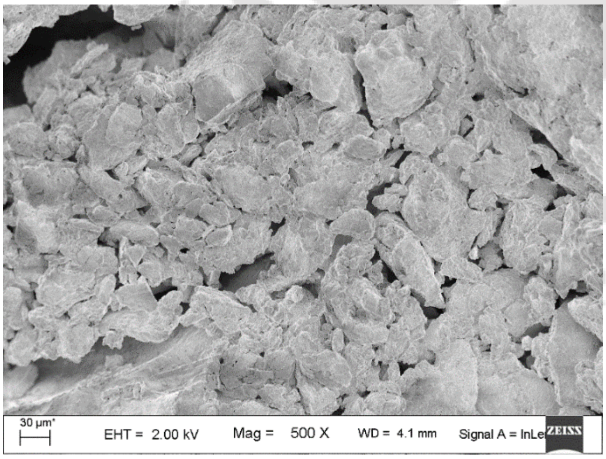


Figure 4.98 MS-B1 90-10 at OMC-MDD

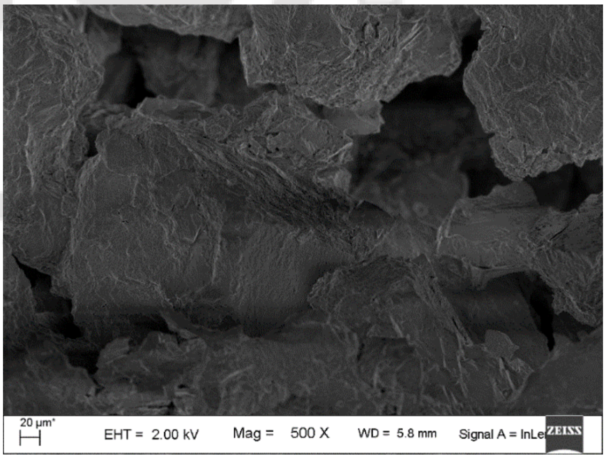


Figure 4.99 FS-B1 90-10 at OMC-MDD

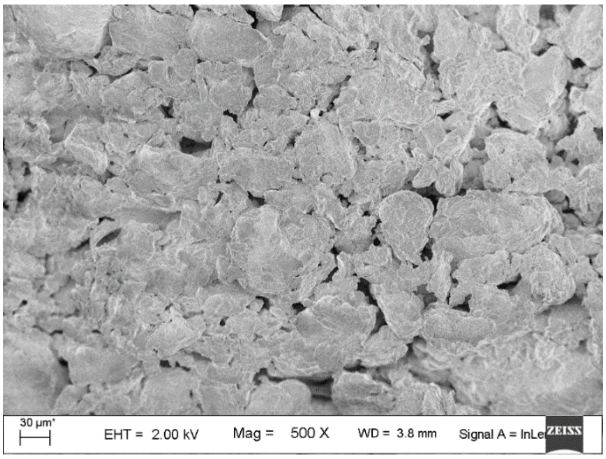


Figure 4.100 MS-B2 50-50 at OMC-MDD

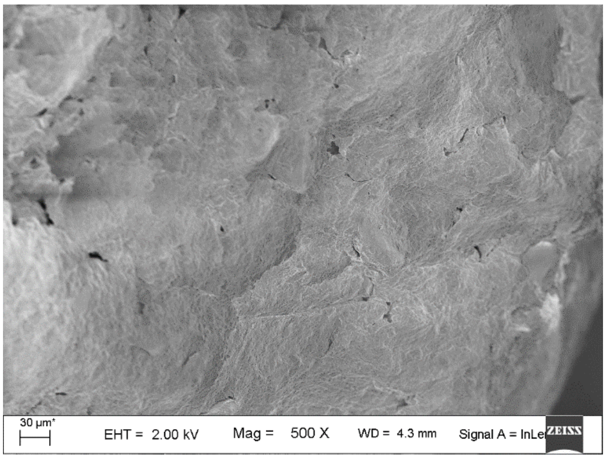


Figure 4.101 FS-B2 50-50 at OMC-MDD

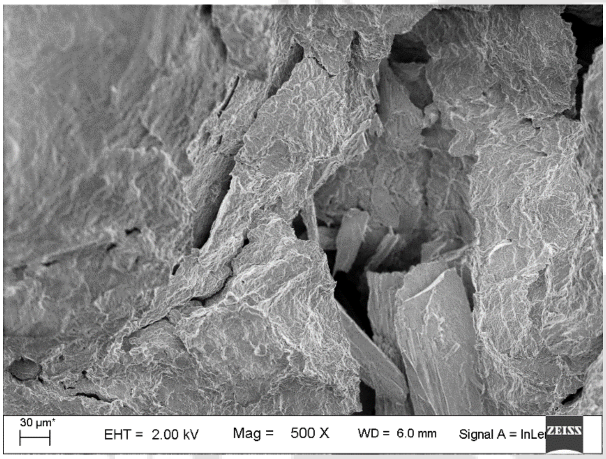


Figure 4.102 MS-B2 70-30 at OMC-MDD

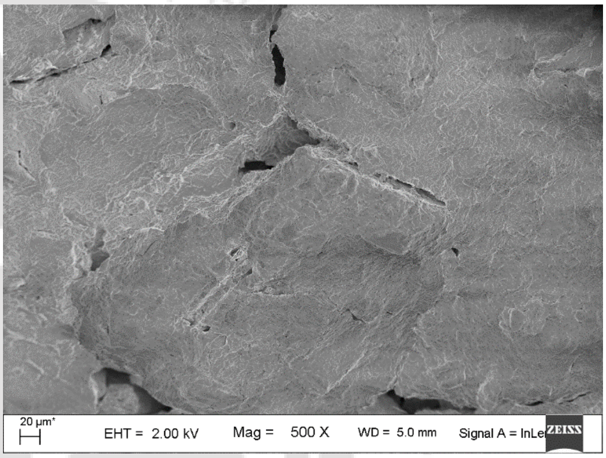


Figure 4.103 FS-B2 70-30 at OMC-MDD

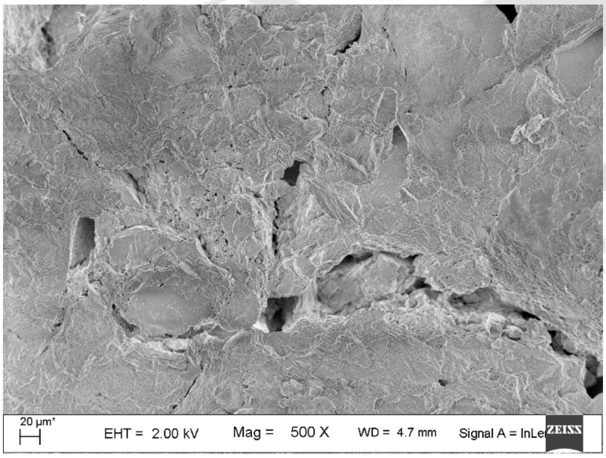


Figure 4.104 MS-B2 90-10 at OMC-MDD

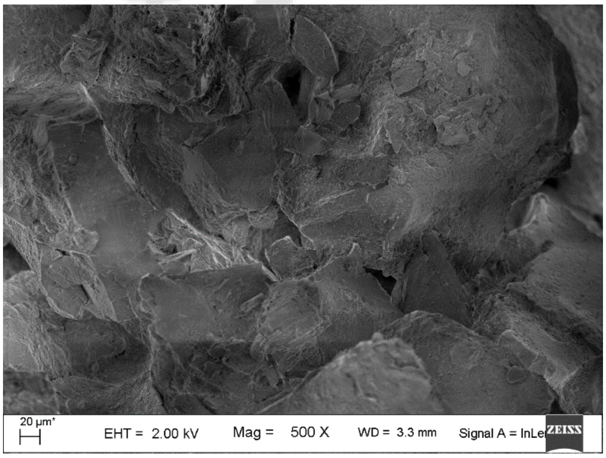


Figure 4.105 FS-B2 90-10 at OMC-MDD

4.1.5 SHRINKAGE CHARACTERISTICS

4.1.5.1 Shrinkage behaviour of fine sand-bentonite-1 and medium sand-bentonite-1 mixes

Volume changes take place when a compacted soil mass is allowed to dry. The study of temperature based volume changes are generally referred to as desiccation studies. Uncontrolled and uneven volume changes lead to cracks, which are undesirable in geotechnical barriers. Since cracks form the pathways for fluid movement through the barrier leading to increased hydraulic conductivity, which is detrimental to the barrier performance. Therefore, desiccation studies assume greater importance while dealing with geotechnical barrier materials. This part of the study is focused on understanding the role of bentonite content, sand particle size and initial compaction condition on the linear and radial shrinkage behavior of FS-B1 and MS-B1 mixtures.

While linear shrinkage represents the change in length, radial shrinkage represents the change in diameter of the compacted soil sample due to drying process. Shrinkage characteristics of FS-B1 and MS-B1 mixtures are presented in Figs. 4.106 through Figs. 4.109. Results indicated that bentonite content plays a dominant role in the shrinkage behavior both linearly and radially. Shrinkage results indicated that MS-B1 mixes were shrinking more than FS-B1 mixes, with FESEM images reinforcing the idea that MS-B1 mixes exhibit relatively larger voids, it can be understood that larger voids undergo volume changes relatively easily with changes in temperature. With samples compacted on wet of OMC shrinking more followed by those at OMC and trailing by those at dry of OMC, it can be noted that shrinkage is proportional to the amount of water available in the sample. Radial shrinkage was relatively higher as compared to linear shrinkage for all mix proportions and compaction conditions.

4.1.5.2 Shrinkage behaviour of fine sand-bentonite-2 and medium sand-bentonite-2 mixes

Shrinkage characteristics of FS-B2 and MS-B2 mixtures are presented in Figs. 4.112 through Figs. 4.117. Medium sand mixtures were found to be exhibiting a relatively higher shrinkage, both linear and radial, as has been the case with FS-B1 and MS-B1 mixtures. Upon close scrutiny, it can be seen that though B1 and B2 are 2 different bentonites with distinct swelling capabilities the shrinkage behavior exhibited is almost similar, indicating the possibility that shrinkage is more of a particle size dependent phenomenon.

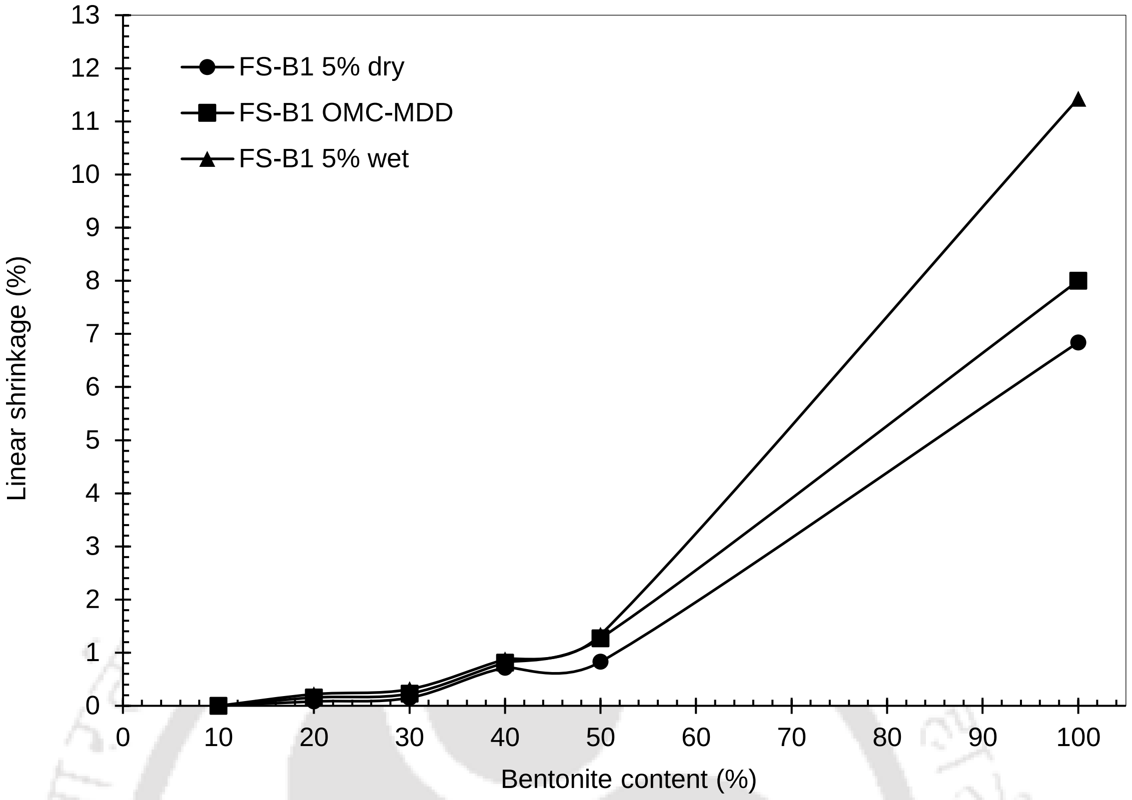


Figure 4.106 Linear shrinkage – bentonite content relationship of FS-B1 samples at three different compaction conditions

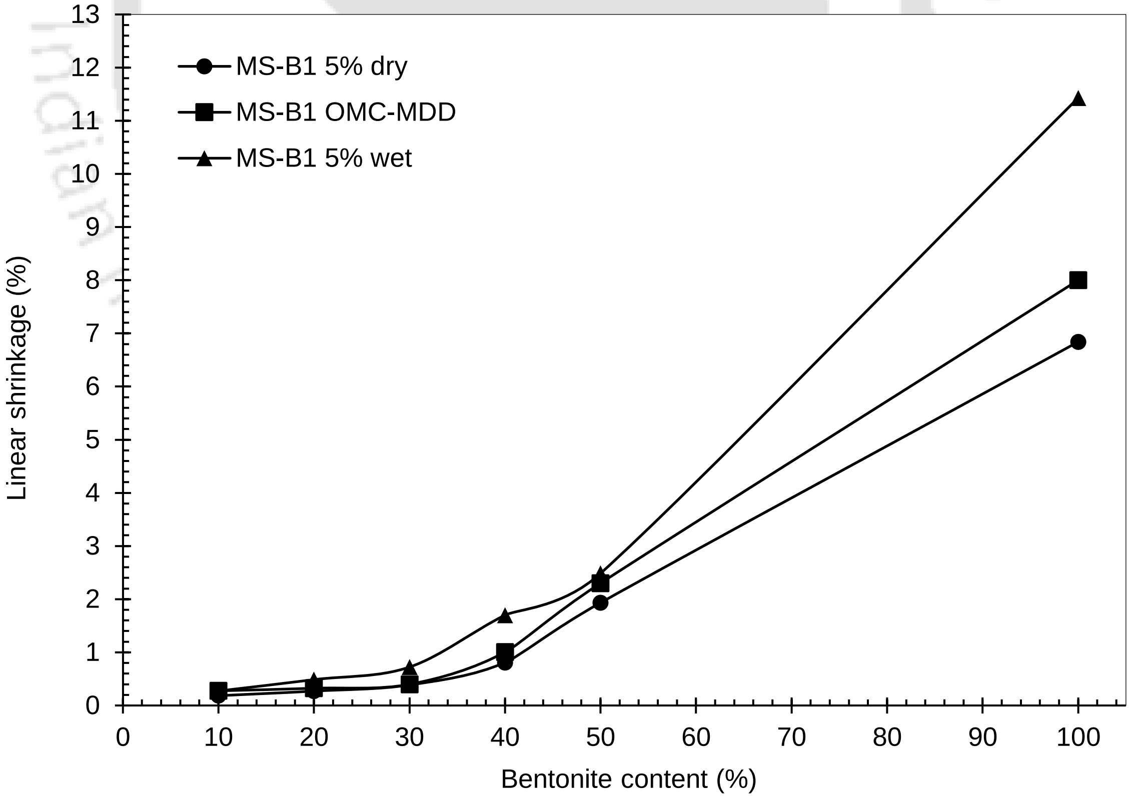


Figure 4.107 Linear shrinkage – bentonite content relationship of MS-B1 samples at three different compaction conditions

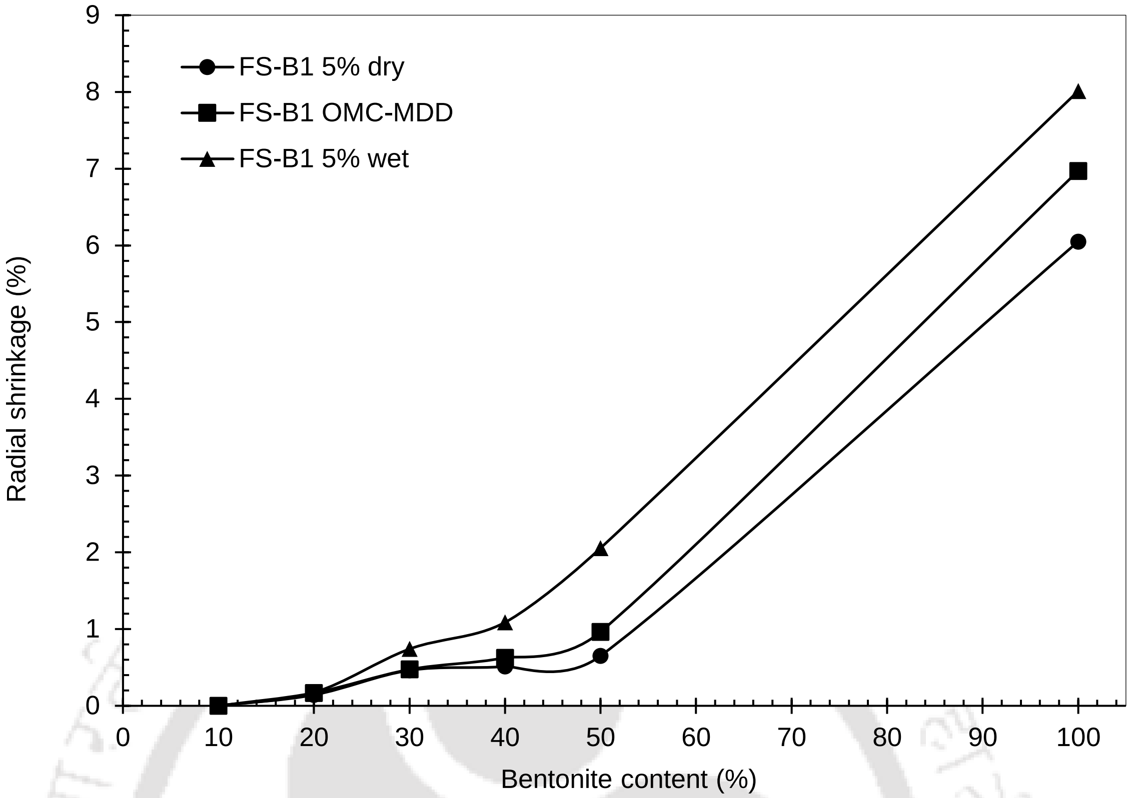


Figure 4.108 Radial shrinkage – bentonite content relationship of FS-B1 samples at three different compaction conditions

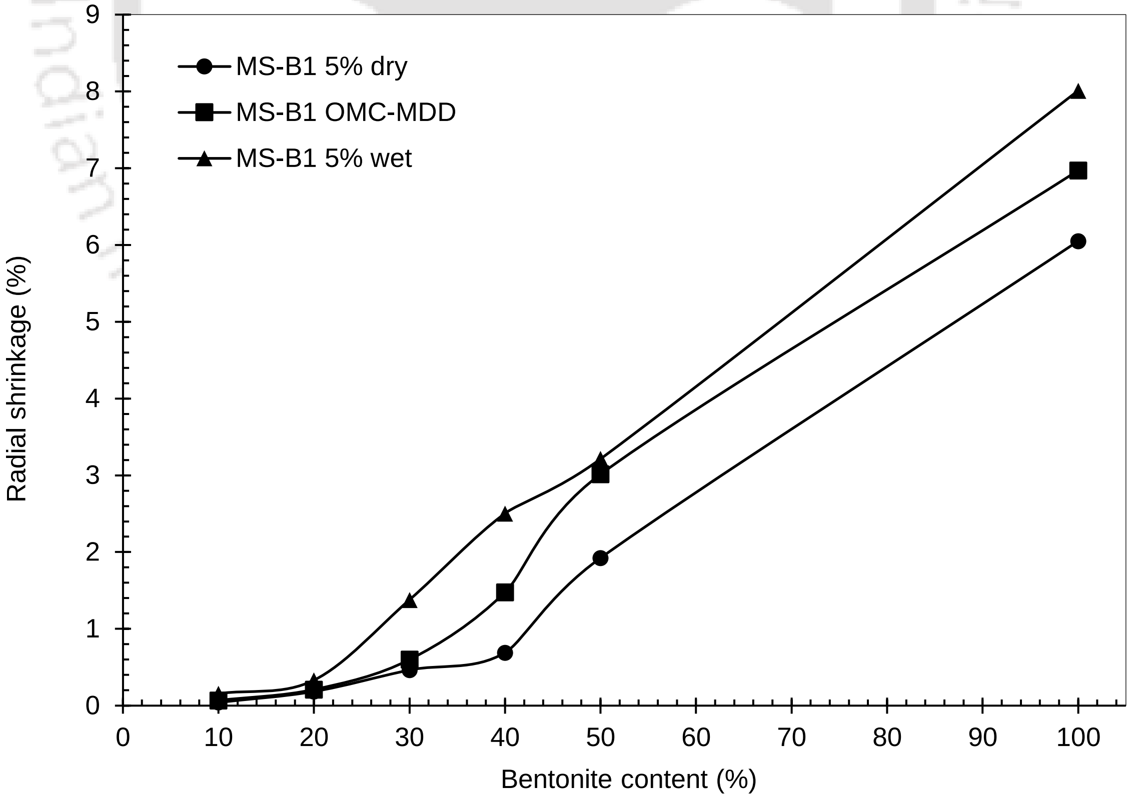


Figure 4.109 Radial shrinkage – bentonite content relationship of MS-B1 samples at three different compaction conditions

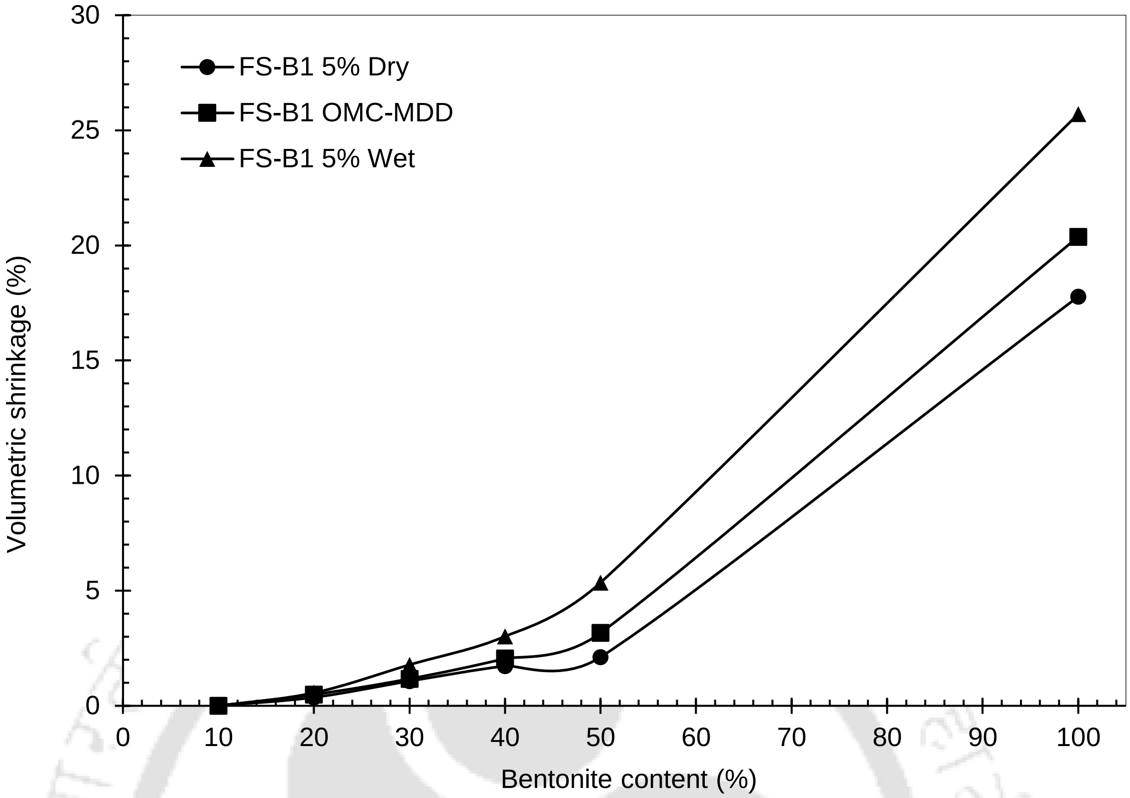


Figure 4.110 Volumetric shrinkage – bentonite content relationship of FS-B1 samples at three different compaction conditions

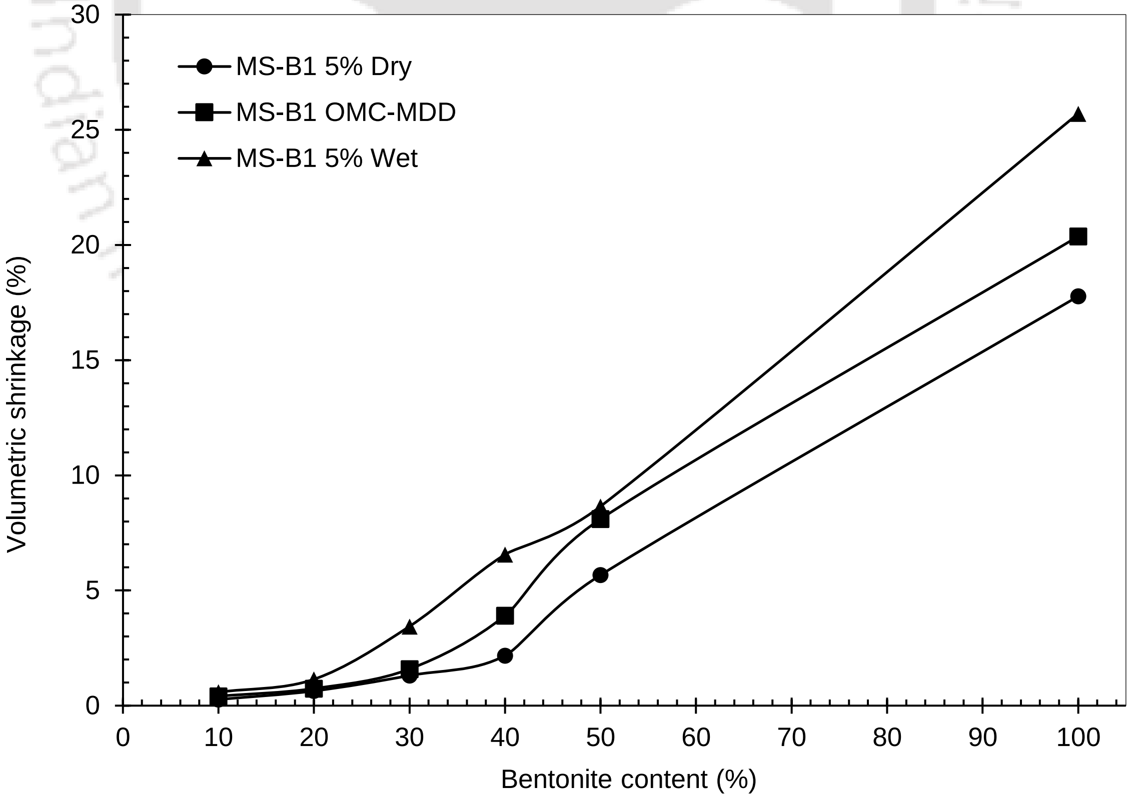


Figure 4.111 Volumetric shrinkage – bentonite content relationship of MS-B1 samples at three different compaction conditions

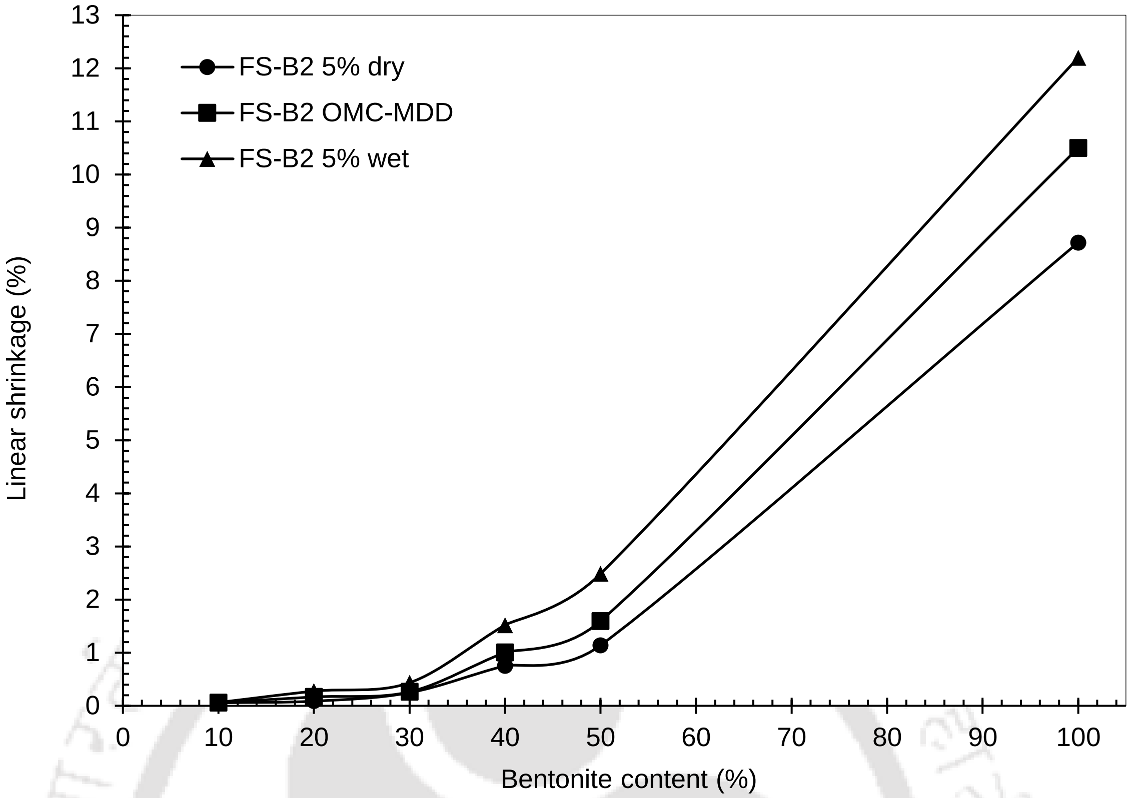


Figure 4.112 Linear shrinkage – bentonite content relationship of FS-B2 samples at three different compaction conditions

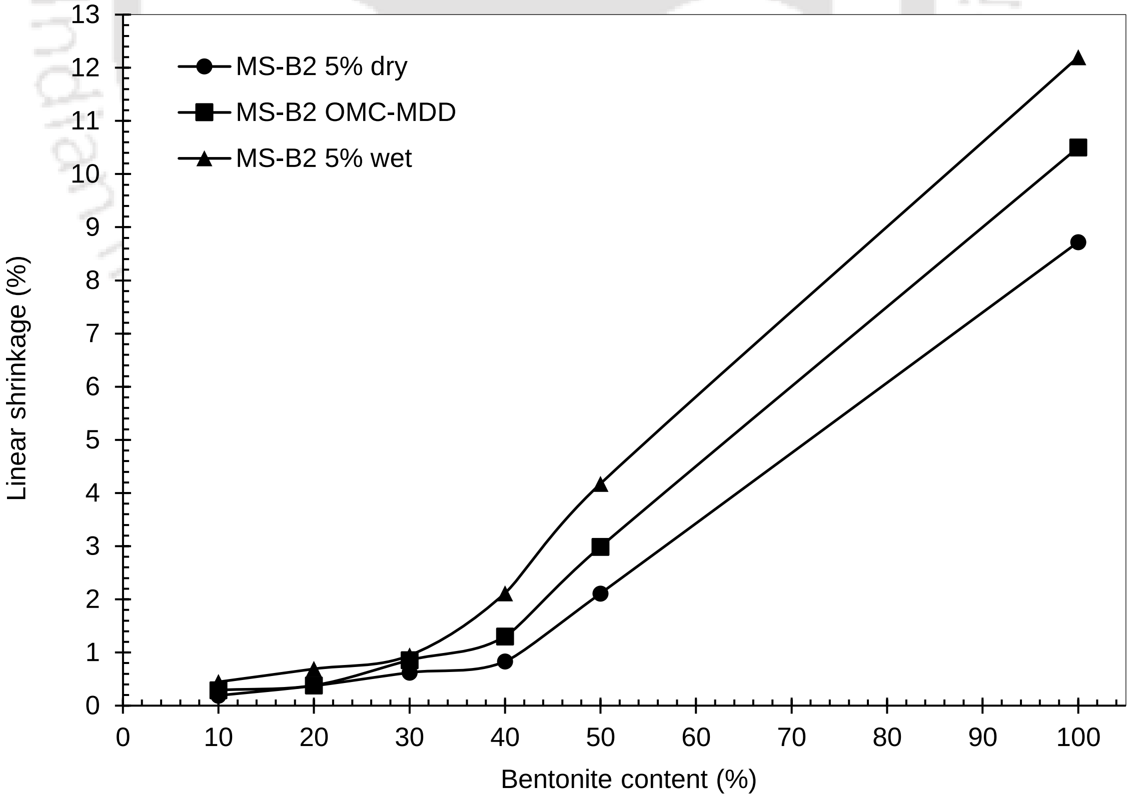


Figure 4.113 Linear shrinkage – bentonite content relationship of MS-B2 samples at three different compaction conditions

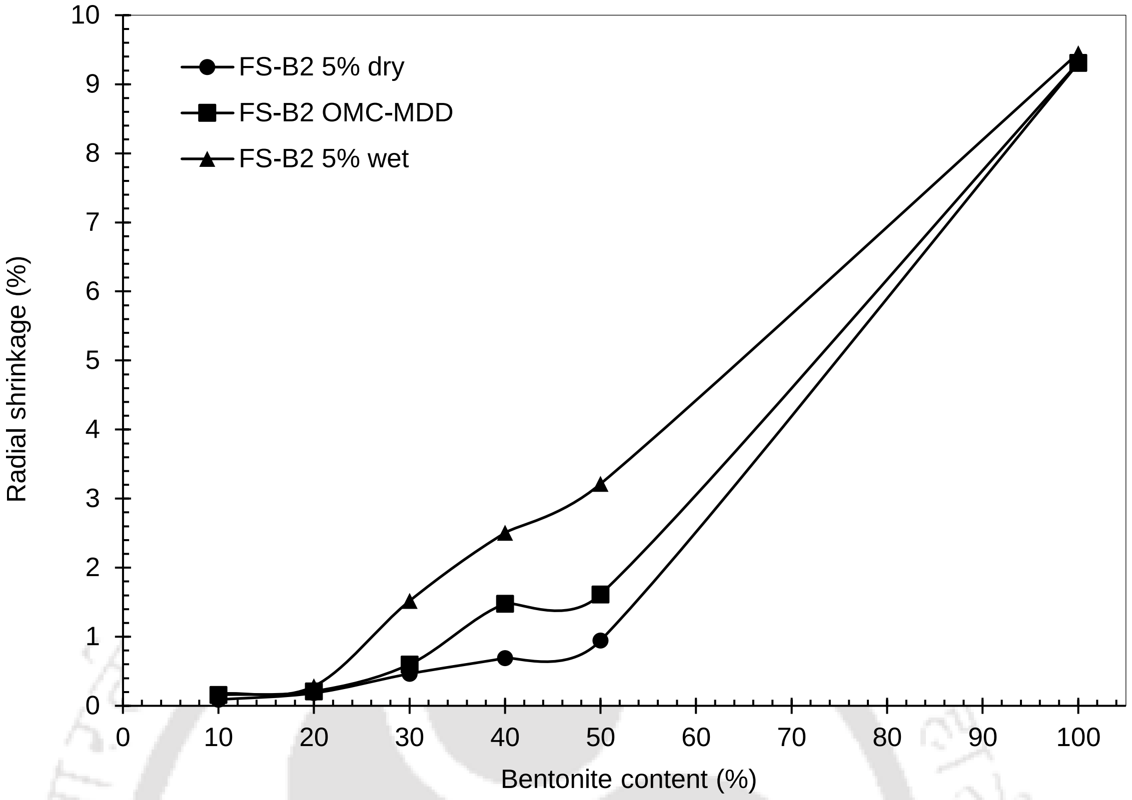


Figure 4.114 Radial shrinkage – bentonite content relationship of FS-B2 samples at three different compaction conditions

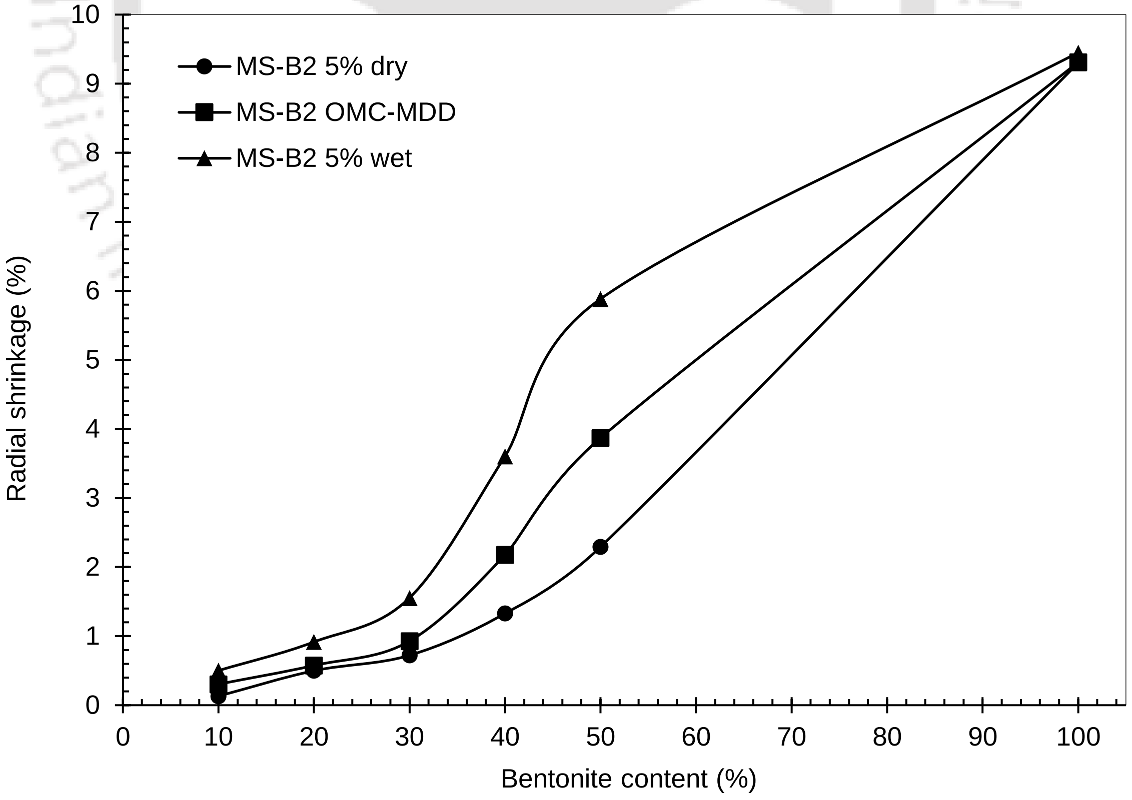


Figure 4.115 Radial shrinkage – bentonite content relationship of MS-B2 samples at three different compaction conditions

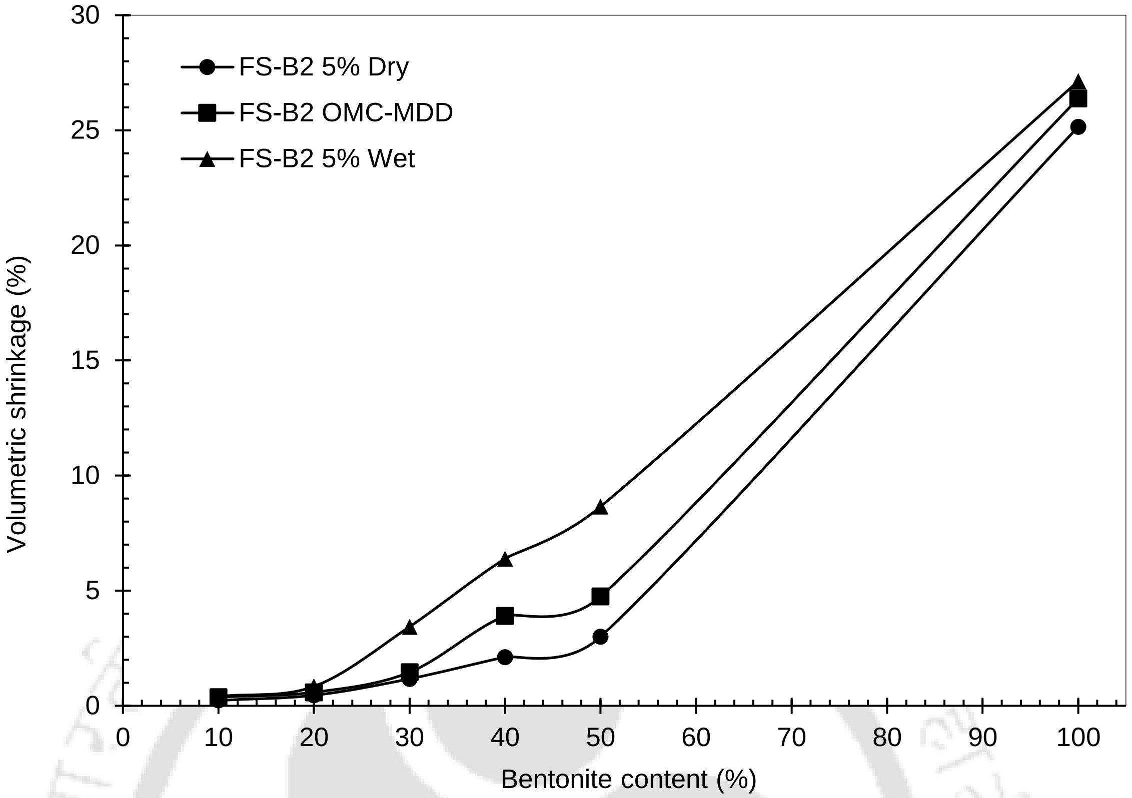


Figure 4.116 Volumetric shrinkage – bentonite content relationship of FS-B2 samples at three different compaction conditions

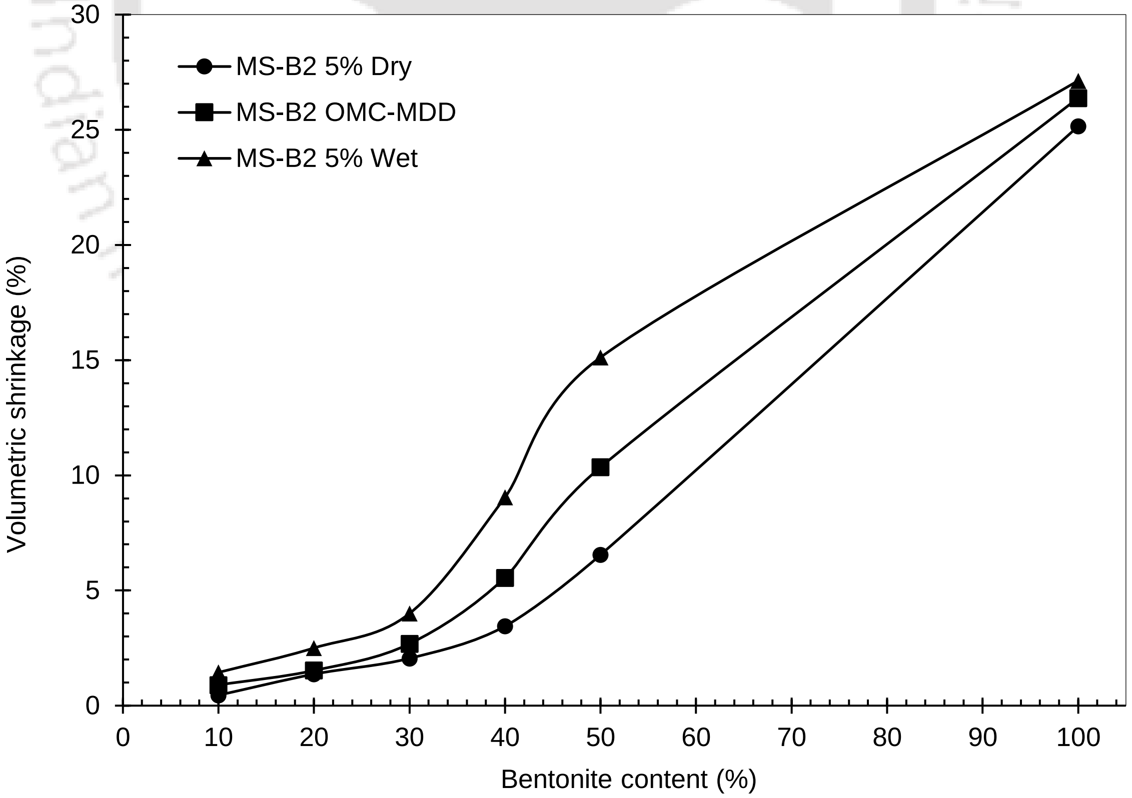


Figure 4.117 Volumetric shrinkage – bentonite content relationship of MS-B2 samples at three different compaction conditions

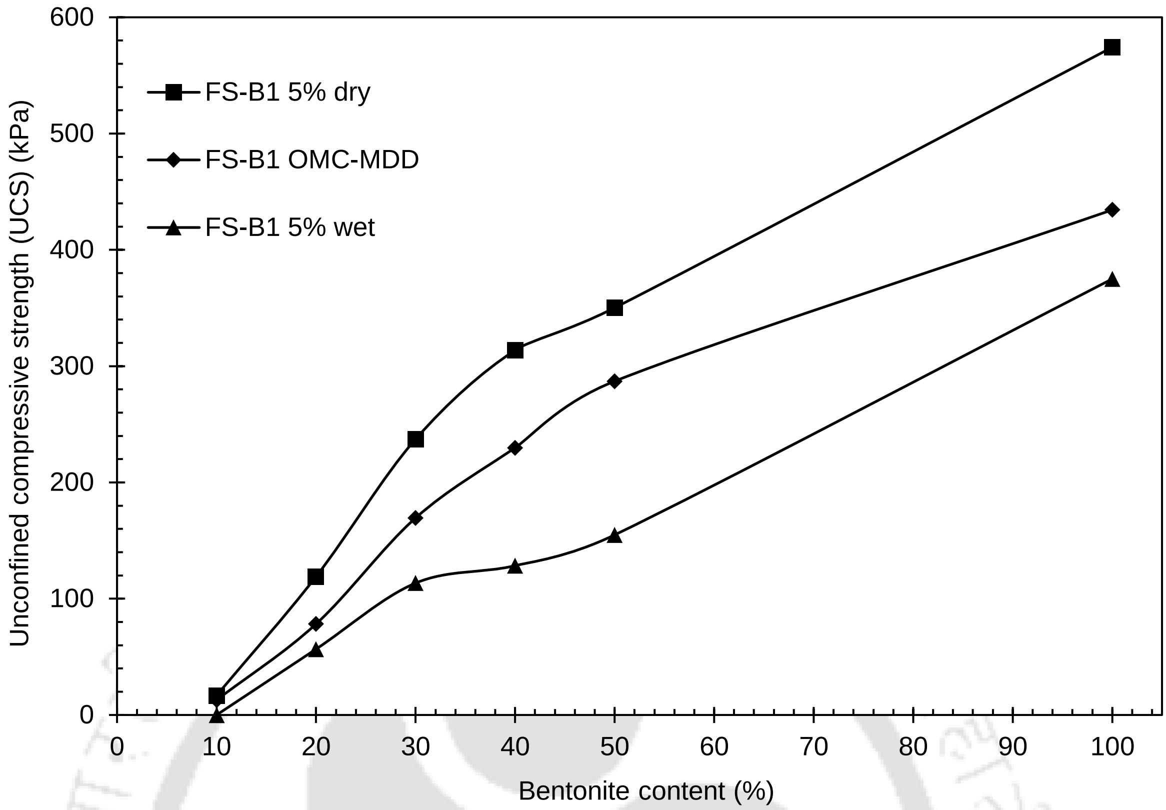


Figure 4.118 Effect of bentonite proportion and compaction condition on unconfined compressive strength of FS-B1 mixes

4.1.6 UNCONFINED COMPRESSIVE CHARACTERISTICS

4.1.6.1 Unconfined compressive strength (UCS) of fine sand-bentonite-1 and medium sand-bentonite-1 mixes

Unconfined compressive strength (UCS) test provides a preliminary idea of the strength characteristics of cohesive soils without going into using complicated triaxial test procedures. Figures 4.118 and Figs. 4.119 present the UCS results of the FS-B1 and MS-B1 mixes. These mixes were compacted at three different compaction conditions. The emphasis of this part of the study was to understand the influence of compaction water content and role of sand type on the strength characteristics of sand-bentonite mixes. The following observations were made from this study;

1) Compressive strength increases with increase in bentonite content. The plots also show that for any compaction condition increase of strength with bentonite content was not linearly proportional to bentonite content in the mixture;
2) Samples compacted on the dry side of OMC exhibited a higher strength and those compacted on the wet of OMC exhibiting lowest strength. At lower water contents bentonite particles share the little amount of water available and the affinity of bentonite clay towards water is high, leading to a higher resistance towards any

external loading. The same resistance is reflected as higher shear strength in case of samples compacted on the dry side of OMC. As more water is added to the sand-bentonite mixture, diffuse double layer starts developing by adsorbing the water on to the surface of clay particles resulting in a lowering affinity towards water resulting in the reduction in strength.

3) FS-B1 mixes exhibited a higher strength compared to medium sand counterparts.

4.1.6.1.2 Unconfined compressive strength of fine sand-bentonite-2 and medium sand-bentonite-2 mixes

Strength characteristics of FS-B2 and MS-B2 mixes are as shown in the Figs. 4.120 and Figs. 4.121. An improvement in the strength characteristics in comparison to FS-B1 and MS-B1 mixes could be seen in the mixes with B2 content less than 30%. Bentonite-2 is a high swelling sodium bentonite and it seems that the effect of this high swelling nature is reflected in the mixes with B2 content less than 30%. In the mixes with B2 content greater than 30%, MS-B2 mixtures are exhibiting higher strength as compared to fine sand counterparts.

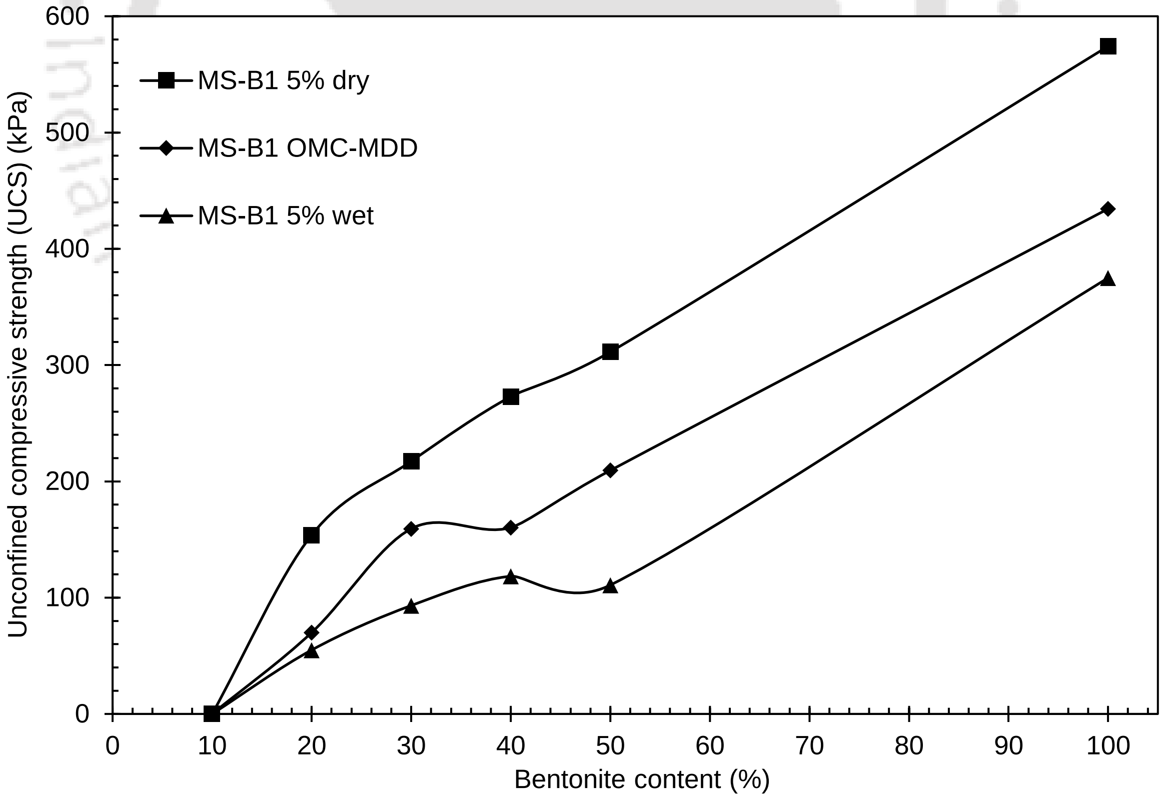


Figure 4.119 Effect of bentonite proportion and compaction condition on unconfined compressive strength of MS-B1 mixes

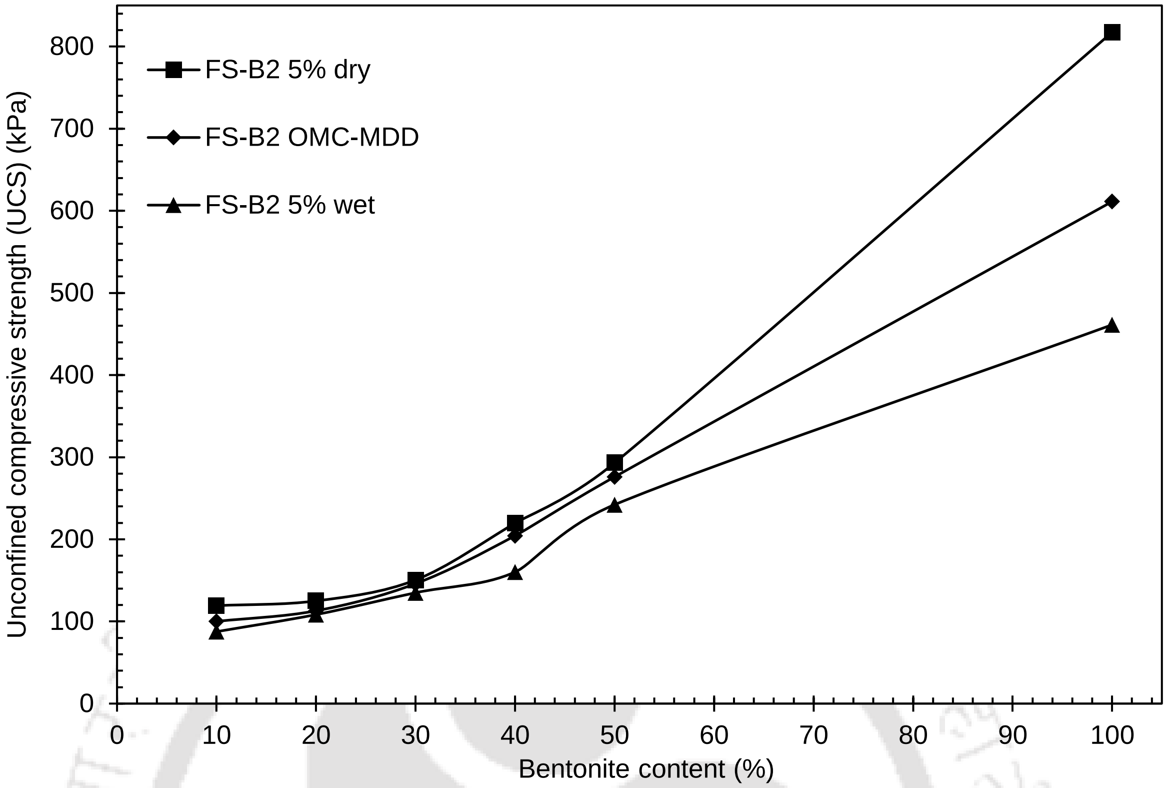


Figure 4.120 Effect of bentonite proportion and compaction condition on unconfined compressive strength of FS-B2 mixes

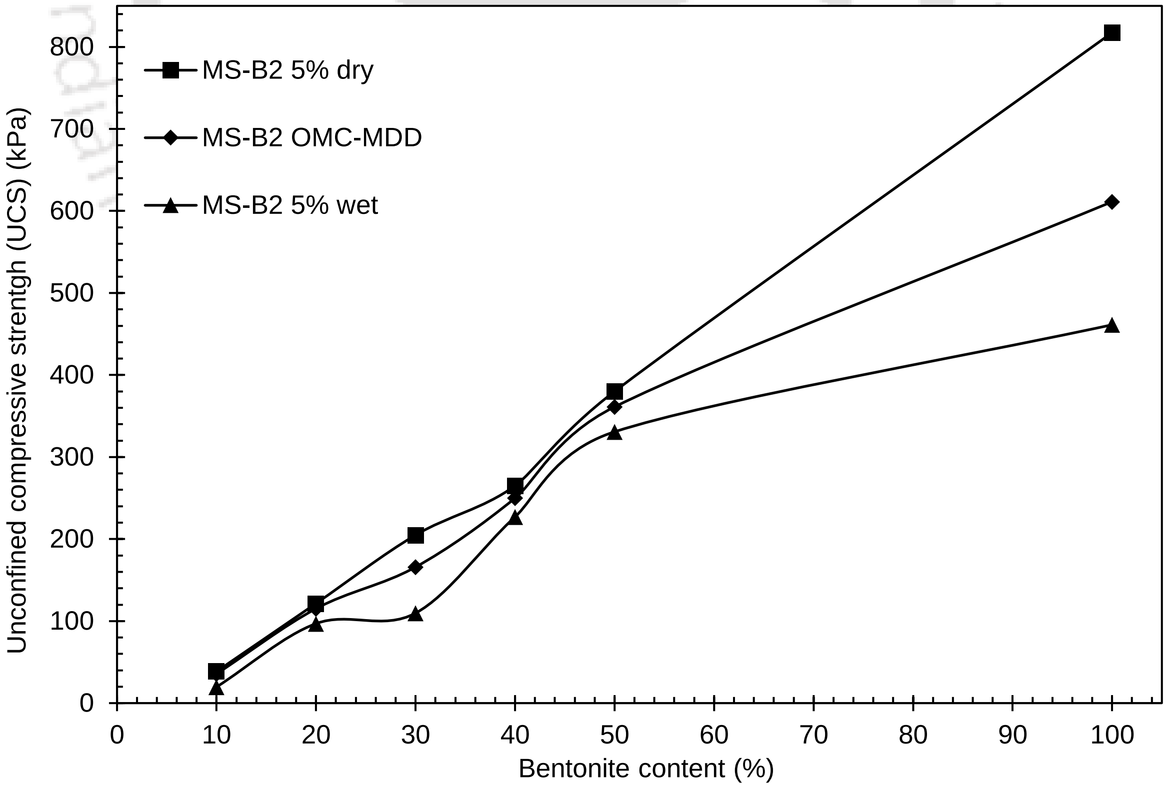


Figure 4.121 Effect of bentonite proportion and compaction condition on unconfined compressive strength of MS-B2 mixes

4.2 INFLUENCE OF FINE AND MEDIUM SAND COMPOSITION ON THE BEHAVIOR OF SAND-BENTONITE MIXTURES

Influence of fine sand and medium sand on the engineering behaviour of sand-bentonite mixtures has been established and presented in section 4.1. Further to study the influence of the sand compositions, tests were performed on various combination of the mixtures of bentonite and sand, with sand containing both fine sand and medium sand in various proportions. The results and analysis of the behaviour of the mixtures are presented in this section. The main purpose of this investigation is to understand the role of sand proportioning, and the extent to which it can influence the engineering behaviour of sand-bentonite mixtures. Atterberg limits, Standard Proctor compaction test, one-dimensional consolidation test, unconfined compressive strength test and shrinkage test were performed on different sand-bentonite mixes with bentonite content ranging from 10% to 50% by dry weight. Sand content in the mixtures was made by mixing fine sand and medium sand in various proportions with fine sand to medium sand proportions varying from 30:70 to 70:30.

4.2.1 ATTERBERG LIMITS OF FINE SAND-MEDIUM SAND-BENTONITE MIXES

Samples were prepared by adding sand containing different proportions of fine sand (FS) and medium sand (MS) to both the bentonites. The sand content in the mixtures was varied from 90% to 50% by dry weight. The proportions of FS and MS in the sand were varied from 30:70 to 70:30. Liquid limit and plastic limit were determined in accordance with ASTM D 4318 (2000). Since the mixes were having high sand content, cone penetration test was carried out to determine the liquid limit of the mixes. The Atterberg limits of different fine sand-medium sand-bentonite-1 (FS-MS-B1) and fine sand-medium sand-bentonite-2 (FS-MS-B2) mixtures are as shown in the Table 4.9 and 4.10 and plotted in Figs. 4.122 and 4.123, respectively. It can be seen from the Fig. 4.122 that for any given B1 content, increasing FS content in the mix resulted in an increased liquid limit value, in fact the change in the liquid limit was very subtle with the difference between highest and the lowest values being less than 5%. Liquid limit of the mixes was seen to change rapidly with the bentonite content in the mixture; where, a general decreasing trend in the liquid limit values was noticed with decreasing bentonite content in the mixture. A similar trend was observed with FS-B1 mixes and MS-B1 mixes as well. Liquid limit result exhibited by FS-MS-B2 mixtures is shown in Fig. 4.123. Liquid limit results for FS-MS-B2 mixtures indicate an increment in liquid limit with increasing fine sand content in the mixture for any given bentonite content. The difference between highest and the lowest values observed for any B2 proportion was in the range of 2-10% water content, indicating a very little influence of sand proportioning on liquid limit. For both FS-MS-B1 and FS-MS-B2 mixtures, even though the differences were small, observed values indicated that liquid limit of soil mixtures exhibited the following order;

FS-B1 > FS-MS-B1 > MS-B1

Table 4.9 Summary of Atterberg limits of FS-MS-B1 mixtures

	Sand –Bentonite 1 (S:B1) proportion	FS-MS proportions				
		30:70	40:60	50:50	60:40	70:30
Liquid limit	50:50	75.0	76.4	77	77	77.7
	60:40	59.3	62.9	63.8	64.4	64.5
	70:30	49.6	50.4	50.5	50.6	52.6
	80:20	41.3	42.7	43.5	44.3	45.6
	90:10	29	30	31.4	34.6	34.7
Plastic limit	50:50	19.6	20.3	20.4	20.5	21.3
	60:40	18.4	19.1	19.6	21.2	22.5
	70:30	16.1	16.2	16.7	17.3	20.6
	80:20	*	*	*	*	*
	90:10	*	*	*	*	*
Shrinkage limit	50:50	15.2	18.9	21.4	21.7	18.5
	60:40	29.7	21.1	28.2	17.4	28.1
	70:30	31.8	28	25.7	23.4	28.0
	80:20	23.9	23.8	25.1	24.2	25.0
	90:10	23.7	24.1	28.5	25.7	25.4
Plasticity Index	50:50	54.7	56.8	55.7	56.6	57.2
	60:40	44.2	46.0	38.1	42.0	43.8
	70:30	34.2	32.3	29.9	34.4	35.9
	80:20	*	*	*	*	*
	90:10	*	*	*	*	*

* Could not be determined

Plastic limit of a soil is identified as the water content at which a 100-fold increment in shear strength relative to that at liquid limit (Haigh et al., 2013). Plastic limit was found to be increasing with increasing bentonite content. For a given bentonite content, fine sand-medium sand-bentonite mixtures exhibited distinct plastic limit values for each fine-sand-medium sand proportion, and no particular trend could be identified as to the influence of sand proportioning is concerned.

Table 4.10 Summary of Atterberg limits of FS-MS-B2 mixtures

	Sand –Bentonite-2 (S:B2) proportions	FS-MS proportions				
		30:70	40:60	50:50	60:40	70:30
Liquid limit	50:50	152.6	153.0	153.5	154.2	156.5
	60:40	124.4	125.5	126.5	128.0	128.5
	70:30	89.7	93.9	94.1	96.3	98.5
	80:20	62.0	62.1	64.3	65.0	67.2
	90:10	38.4	38.8	38.8	39.9	40.0
Plastic limit	50:50	20.5	22.4	21.0	20.2	21.4
	60:40	19.5	23.9	23.0	24.1	26.9
	70:30	20.4	22.8	22.1	24.2	26.2
	80:20	17.8	21.1	17.7	21.1	22.4
	90:10	24.9	19.9	19.5	21.9	22.5
Shrinkage limit	50:50	28.7	31.2	30.2	28.5	27.2
	60:40	34.4	35.5	39.4	38.1	40.7
	70:30	35.6	35.0	36.2	34.1	34.7
	80:20	37.5	36.8	35.3	37.5	37.6
	90:10	27.7	26.9	27.3	28.7	30.3
Plasticity index	50:50	136.0	131.1	133.2	132.4	131.6
	60:40	106.0	97.6	105.0	100.3	99.6
	70:30	73.7	75.7	67.6	69.7	70.1
	80:20	46.5	46.1	44.4	40.9	42.6
	90:10	13.9	18.5	20.4	16.9	17.4

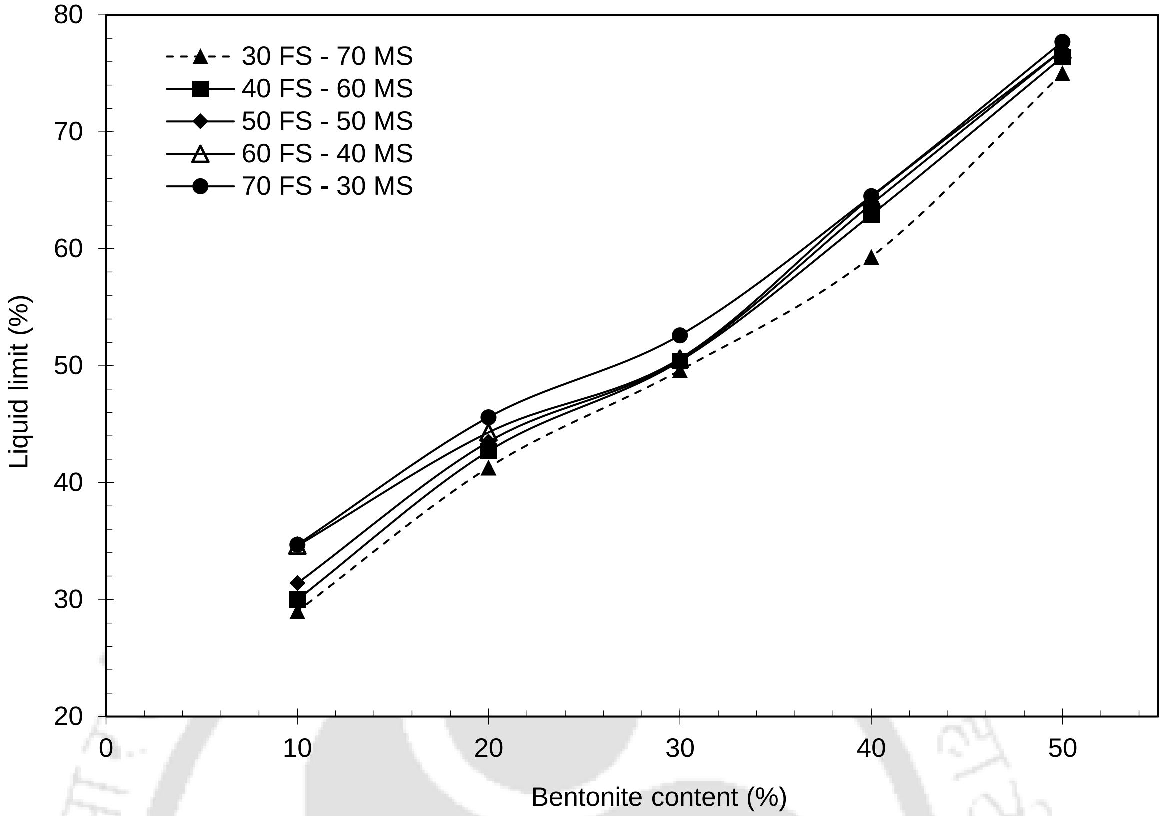


Figure 4.122 Variation of liquid limit of FS-MS-B1 mixtures with sand proportioning

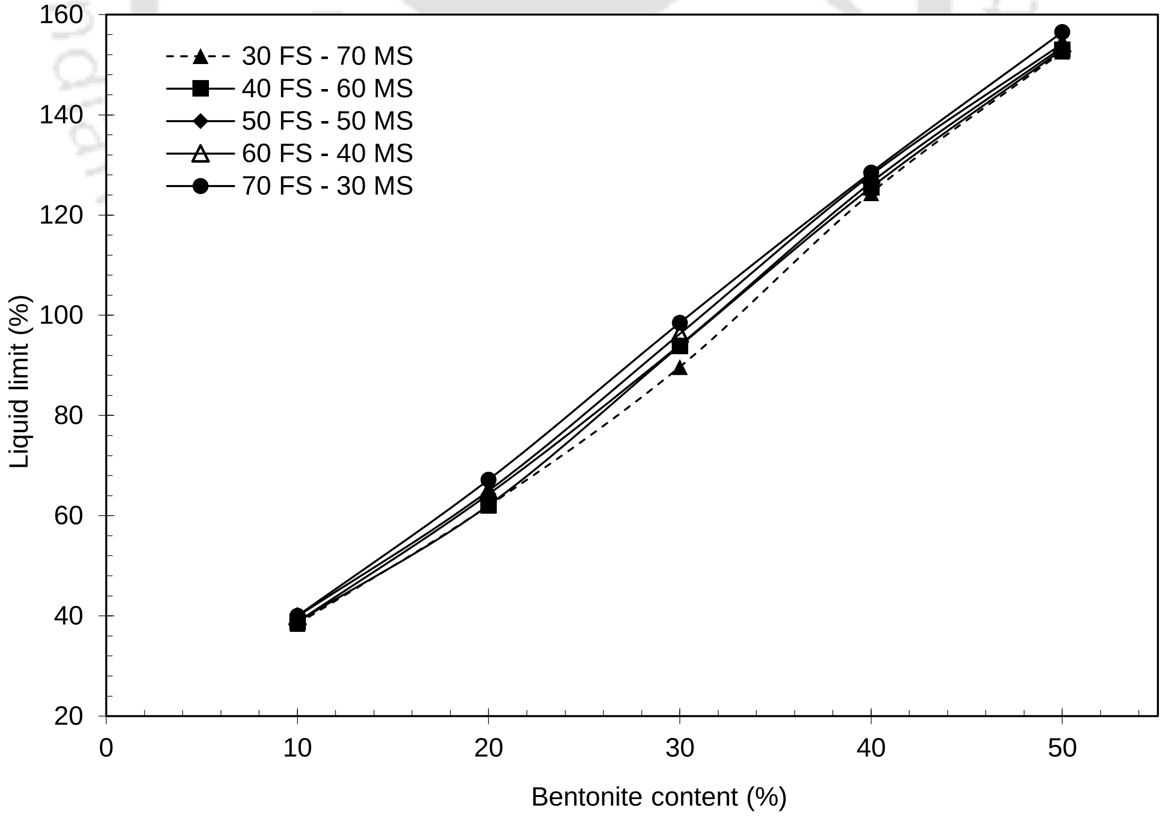


Figure 4.123 Variation of liquid limit of FS-MS-B2 mixtures with sand proportioning

Sridharan and Prakash (1998) indicated that shrinkage limit of a soil is a physical phenomenon unlike other Atterberg limits, and is primarily dependent on its particle size distribution. It can be understood from Table 4.9 and Table 4.10 that for any given bentonite content, there exists a unique FS-MS proportion that results in lowest shrinkage limit. Upon comparing FS-MS-B1 and FS-MS-B2 with FS-B1, MS-B1, FS-B2 and MS-B2 mixtures, increasing the sand proportion in the mix is not necessarily reflected as increased shrinkage limit indicating and reinforcing the idea that shrinkage limit is a relative packing phenomenon as proposed by Sridharan and Prakash (1998).

4.2.2 COMPACTION CHARACTERISTICS OF FINE SAND-MEDIUM SAND-BENTONITE MIXES

All the fine sand-medium sand-bentonite mixtures were compacted with standard compactive effort in accordance with ASTM D 698 (2012). Compaction characteristics exhibited by FS-MS-B1 and FS-MS-B2 mixtures are presented in the Table 4.11 through Table 4.14. Optimum moisture content (OMC) values displayed by FS-MS-B1 mixtures shows that, for any given bentonite proportion the variation in OMC values for all the various fine sand-medium sand proportions was less than 3% and increasing fine sand content in these mixtures had a very little influence on the OMC indicating that the variation in OMC is primarily a function of bentonite type and content in the mixture. For all sand-bentonite-1 proportions, mixes with 30% FS+70% MS seem to provide better packing and hence higher dry densities.

Table 4.11 Compaction test results (OMC) of FS-MS-B1 mixtures

S-B1 Mix. proportions	Optimum moisture content (OMC, %)				
	FS-MS proportions				
	30:70	**40:60**	**50:50**	**60:40**	**70:30**
50:50	20.1	19.4	18.7	17.9	17.2
60:40	17.8	17.5	17.3	17.0	17.8
70:30	15.8	15.9	16.0	16.1	16.2
80:20	16.5	16.5	16.5	16.4	16.4
90:10	17.3	17.1	16.8	16.6	16.4

Table 4.12 Compaction test results (MDD) of FS-MS-B1 mixtures

S-B1 Mix. proportions	Maximum dry density (MDD, g/cc)				
	FS-MS proportions				
	30:70	40:60	50:50	60:40	70:30
50:50	1.618	1.610	1.603	1.595	1.588
60:40	1.623	1.621	1.619	1.617	1.615
70:30	1.716	1.708	1.700	1.692	1.684
80:20	1.712	1.710	1.707	1.704	1.702
90:10	1.669	1.665	1.662	1.658	1.654

Table 4.13 Compaction test results (OMC) of FS-MS-B2 mixtures

S-B2 Mix. proportions	Optimum moisture content (OMC, %)				
	FS-MS proportions				
	30:70	40:60	50:50	60:40	70:30
50:50	15.3	16.1	16.9	17.7	18.5
60:40	14.9	15.7	16.4	17.2	17.9
70:30	17.9	18.0	18.1	18.2	18.4
80:20	19.3	19.3	19.5	19.7	19.9
90:10	19.3	19.7	20.2	20.6	21.1

Compaction characteristics exhibited by FS-MS-B2 mixtures are presented in Table 4.13 and Table 4.14. Increasing the sand content in the mixtures resulted in a higher density to an optimum sand content after which a decrease in density was observed. This optimum percentage of sand in FS-MS-B2 mixes was seen to be around 70-80% sand content in the mixture. FS-MS-B2 mixes were seen to have attained higher densities with sand made up of 30% FS+70% MS for most mixes as in the case with FS-MS-B1 mixes. For any given sand-bentonite-2 (S-B2) proportion, OMC was found to be increasing and MDD decreasing with increasing in the fine sand content. The difference between the highest and the lowest OMC observed for any given bentonite proportion was found to be less than 3%.

Table 4.14 Compaction test results (MDD) of FS-MS-B2 mixtures

S-B2 Mix. proportions	Maximum dry density (MDD, g/cc)				
	FS-MS proportions				
	30:70	**40:60**	**50:50**	**60:40**	**70:30**
50:50	1.585	1.581	1.577	1.572	1.568
60:40	1.609	1.605	1.601	1.597	1.593
70:30	1.642	1.637	1.632	1.627	1.622
80:20	1.635	1.632	1.628	1.624	1.601
90:10	1.601	1.598	1.595	1.592	1.589

4.2.3 CONSOLIDATION CHARACTERISTICS OF FINE SAND-MEDIUM SAND-BENTONITE MIXES

4.2.3.1 Time-Swelling characteristics of fine sand-medium sand-bentonite mixes

4.2.3.1.1 Effect of sand proportioning on time-swelling relationship of FS-MS-B1 mixes

Fine sand-medium sand-bentonite mixtures were made with various proportions of fine sand, medium sand and bentonite. The bentonite amount in the mixtures was varied from 10% to 50% by dry weight of the mixtures while sand accounted for the rest sand proportion used in the mixes is made up of fine sand and medium sand, mixed in various proportions. Fine sand to medium sand ratio used in mixtures is varied from 30:70 to 70:30. The samples were prepared at MDD-OMC compaction conditions. All the samples were mixed with water content equal to their respective OMC and were left for moisture equilibrium for a period of 24 hours after being packed in airtight polythene bags. After allowing for moisture equilibrium, these samples were statically compacted in consolidation rings at their respective MDD. Samples were then submerged in the odometer ring and allowed to swell under a seating pressure of 4.9 kPa, till the difference between two consecutive readings taken 24 hours apart became minimal on the dial gauge. Influence of sand particle size, bentonite type and content on the time-swelling relationship of compacted sand-bentonite mixtures when mixed and tested with deionized (DI) water has been established and presented in section 4.1.3.1. This part of the study attempts to understand the role of sand proportioning on the time-swelling characteristics of compacted FS-MS-B1 mixtures. Swelling characteristics exhibited by various FS-MS-B1 mixtures are presented in Figs. 4.124 through Figs. 4.128.

FS-MS-B1 mixtures with a high bentonite content took about 210 hours for swelling to complete, while the same was achieved in 96 hours in case of FS-B1 and MS-B1 mixtures. The plots also shows that the introduction of various proportions of FS and MS in the sand-bentonite-1 (S-B1) mixture resulted in an increase in the time required for swelling as compared to FS-B1 and MS-B1 mixtures. It was observed that samples with higher bentonite content (50% and 40%) exhibited higher swelling volume followed by other samples. No appreciable swelling has been observed in case of samples with bentonite content less than 20%. FS-MS-B1 mixtures exhibited unique swelling potential for different FS-MS proportions. It turns out that increasing the FS proportion in the sand resulted in an increasing percentage swelling for any bentonite proportion considered. Percentage swelling observed reveals a range of values, for any bentonite proportion, indicating the importance of sand proportioning. For a given bentonite content, the difference between highest and lowest swelling potentials observed was in the range of 0-7.2%. It can be concluded from the figures that, apart from bentonite content, sand proportioning also plays an important role in the swelling behavior of FS-MS-B1 mixtures. The plot also shows that the time swelling curve for the mixtures with a bentonite content higher than 40% follows a “S” pattern and the distinction between the initial, primary and secondary portion of the swelling curve is well marked. However, this behavior was not shown by the mixture with a bentonite content lower than 40%. The plot shows that the time required to complete the initial swelling varied from 0.2 to 30 minutes; whereas, the time to complete the primary swelling varied from around 900 to 1000 minutes for the mixture with 50% bentonite content. A comparison among various FS-MS proportions, for any given B1 content, indicates that the time to complete the swelling is also dependent upon the proportion of MS and FS in the mixture. Mixtures with a higher proportion of FS were seen to exhibit higher time to complete the initial and primary part of swelling.

4.2.3.1.2 Effect of sand proportioning on time-swelling relationship of FS-MS-B2 mixes

Consolidation samples of FS-MS-B2 mixtures were made and tested in the same way as described in case of FS-MS-B1 mixtures. Bentonite-2 (B2) being a high swelling bentonite, FS-MS-B2 mixtures with high bentonite content took about 275 hours for swelling to complete, for the sake of uniformity all the FS-MS-B2 mixes were allowed to swell for the above said period.

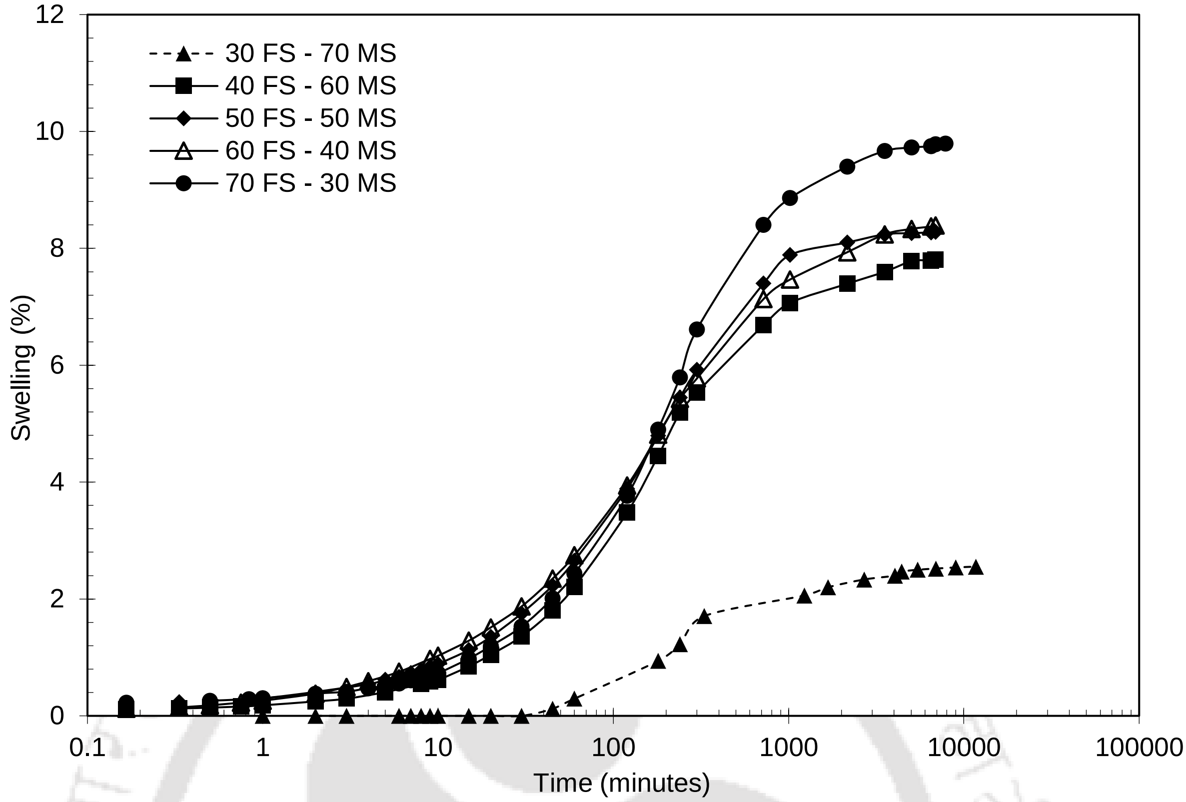


Figure 4.124 Time-Swelling plot for 50% sand-50% B1 mixes compacted at OMC-MDD

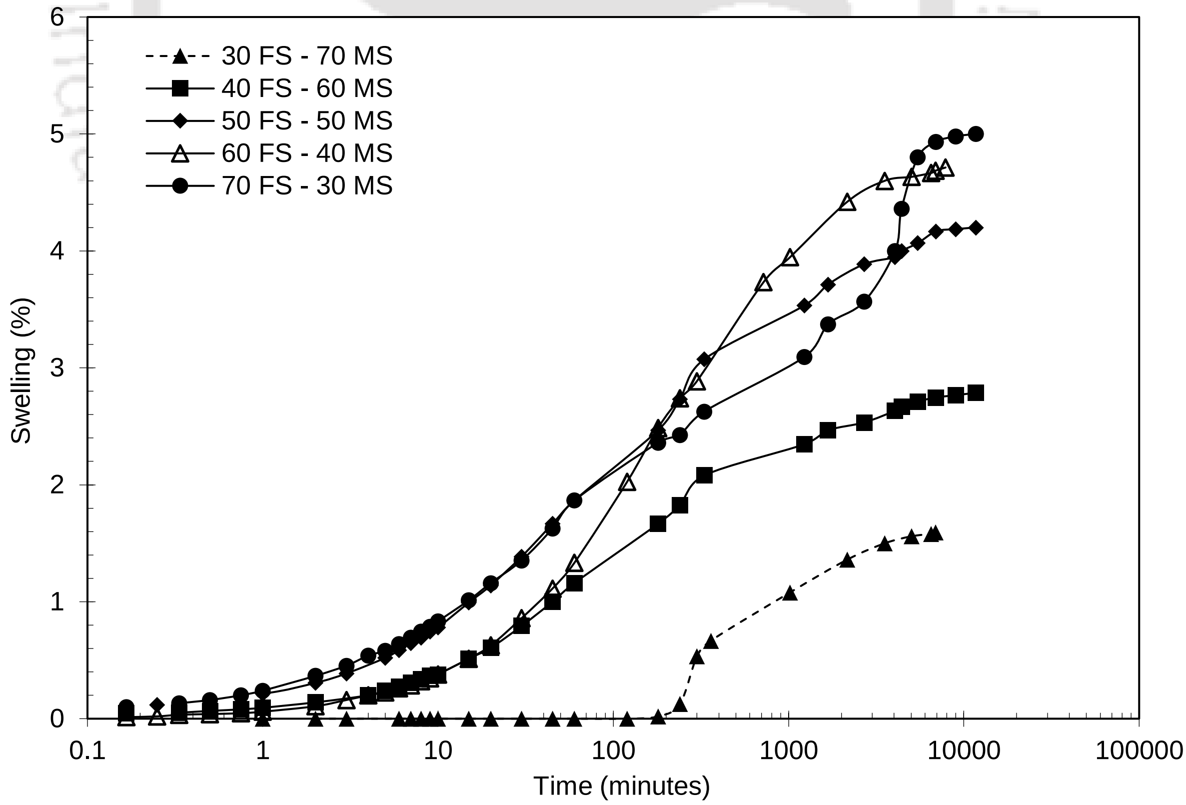


Figure 4.125 Time-Swelling plot for 60% sand-40% B1 mixes compacted at OMC-MDD

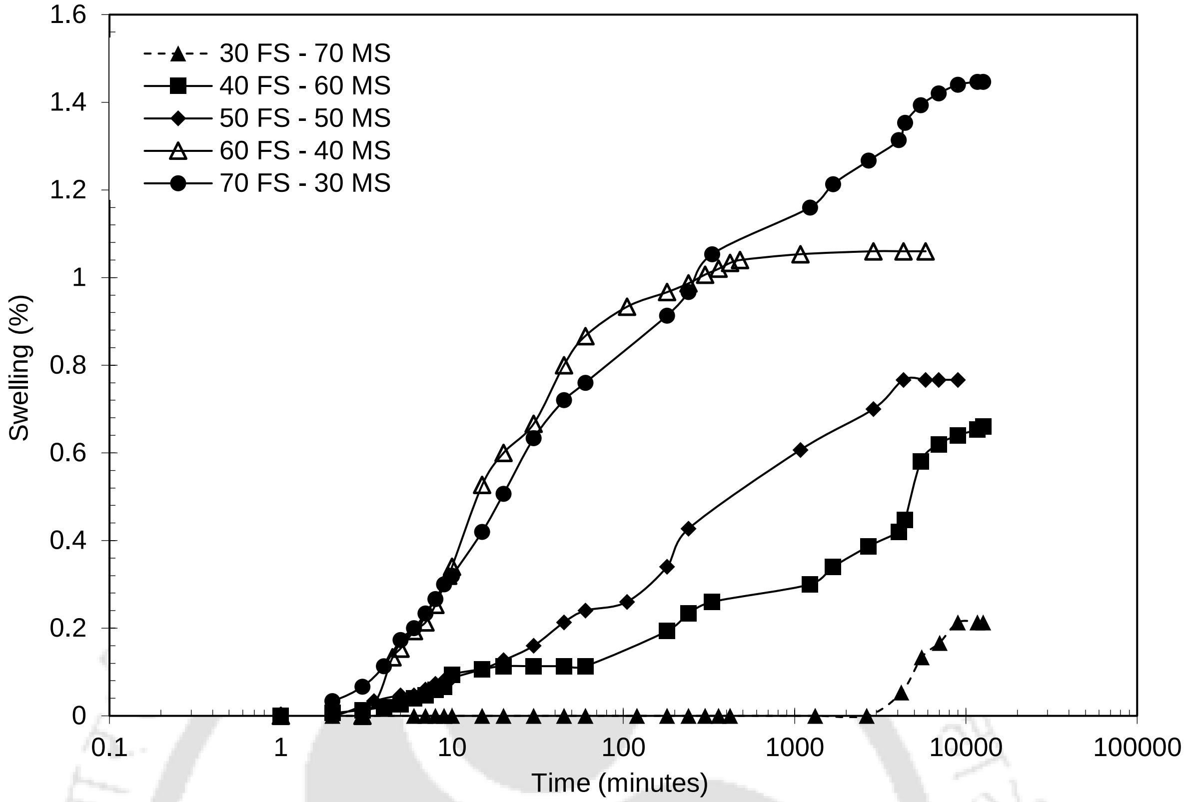


Figure 4.126 Time-Swelling plot for 70% sand-30% B1 mixes compacted at OMC-MDD

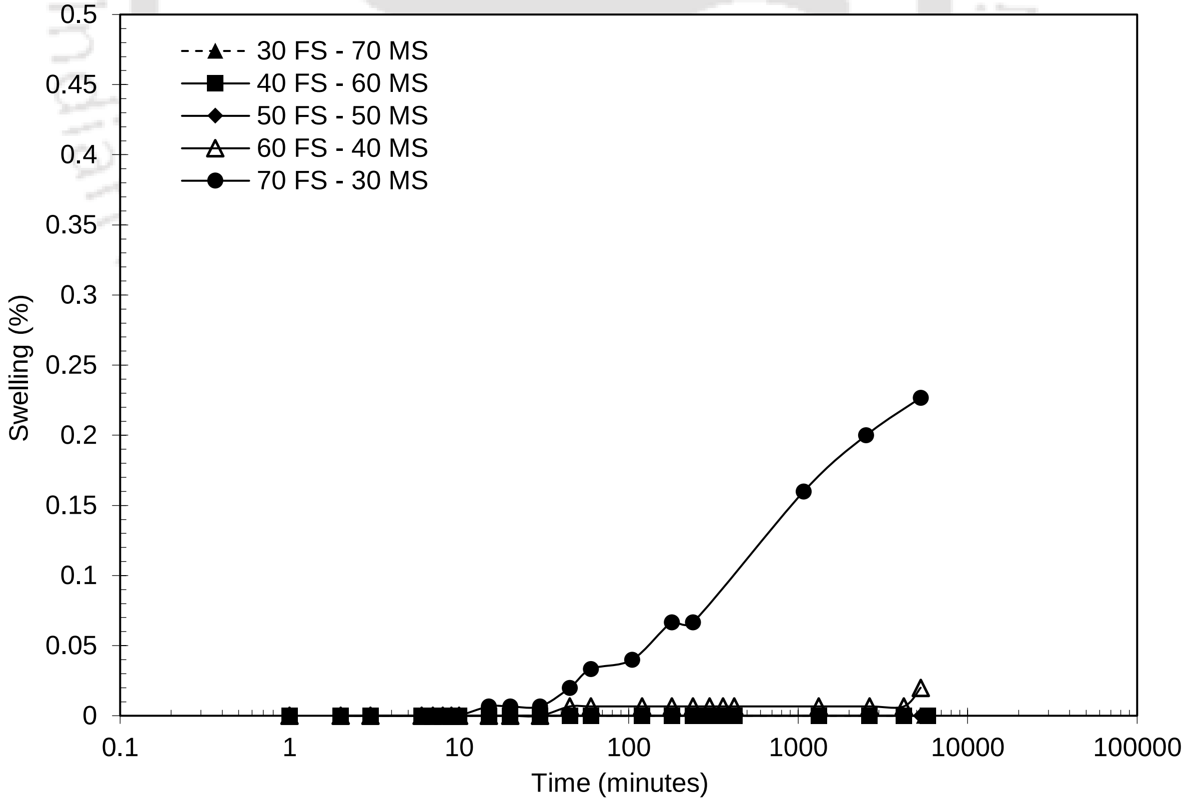


Figure 4.127 Time-Swelling plot for 80% sand-20% B1 mixes compacted at OMC-MDD

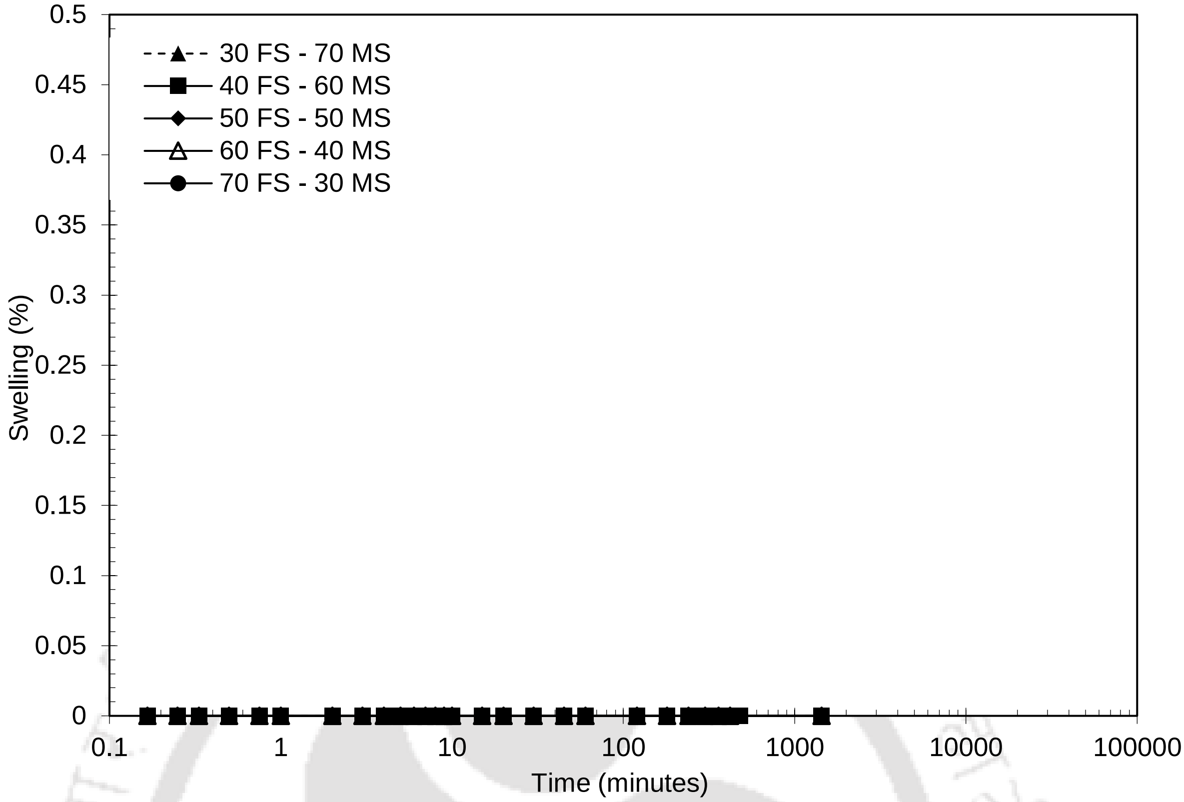


Figure 4.128 Time-Swelling plot for 90% sand-10% B1 mixes compacted at OMC-MDD

Time-Swelling relationship exhibited by FS-MS-B2 mixtures is as shown in Figs. 4.129 through Figs. 4.133. Plots shows that the FS-B2 and MS-B2 mixes took about 192 hours for swelling to seize, introduction of various proportions of FS and MS in the sand-bentonite-2 mixture resulted in an increase in the time required for swelling as compared to FS-B2 and MS-B2 mixtures. FS-MS-B2 mixes with 80% and 90% sand content indicated an improvement in swelling percentage compared to those of FS-B2 and MS-B2. Comparing swelling potential results of FS-B2 and MS-B2 mixes compacted at OMC-MDD with the FS-MS-B2 results indicated a general increase in the swelling potential. Akin to FS-MS-B1 mixtures, for any given bentonite content, FS-MS-B2 mixtures exhibited unique swelling potential for different FS-MS proportions. Swelling potential exhibited by FS-MS-B2 mixtures is higher compared to FS-MS-B1 mixtures and the time for swelling process to complete is also higher in case of FS-MS-B2 mixtures. For a given bentonite content, the difference between highest and lowest swelling potentials observed is in the range of 0.1-18.6%. These variations and the improvement in swelling potential can be seen as an indicator of the importance of role played by sand type and the necessity towards designing sand proportioning. The plots also show that the time swelling curve for the mixture with a bentonite content higher than 30% follows a "S" trend and the distinction between the initial, primary and secondary portion of the swelling curve is well marked. However, this behavior was not shown by the mixture with a bentonite content lower than 30%. The plot shows that the time required to complete the initial swelling varied from 2 to 10 minutes; whereas, the time to complete the primary swelling varied from 7500 to 11200 minutes for the mixtures with 50% bentonite content.

A comparison among the curves, for a constant bentonite content, shows that the time to complete the swelling is also dependent upon the proportion of MS and FS in the mixture. While, mixtures with a higher FS content were seen to exhibit higher time to complete the initial and primary part of swelling as has been the case with FS-MS-B1 mixtures.

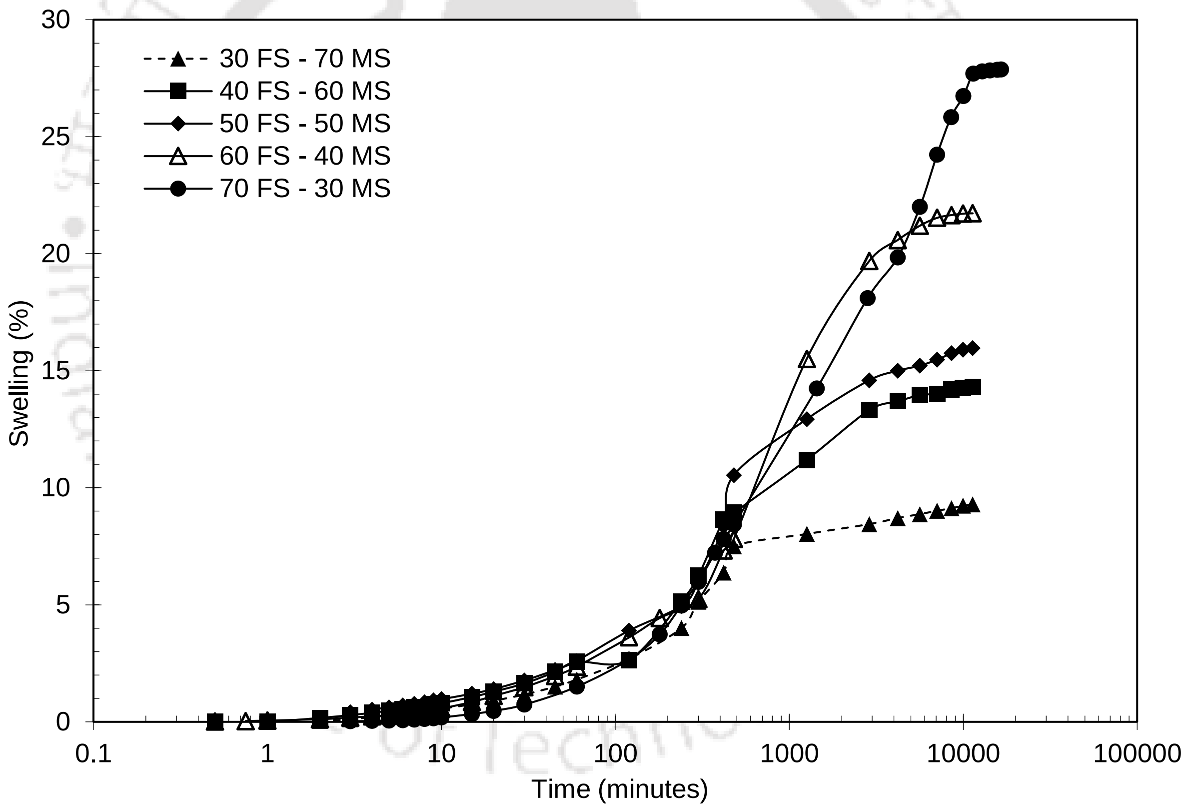


Figure 4.129 Time-Swelling plot for 50% sand-50% B2 mixes compacted at OMC-MDD

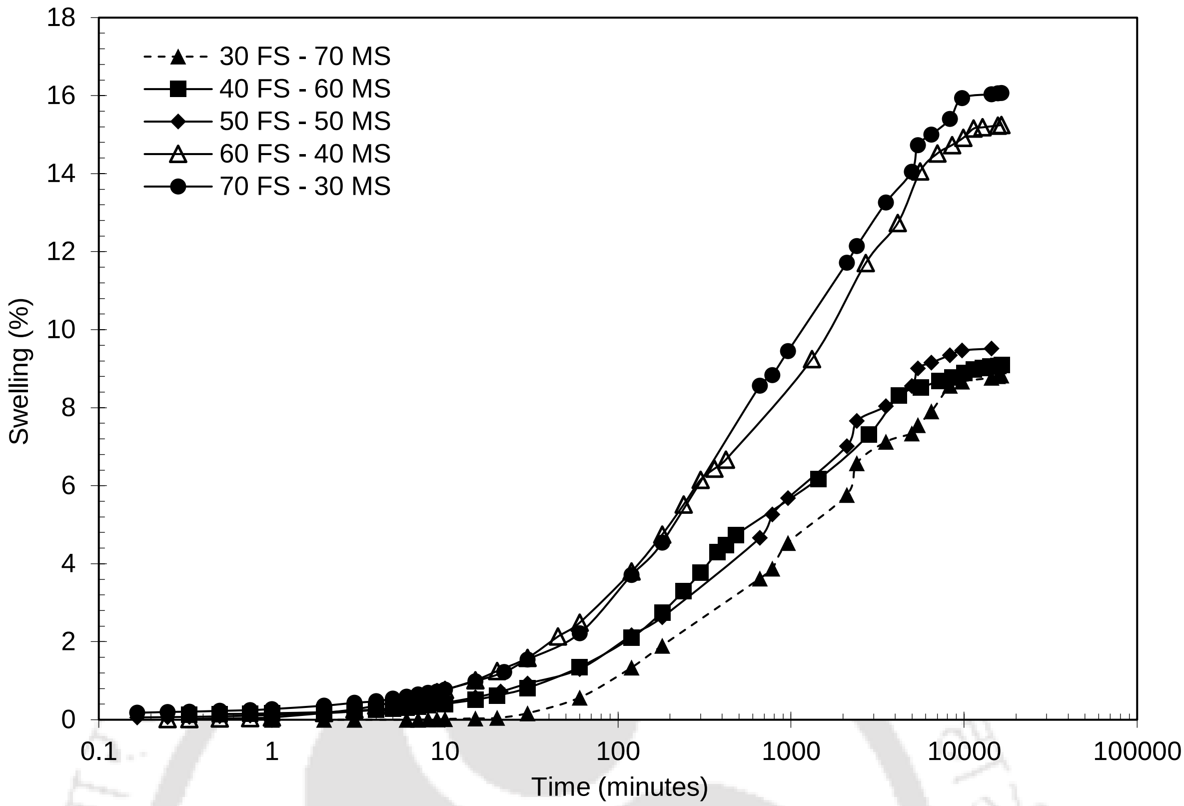


Figure 4.130 Time-Swelling plot for 60% sand-40% B2 mixes compacted at OMC-MDD

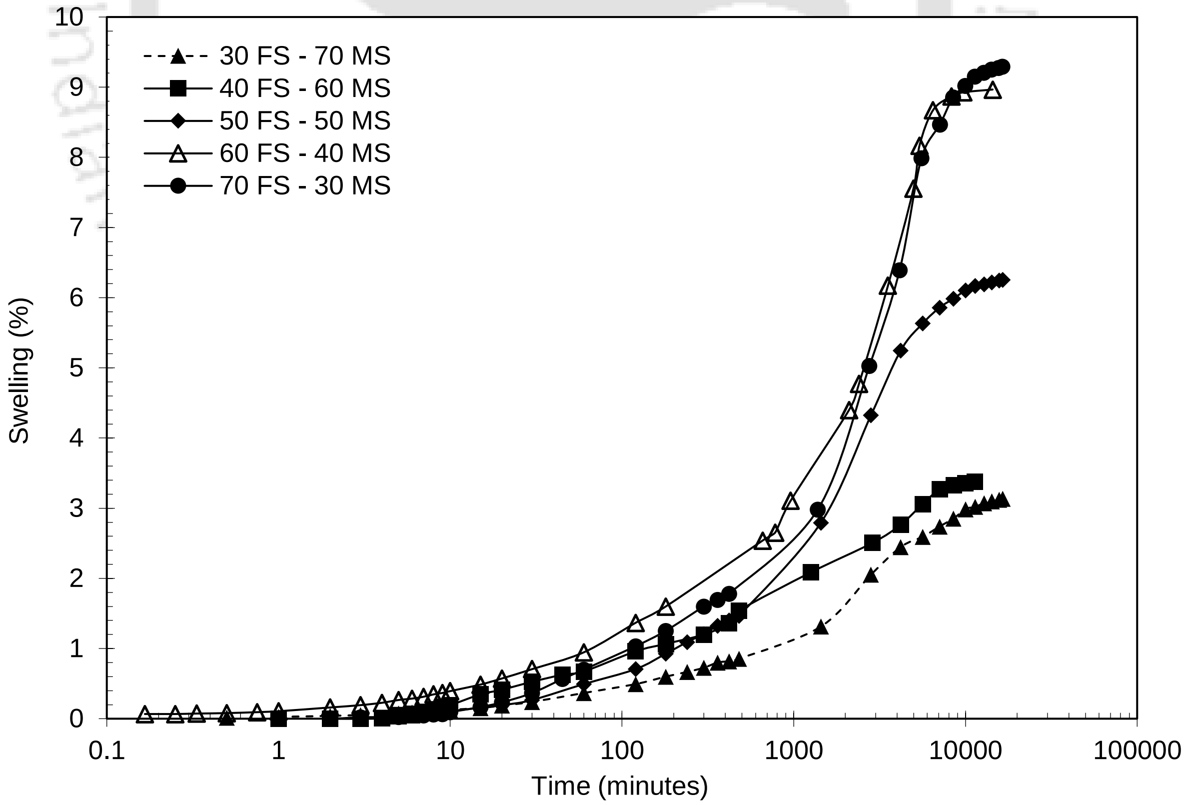


Figure 4.131 Time-Swelling plot for 70% sand-30% B2 mixes compacted at OMC-MDD

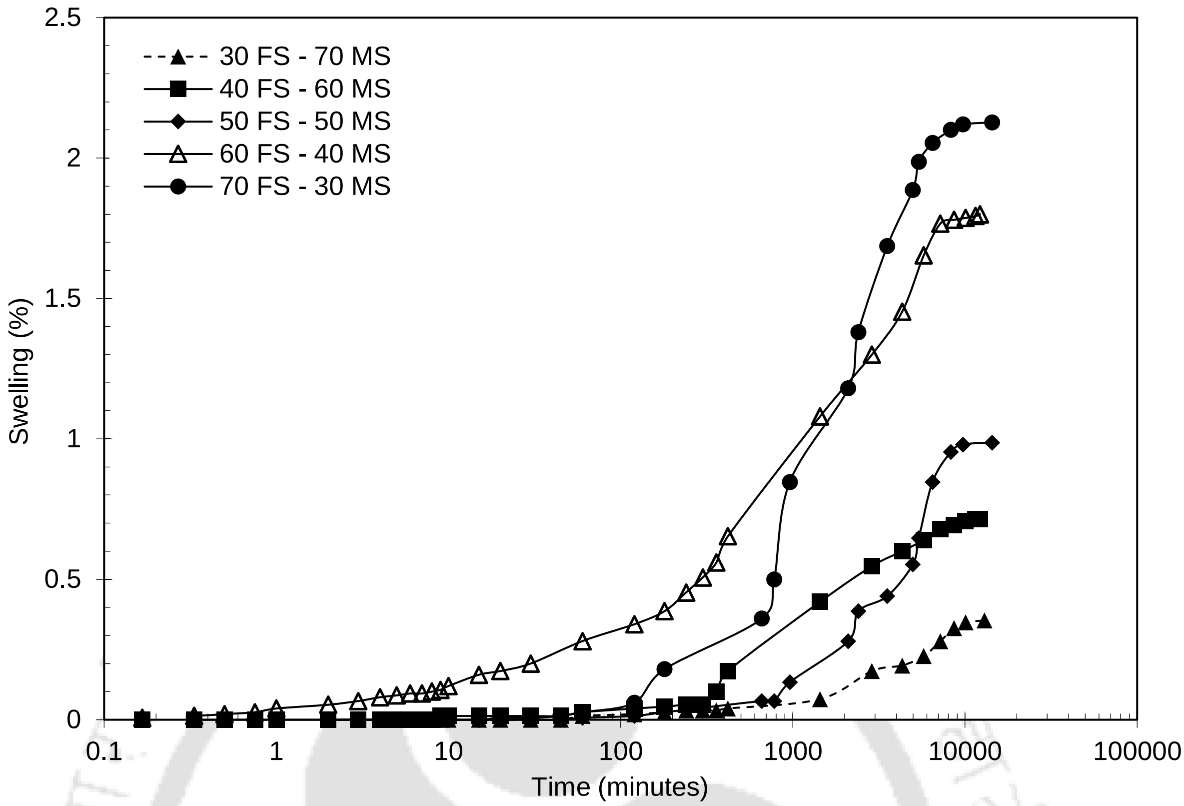


Figure 4.132 Time-Swelling plot for 80% sand-20% B2 mixes compacted at OMC-MDD

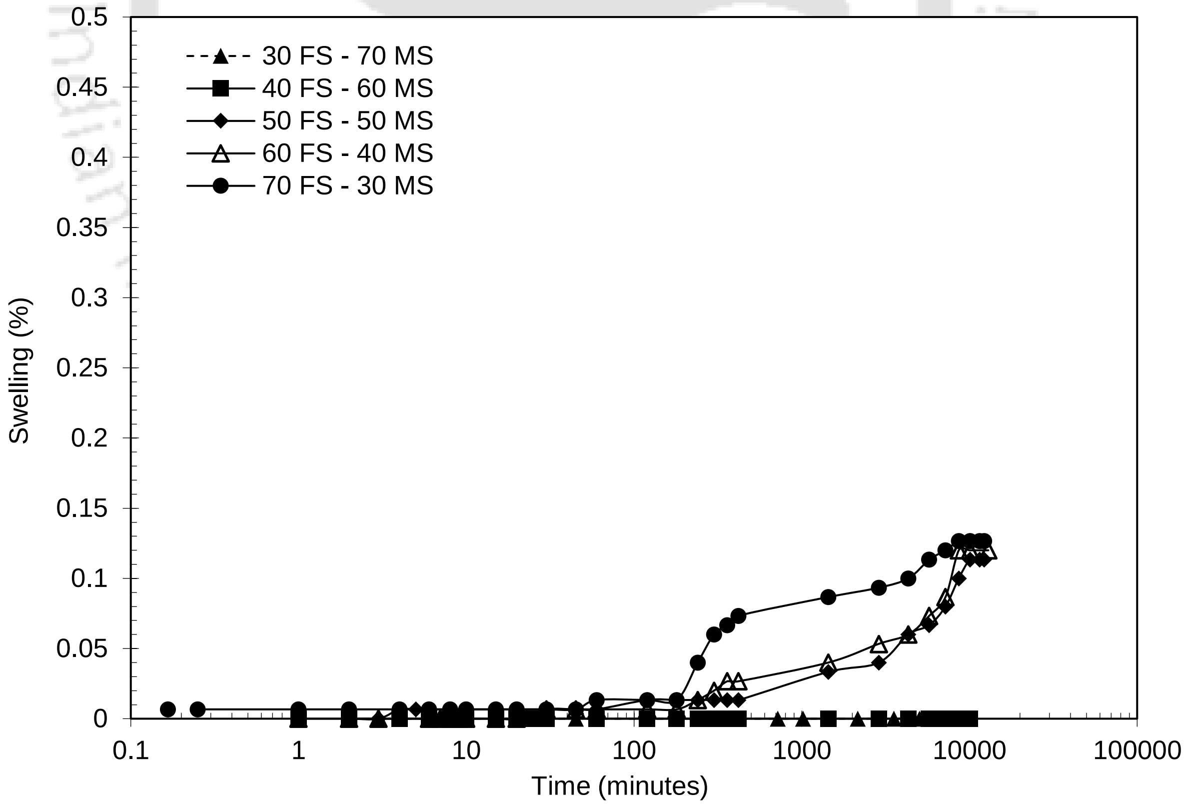


Figure 4.133 Time-Swelling plot for 90% sand-10% B2 mixes compacted at OMC-MDD

4.2.3.2 Swelling potential of fine sand-medium sand-bentonite mixes

4.2.3.2.1 Swelling potential of FS-MS-B1 mixtures

Swelling characteristics exhibited by FS-MS-B1 samples compacted at OMC-MDD are shown in the Table 4.15. For a constant B1 content, swelling potential was found to be increasing with increasing FS content in the mixture. It can be said that, for a constant bentonite content, the size and distribution of voids formed and later filled by the swelling of bentonite are dependent on the sand proportioning. FS-MS-B1 mixtures with bentonite content of 30% and less are exhibiting relatively low swelling potential indicating that bentonite content is not sufficient for filling all the voids created by the sand skeleton. Comparing the swelling potential data of FS-MS-B1 mixtures with those of FS-B1, MS-B1 mixtures compacted at OMC-MDD indicated that, for any given bentonite content, a range of swelling potential values are possible by varying the sand constitution. For most cases, swelling potential of FS-MS-B1 mixtures were found to be lying in between those of FS-B1 and MS-B1 mixtures with MS-B1 mixtures forming the lower limit of observed range. Though the range of values observed isn't alarming, it is a variation nonetheless.

Table 4.15 Summary of swelling potential results of FS-MS-B1 mixtures

S-B1 Mix. proportions	Swelling potential (%)				
	FS-MS proportions				
	30:70	40:60	50:50	60:40	70:30
50:50	2.55	7.81	8.28	8.39	9.79
60:40	1.59	2.79	4.20	4.71	5.00
70:30	0.21	0.66	0.77	1.06	1.45
80:20	0.00	0.00	0.00	0.02	0.23
90:10	0.00	0.00	0.00	0.00	0.00

4.2.3.2.2 Swelling potential of FS-MS-B2 mixtures

Swelling characteristics exhibited by FS-MS-B2 samples compacted at OMC-MDD are shown in the Table 4.16. For any given B2 content, swelling potential exhibited by each FS-MS proportion was found to be distinct as was the case with FS-MS-B1 mixtures indicating that swelling characteristics are also dependent on sand proportioning. FS-MS-B2 mixtures with bentonite content of 20% and less exhibited relatively low swelling potential indicating that bentonite content is not sufficient for filling all the voids created by the sand skeleton.

Table 4.16 Summary of swelling potential results of FS-MS-B2 mixtures

S-B2 Mix. proportions	**Swelling potential (%)**				
	FS-MS proportions				
	30:70	**40:60**	**50:50**	**60:40**	**70:30**
50:50	9.29	14.31	15.97	21.73	27.88
60:40	8.83	9.09	9.51	15.25	16.07
70:30	3.13	3.38	6.25	8.97	9.29
80:20	0.35	0.71	0.99	1.80	2.13
90:10	0.00	0.00	0.11	0.12	0.13

Comparing the swelling potential data of FS-MS-B2 mixtures with those of FS-B2, MS-B2 mixtures compacted at OMC-MDD, a phenomenon similar to those exhibited by sand-bentonite-1 mixtures is observed i.e. a range of swelling potential values by varying sand constitution for any given bentonite content. The range of values observed in case of FS-MS-B2 mixtures was higher in comparison to those of FS-MS-B1 mixtures reflecting the relatively higher swelling nature of B2. Variability in swelling potential with sand constitution for any given bentonite content is higher in case of FS-MS-B2 mixtures indicating a relatively higher dependence on the sand constitution.

4.2.3.3 Swelling pressure of fine sand-medium sand-bentonite mixes

4.2.3.3.1 Swelling pressure of FS-MS-B1 mixtures

Swelling pressure is probably the most sought after criterion, second only to hydraulic conductivity, while deciding the materials to be used as a geotechnical barrier material. Swelling pressure characteristics exhibited by FS-MS-B1 mixtures are summarized in Table 4.17. Swelling pressure results indicated a trend similar to those of FS-B1 and MS-B1 mixtures, where, the swelling pressure was found to be decreasing with a decrease in the bentonite content in the mixture. Mixes with high bentonite contents (50% and 40%) exhibited higher swelling pressures. Upon close scrutiny, it has been seen that swelling pressure exhibited by FS-MS-B1 mixtures is less than FS-B1 mixes and greater than MS-B1 mixes. It needs to be understood that a range of swelling pressures are possible by a little tweaking with the sand type used in the study, for any given bentonite content in the mixture. For any B1 content, variability in swelling pressures observed may serve as a means to represent the sensitivity associated with sand constitution in the swelling process.

Table 4.17 Summary of swelling pressure results of FS-MS-B1 mixtures

S-B1 Mix. proportions	Swelling pressure (kPa) FS-MS proportions				
	30:70	**40:60**	**50:50**	**60:40**	**70:30**
50:50	68.7	105.0	114.8	143.2	167.8
60:40	41.2	70.6	72.6	73.6	87.3
70:30	19.6	48.1	50.0	54.0	57.9
80:20	0.0	0.0	0.0	12.8	21.6
90:10	0.0	0.0	0.0	0.0	0.0

4.2.3.3.2 Swelling pressure of FS-MS-B2 mixtures

Swelling pressure characteristics exhibited by FS-MS-B2 mixtures are summarized in Table 4.18. Although considerable variation was observed among the mixes, mixes with high bentonite content (50%) exhibited relatively high swelling pressures. Mixes with 70% FS+30% MS seem to have taken advantage of the gap grading i.e. B2, FS effectively filling the voids created by MS. While certainly there has been a relative increase in the swelling pressure in case of mixes with B2 content less than 30% as compared to FS-B2 and MS-B2 mixes, the individual contributions of say B2 and FS or MS proportioning is unclear. Comparing the swelling pressure data of FS-MS-B2 mixtures with those of FS-B2, MS-B2 mixtures indicated a considerable variability in observed values with variation in sand constitution for any B2 content. Upon comparing sand-bentonite-1 and sand-bentonite-2 mixtures, it is seen that the variability among various FS-MS proportions is also relatively higher in case of sand-bentonite-2 mixtures. The variabilities observed indicate a need to consider sand proportioning while designing geotechnical barriers where swelling pressure is an important criterion.

Table 4.18 Summary of swelling pressure results of FS-MS-B2 mixtures

S-B2 Mix. proportions	Swelling pressure (kPa) FS-MS proportions				
	30:70	**40:60**	**50:50**	**60:40**	**70:30**
50:50	197.2	217.8	297.2	366.9	406.1
60:40	160.9	172.7	183.5	184.4	191.3
70:30	101.0	121.6	121.6	126.6	170.7
80:20	27.5	46.1	50.0	53.0	62.8
90:10	0.0	0.0	20.6	20.6	23.5

4.2.3.4 Effect of sand proportioning on *e*–log *k* for various fine sand-medium sand-bentonite mixes

4.2.3.4.1 Effect of sand proportioning on *e*–log *k* for FS-MS-B1 mixes

The influence of sand particle size, bentonite content and initial compaction criterion on the hydraulic characteristics of sand-bentonite mixtures has been investigated and presented in section 4.1.3.4. Current part of the study presents the influence of bentonite content and sand proportioning on the hydraulic characteristics of FS-MS-B1 and FS-MS-B2 samples compacted at OMC-MDD. Hydraulic characteristics exhibited by FS-MS-B1 mixtures compacted at OMC-MDD are as shown in Figs. 4.134 through Figs. 4.138. Hydraulic conductivity of FS-MS-B1 mixtures was found to be reducing with increasing bentonite content, as has been the case with FS-B1 and MS-B1 mixtures compacted at OMC-MDD. For any given B1 content, hydraulic conductivity exhibited by mixtures varied with FS-MS proportion, distinct trends were observed for each FS-MS proportion. A reduction in hydraulic conductivity has been observed with increasing the FS proportion in the FS-MS mixture, for a constant B1 content.

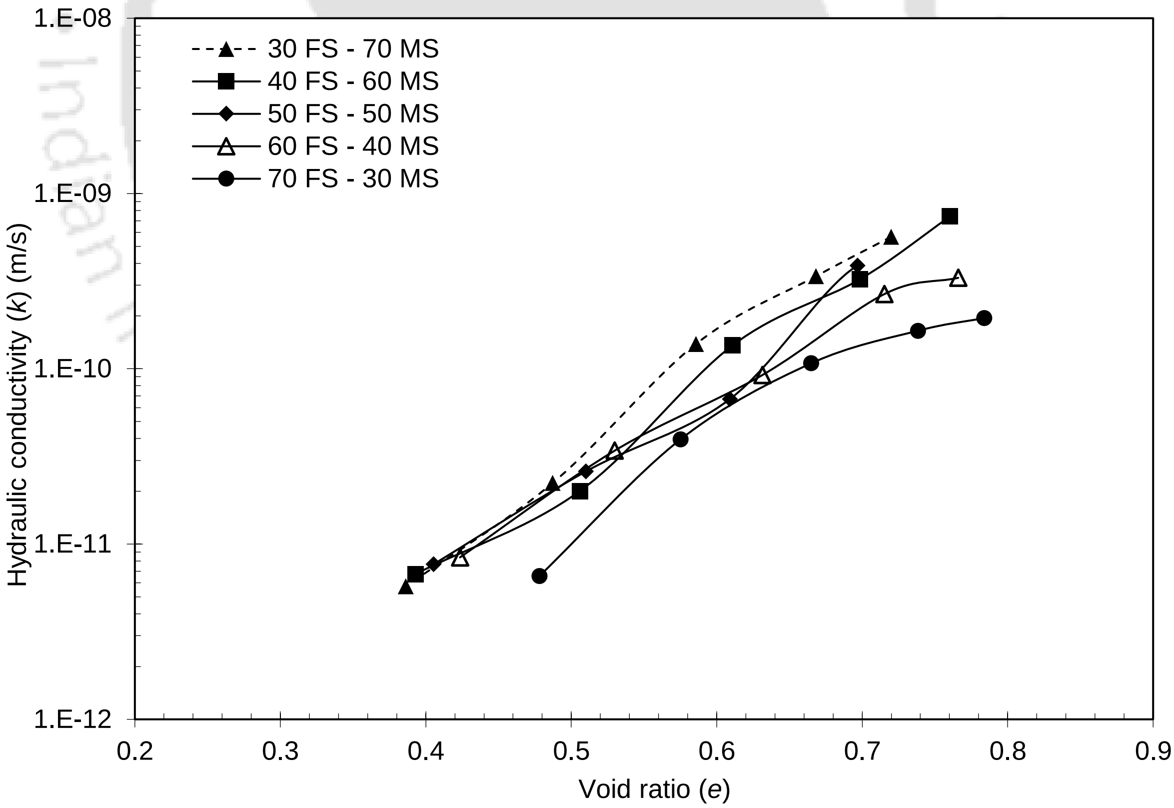


Figure 4.134 *e*-log *k* plot for 50% sand-50% B1 mixes compacted at OMC-MDD

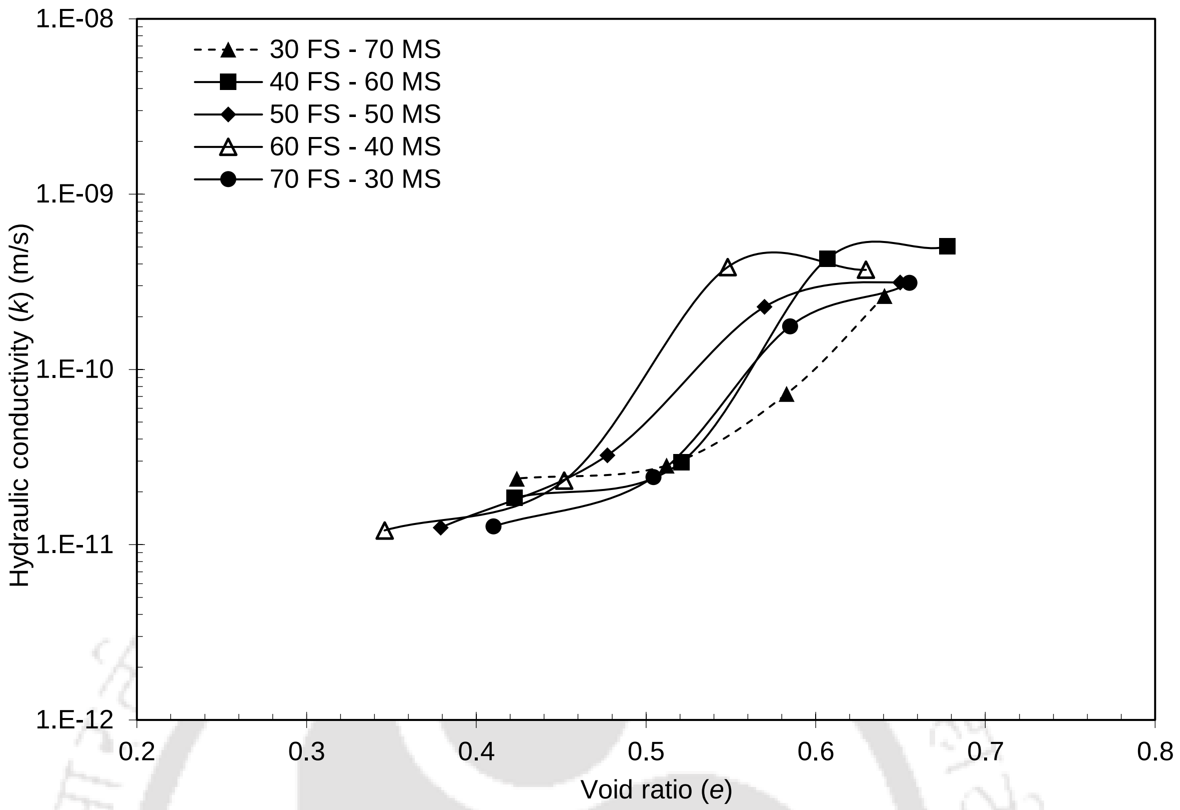


Figure 4.135 *e*-log *k* plot for 60% sand-40% B1 mixes compacted at OMC-MDD

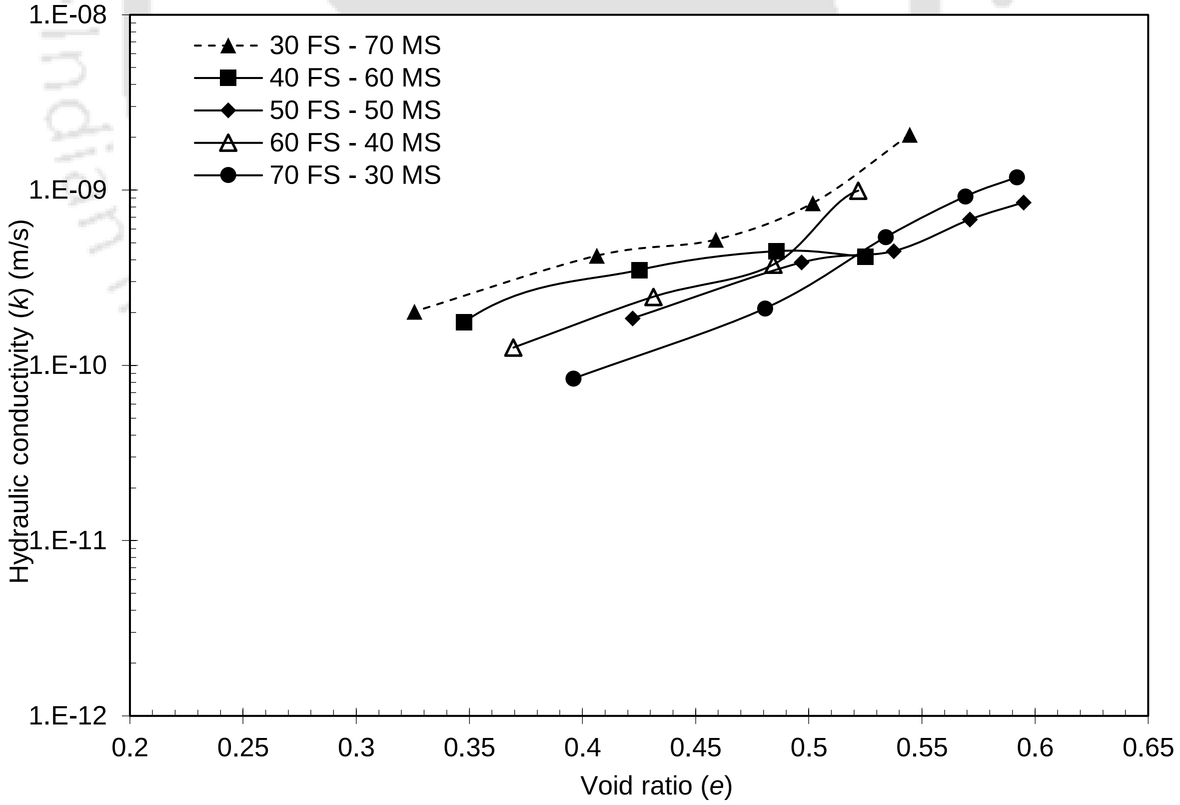


Figure 4.136 *e*-log *k* plot for 70% sand-30% B1 mixes compacted at OMC-MDD

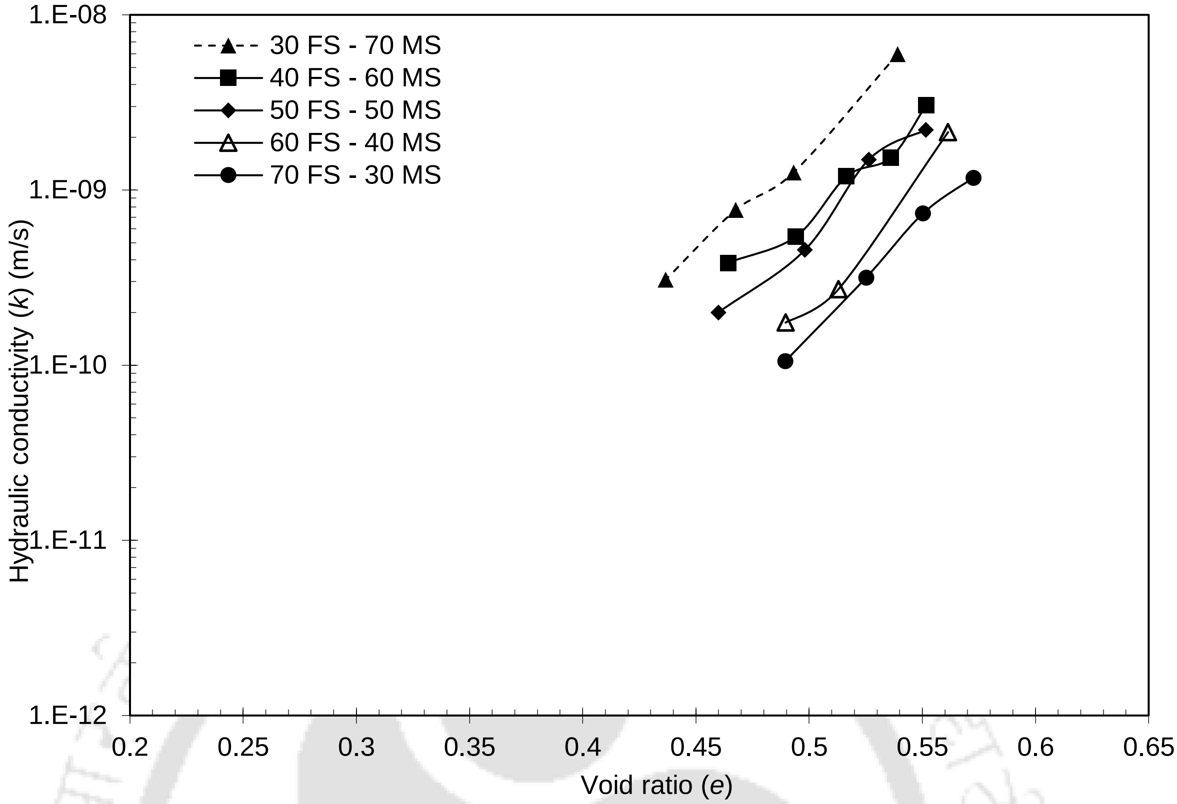


Figure 4.137 *e*-log *k* plot for 80% sand-20% B1 mixes compacted at OMC-MDD

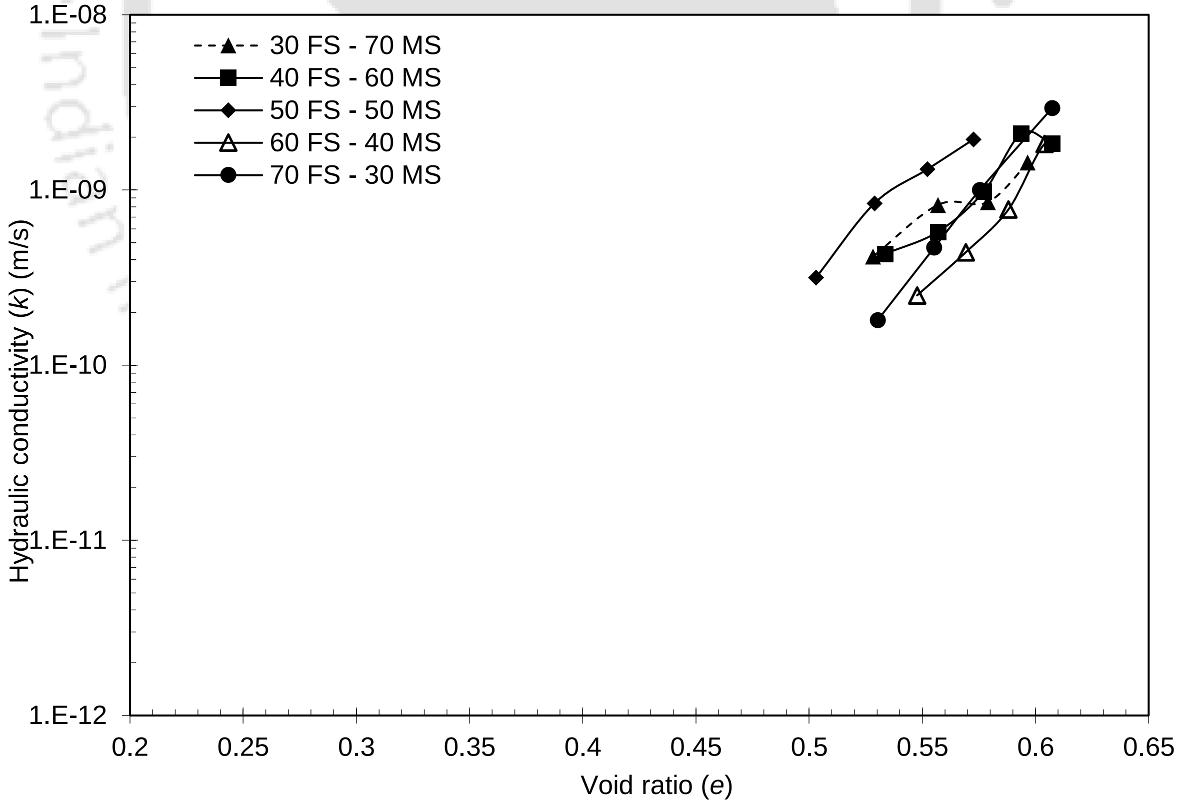


Figure 4.138 *e*-log *k* plot for 90% sand-10% B1 mixes compacted at OMC-MDD

In case of 50% sand+50% B1 mixes, initial and final hydraulic conductivities exhibited by various FS-MS proportions varied in the range of 1.9×10^{-10} to 7.4×10^{-10} m/sec and

$5.7x10^{-12}$ to $8.4x10^{-12}$ m/sec respectively. In case of 60% sand+40% B1 mixes, initial and final hydraulic conductivities exhibited by various FS-MS proportions varied in the range of $2.6x10^{-10}$ to $3.1x10^{-10}$ m/sec and $1.2x10^{-11}$ to $2.4x10^{-11}$ m/sec respectively. In case of 70% sand+30% B1 mixes, initial and final hydraulic conductivities exhibited by various FS-MS proportions varied in the range of $4.2x10^{-10}$ to $2.1x10^{-9}$ m/sec and $8.4x10^{-11}$ to $2.0x10^{-10}$ m/sec respectively. In case of 80% sand+20% B1 mixes, initial and final hydraulic conductivities exhibited by various FS-MS proportions varied in the range of $1.2x10^{-9}$ to $6x10^{-9}$ m/sec and $1.0x10^{-10}$ to $3.1x10^{-10}$ m/sec respectively. In case of 90% sand+10% B1 mixes, initial and final hydraulic conductivity exhibited by various FS-MS proportions varied in the range of $1.8x10^{-9}$ to $2.9x10^{-9}$ m/sec and $1.8x10^{-10}$ to $4.3x10^{-10}$ m/sec, respectively. Minimum hydraulic conductivity requirement for a landfill liner application has been specified as $1x10^{-9}$ m/sec by various environmental agencies (USEPA, 1988). For all FS-MS proportions, mixes with higher bentonite content (50%, 40% and 30%) exhibited lower hydraulic conductivity as has been the case with FS-B1 and MS-B1 mixtures as stated before. Though FS-MS-B1 mixtures with B1 content less than 20% are exhibiting higher *k* values, an improvement in hydraulic behavior relative to FS-B1, MS-B1 mixes has been observed. Comparing FS-MS-B1 mixtures with FS-B1 and MS-B1 mixes compacted at OMC-MDD indicated that sand proportioning resulted in a 5-fold reduction in hydraulic conductivity in case of 50% sand+50% B1 mixes, 4-fold reduction in case of 60% sand+40% B1 mixes, 1 to 4-fold reduction in case of 70% sand+30% B1 mixes, at least 10-fold reduction in case of 80% sand+20% B1 mixes, and 100-fold reduction in case of 90% sand+10% B1 mixes.

4.2.3.4.2 Effect of sand proportioning on *e*–log *k* for FS-MS-B2 mixes

Hydraulic characteristics exhibited by FS-MS-B2 mixtures compacted at OMC-MDD are shown in Figs. 4.139 to Figs. 4.143. Hydraulic conductivity of FS-MS-B2 mixtures was found to be reducing with increasing bentonite content, as has been the case with FS-MS-B1 mixtures. For any given bentonite content and FS-MS proportion, hydraulic conductivity exhibited by FS-MS-B2 mixtures was relatively lower than FS-MS-B1 mixtures. In case of 50% sand+50% B2 mixes, initial and final hydraulic conductivities exhibited by various FS-MS proportions varied in the range of $5.3x10^{-11}$ to $8.6x10^{-11}$ m/sec and $4x10^{-12}$ to $6.4x10^{-12}$ m/sec, respectively. In case of 60% sand+40% B2 mixes, initial and final hydraulic conductivities exhibited by various FS-MS proportions varied in the range of $4.0x10^{-11}$ to $3.6x10^{-10}$ m/sec and $6.2x10^{-12}$ to $9.3x10^{-12}$ m/sec, respectively.

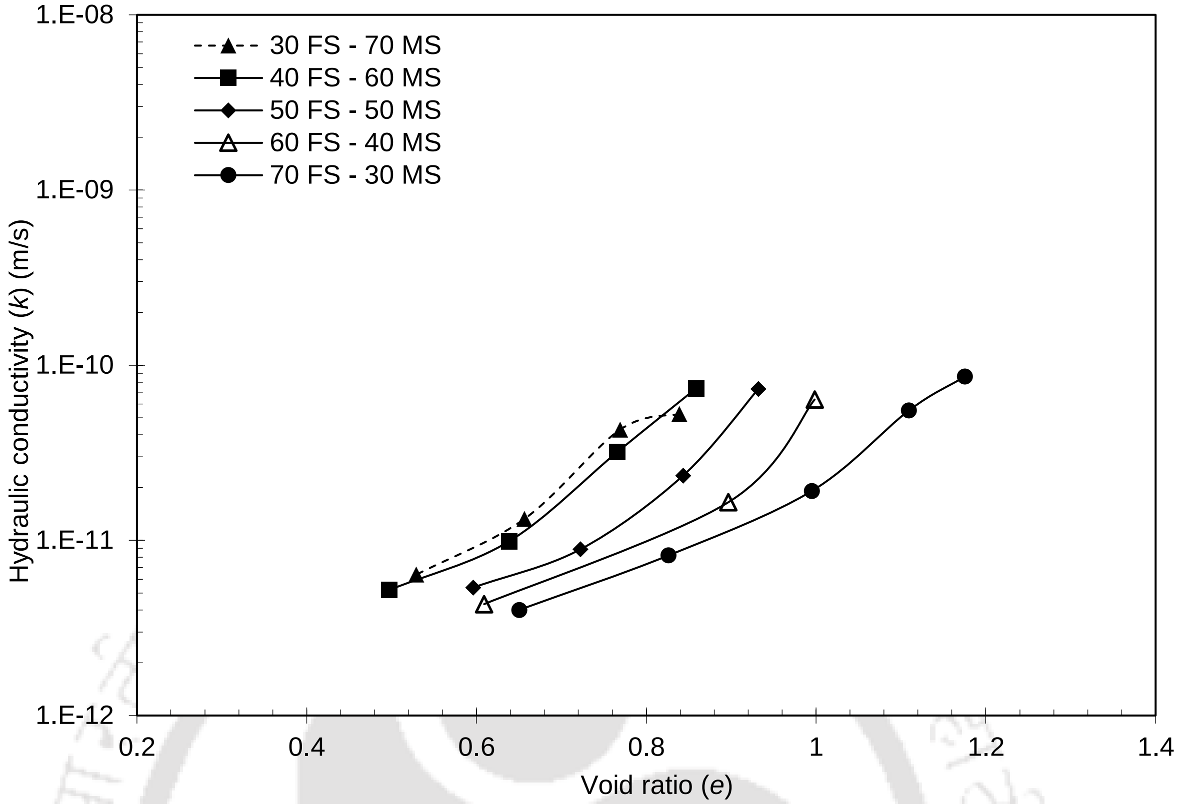


Figure 4.139 *e*-log *k* plot for 50% sand-50% B2 mixes compacted at OMC-MDD

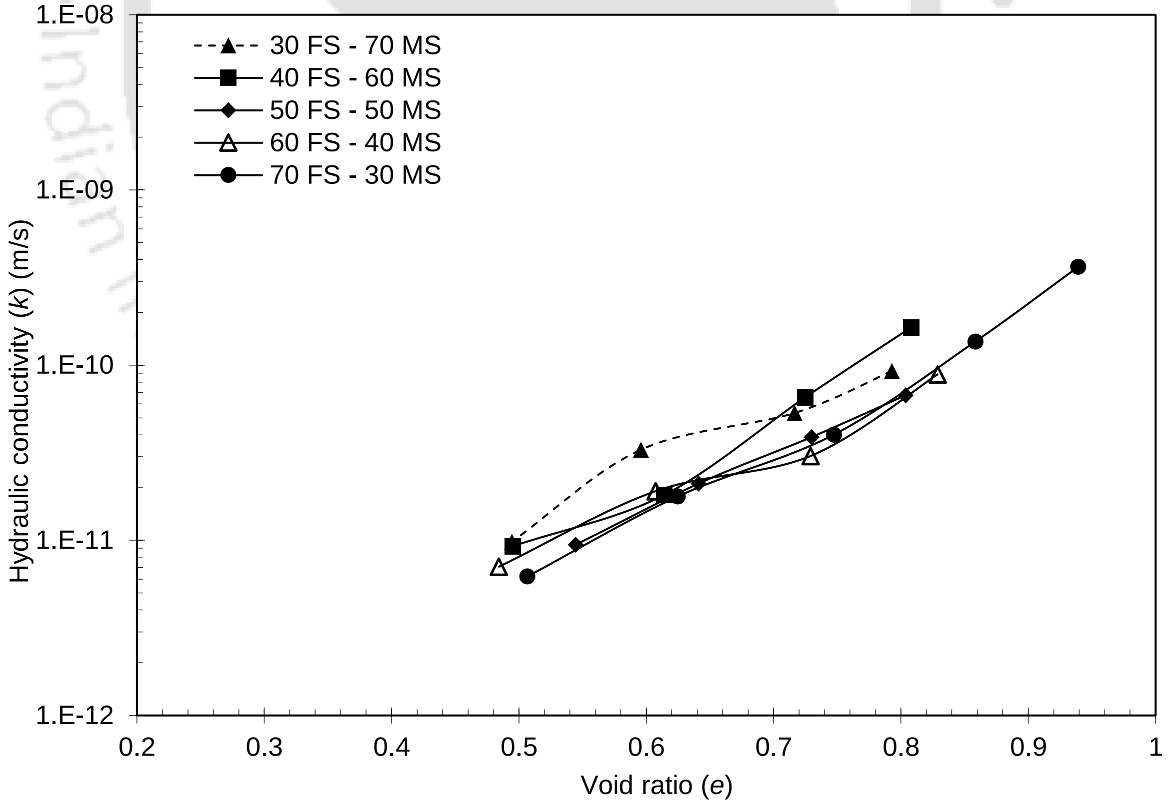


Figure 4.140 *e*-log *k* plot for 60% sand-40% B2 mixes compacted at OMC-MDD

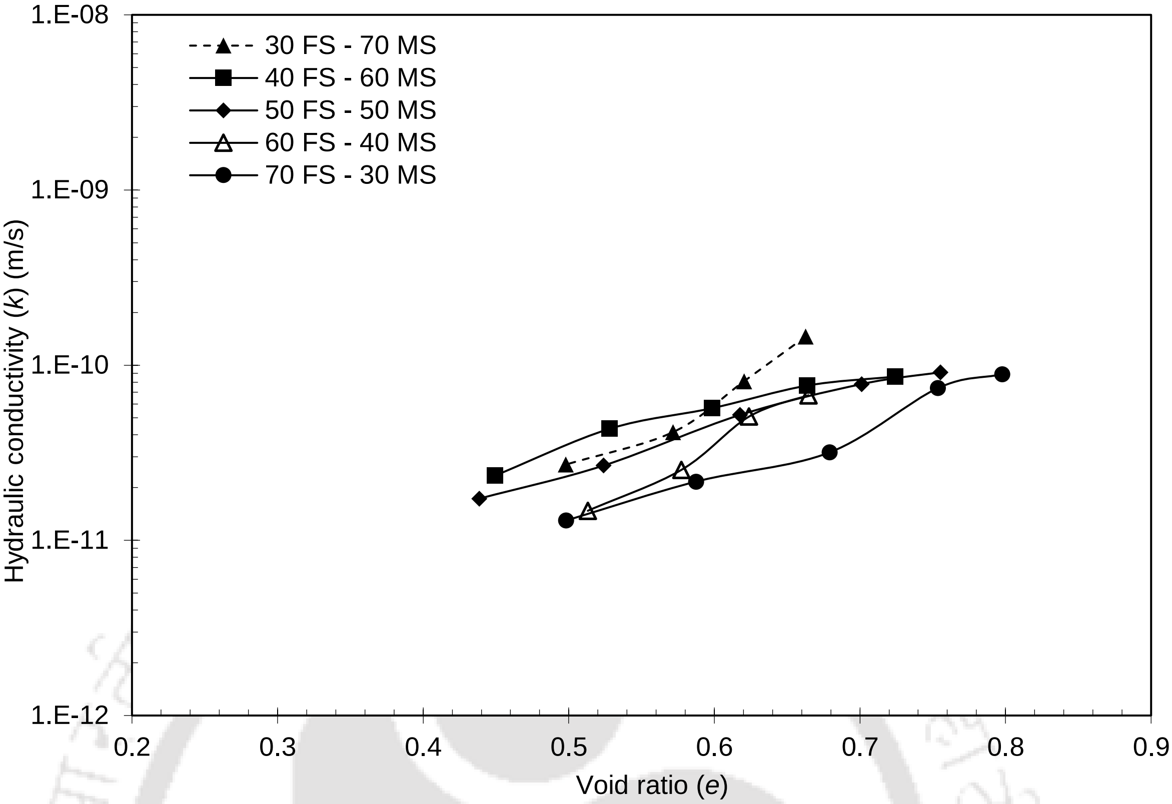


Figure 4.141 *e*-log *k* plot for 70% sand-30% B2 mixes compacted at OMC-MDD

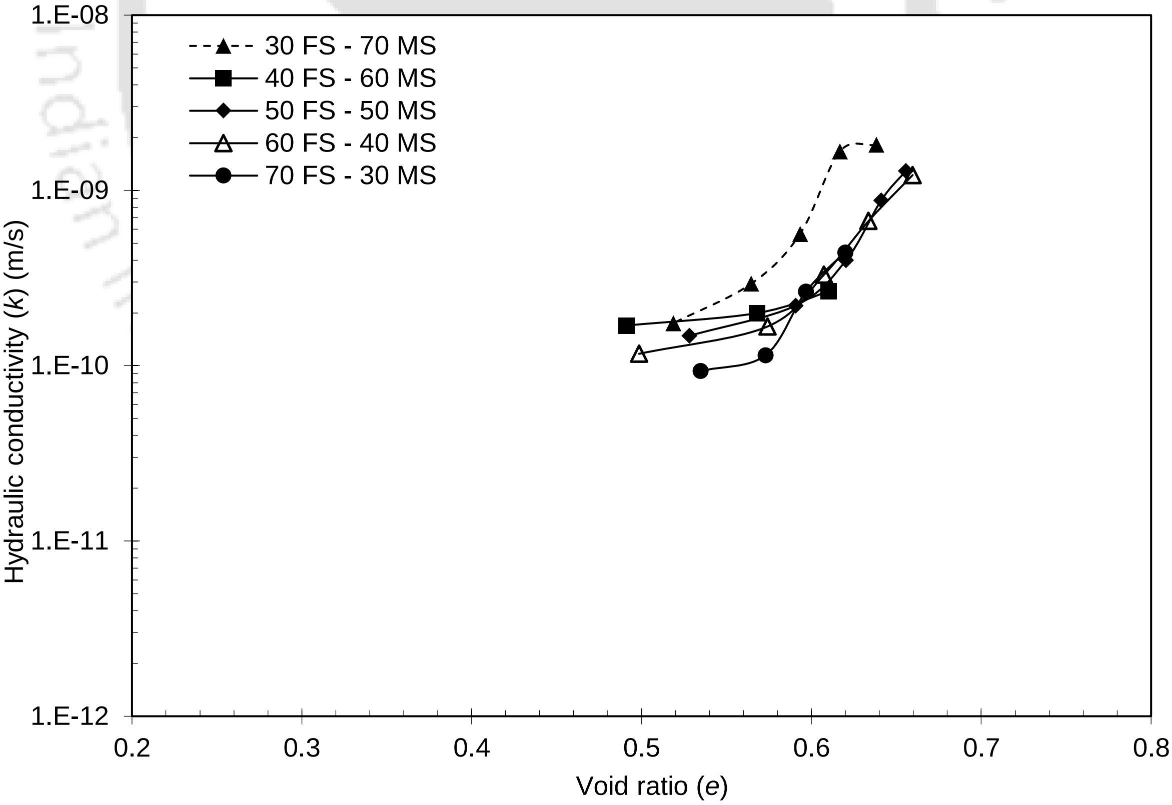


Figure 4.142 *e*-log *k* plot for 80% sand-20% B2 mixes compacted at OMC-MDD

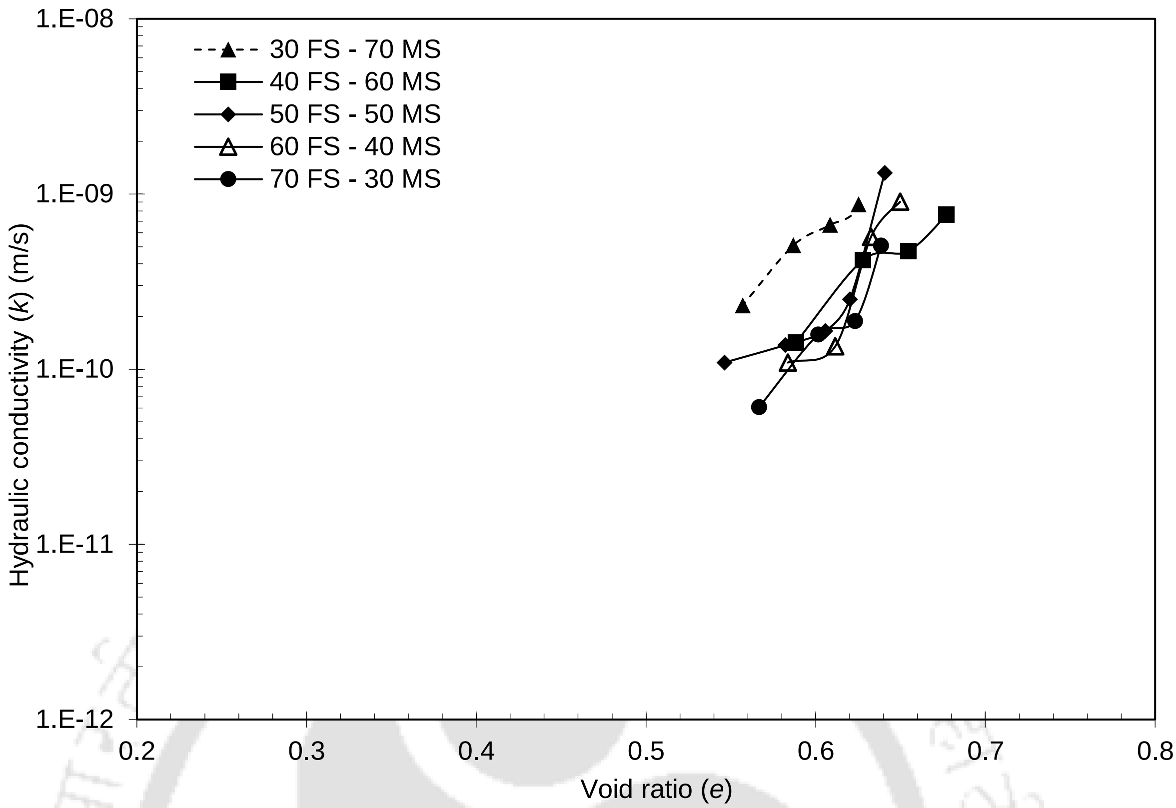


Figure 4.143 *e*-log *k* plot for 90% sand-10% B2 mixes compacted at OMC-MDD

In case of 70% sand+30% B2 mixes, initial and final hydraulic conductivities exhibited by various FS-MS proportions varied in the range of $6.7x10^{-11}$ to $1.5x10^{-10}$ m/sec and $1.3x10^{-11}$ to $2.7x10^{-11}$ m/sec respectively. In case of 80% sand+20% B2 mixes, initial and final hydraulic conductivities exhibited by various FS-MS proportions varied in the range of $4.4x10^{-10}$ to $1.8x10^{-9}$ m/sec and $9.3x10^{-11}$ to $1.75x10^{-10}$ m/sec respectively. In case of 90% sand+10% B2 mixes, initial and final hydraulic conductivities exhibited by various FS-MS proportions varied in the range of $5.1x10^{-10}$ to $1.3x10^{-9}$ m/sec and $6.1x10^{-11}$ to $2.3x10^{-10}$ m/sec respectively. Minimum hydraulic conductivity requirement for a landfill liner application being $1x10^{-9}$ m/sec. For all FS-MS proportions, mixes with high bentonite content (50%, 40% and 30%) exhibited low hydraulic conductivity, as in the case with FS-B2 and MS-B2 mixtures. Comparing FS-MS-B2 mixtures with FS-B2, MS-B2 mixes compacted at OMC-MDD indicated that sand proportioning resulted in no notable reduction in hydraulic conductivity in case of 50% sand+50% B2 mixes, 60% sand+40% B2 mixes and 70% sand+30% B2 mixes, a 2-fold reduction in case of 80% sand+20% B2 mixes, and 4 to 8-fold reduction in case of 90% sand+10% B2 mixes. Improvement in hydraulic behavior of FS-MS-B2 mixtures with bentonite content less than 20% has been observed as compared to FS-B2, MS-B2 mixes. Overall a positive effect of sand proportioning has been observed in terms of hydraulic behavior.

4.2.3.5 Effect of sand proportioning on *e*-log *P* relationship for various fine sand-medium sand-bentonite mixes

4.2.3.5.1 Effect of sand proportioning on *e*-log *P* relationship for FS-MS-B1 mixes

Influence of bentonite content, bentonite quality, sand particle size and initial compaction condition on the consolidation characteristics of sand-bentonite mixtures has been reported in section 4.1.3.5. This part of the study deals with understanding the influence of sand proportioning on the load-deformation behavior of different sand-bentonite mixtures. One dimensional consolidation tests were conducted on FS-MS-B1 mixtures, statically compacted at OMC-MDD. Five different proportions of B1 and FS-MS proportions were used in this part of the study. For each proportion of sand-bentonite, five different proportion of FS-MS were studied. Void ratio-Pressure relationship exhibited by FS-MS-B1 mixtures statically compacted at OMC-MDD are represented in Figs. 4.144 through Figs. 4.148. Even for a constant bentonite content, various FS-MS proportions resulted in distinct void ratio-Pressure (*e*-log *P*) relationships. In a sand-bentonite mixture, bentonite forms the swelling member while sand acts as the skeleton and a non-swelling member. For a sand-bentonite proportion the amount of swelling mineral present in the mixture is fixed and hence the capability for swelling and compressibility is also fixed, so if a difference in initial void ratio, compressibility etc. among the various mixtures is noticed because of change in the constitution of sand, the differences have to be caused because of sand proportioning. Therefore, it can be understood from the figures that, for a constant B1 content, sand proportioning has an undeniable influence on the formation and stiffness characteristics of sand skeleton, wherein the bentonite particles occupy the void spaces in the sand skeleton. Bentonite rich mixtures (50%, 40% and 30%) were seen to be highly compressible compared to mixes with B1 content less than 20%, a similar phenomenon has been observed in the case of FS-B1 and MS-B1 mixtures. For all different FS-MS proportions, mixes with high bentonite content (50% and 40%) resulted in high swelling and high initial void ratio’s as has been the case with FS-B1 and MS-B1 mixes stated before. Mixtures with bentonite content less than 20% are clearly sand dependent for their compressibility behavior for all FS-MS proportions. Comparing the void ratio-Pressure relationship for FS-MS-B1 mixes with those of FS-B1 and MS-B1 mixtures compacted at OMC-MDD revealed that the initial void ratio’s exhibited by FS-MS-B1 mixes are lower than FS-B1 mixes and higher than MS-B1 mixes, for a given B1 content.

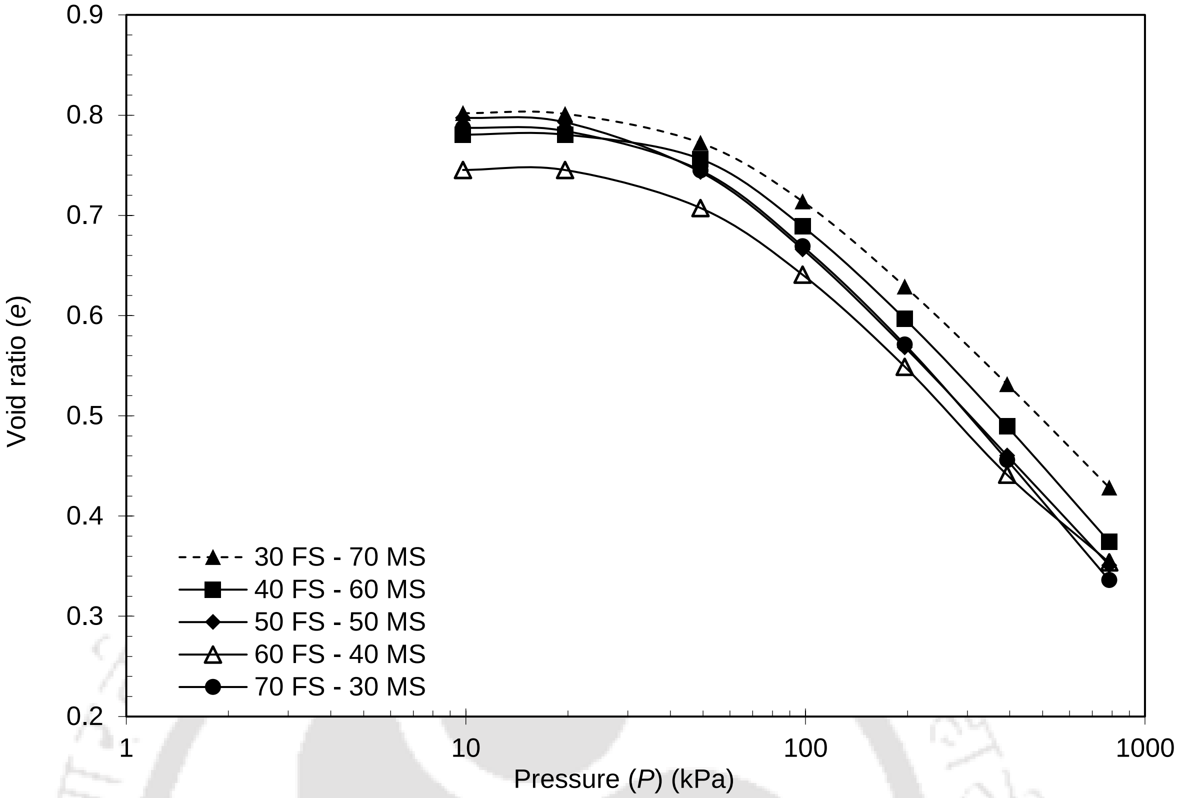


Figure 4.144 *e*-log *P* plot for 50% sand-50% B1 mixes compacted at OMC-MDD

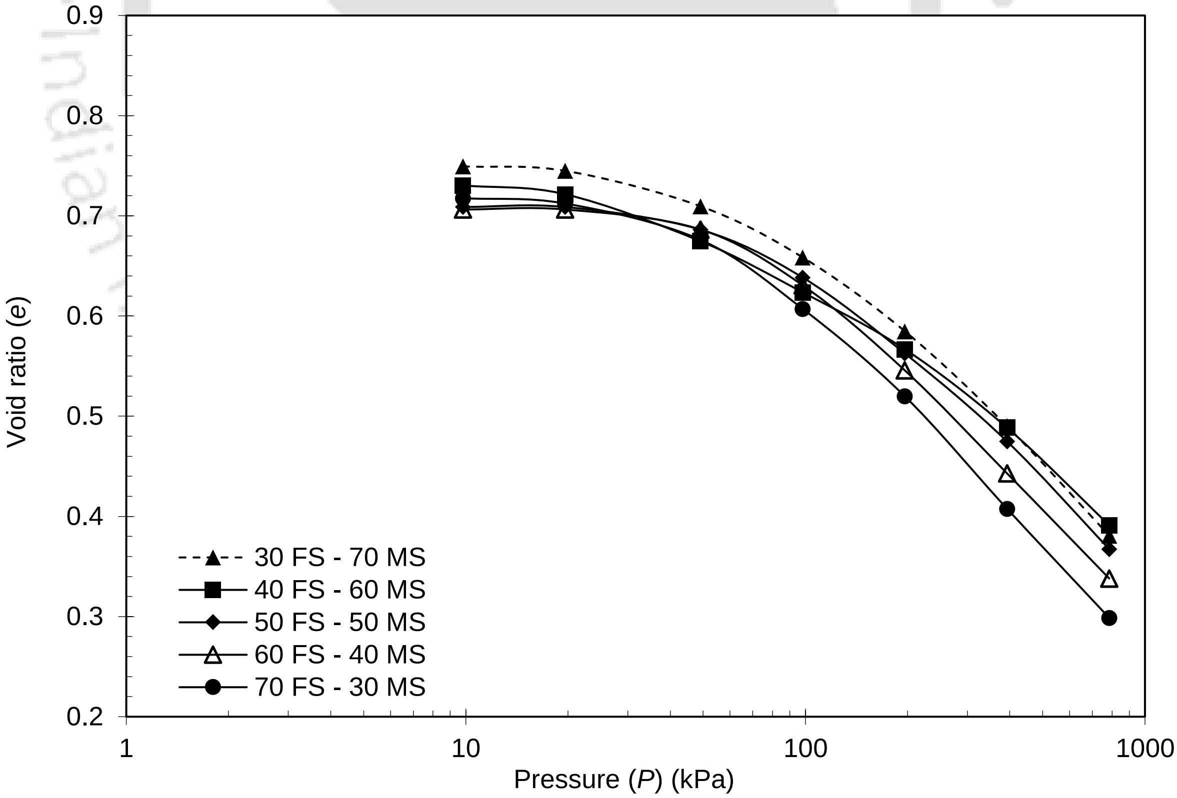


Figure 4.145 *e*-log *P* plot for 60% sand-40% B1 mixes compacted at OMC-MDD

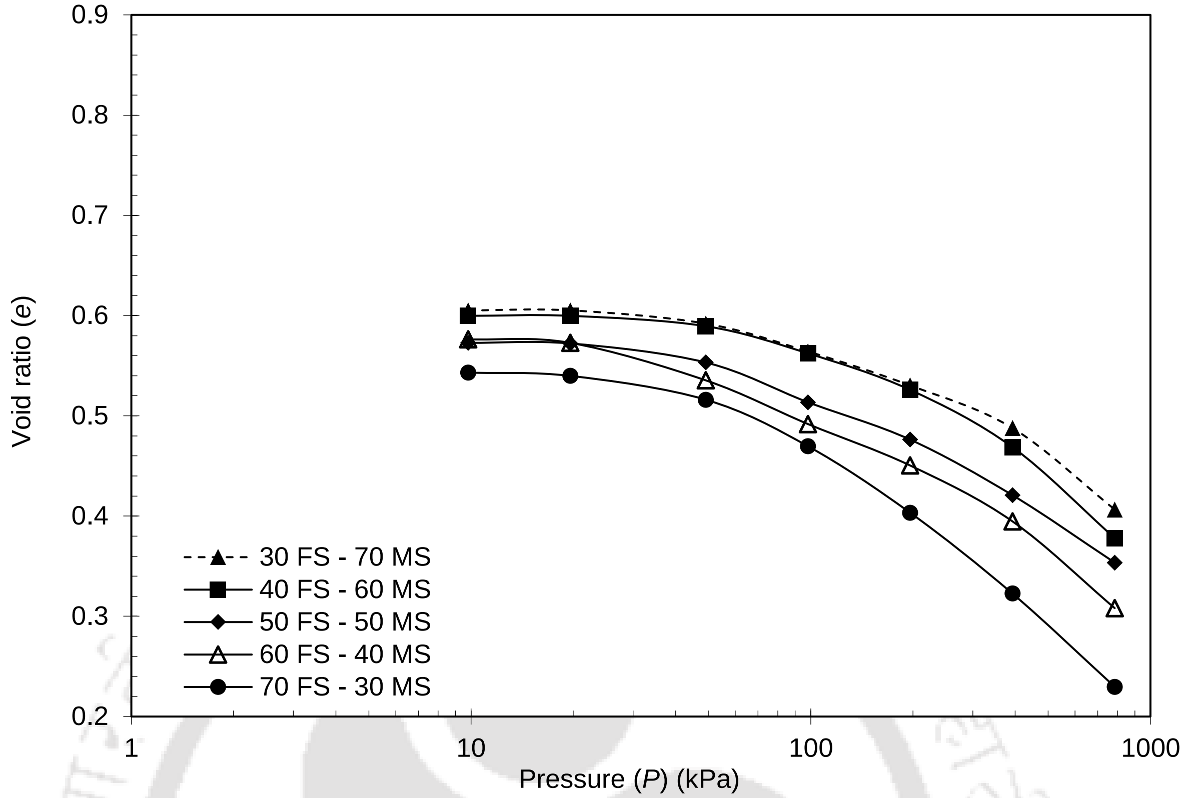


Figure 4.146 *e*-log *P* plot for 70% sand-30% B1 mixes compacted at OMC-MDD

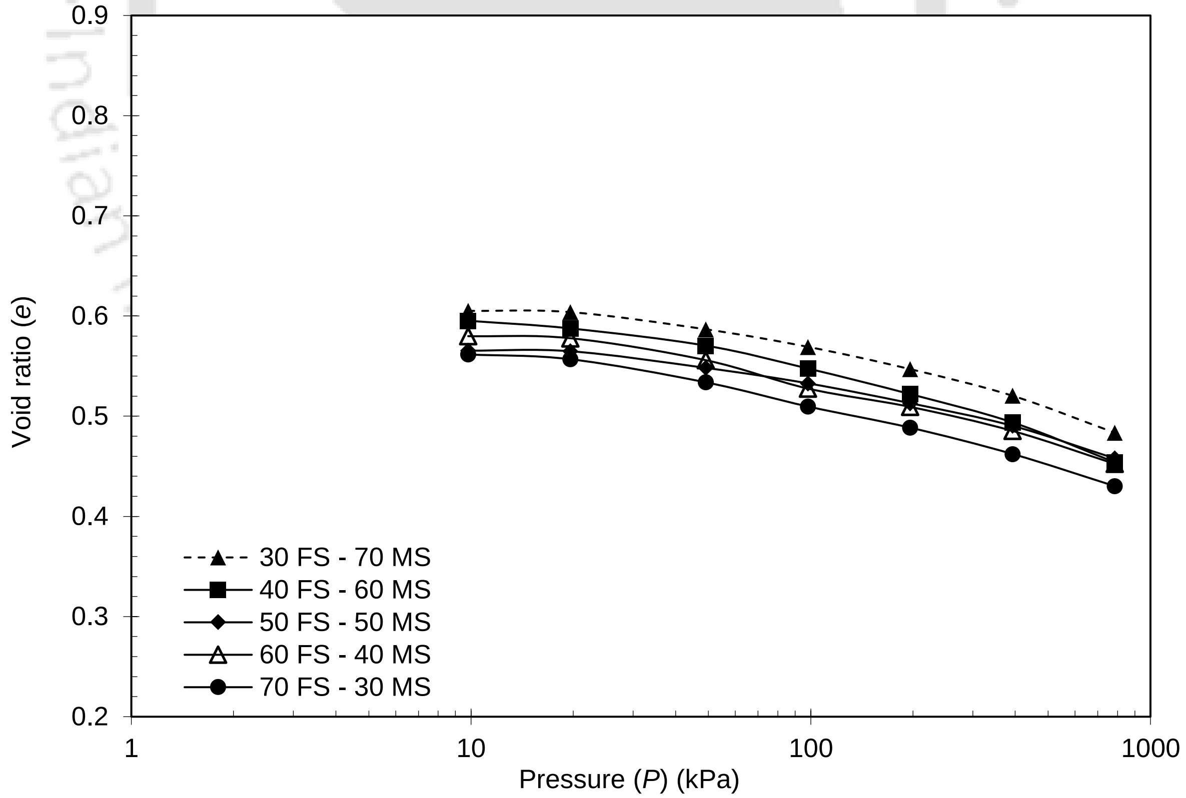


Figure 4.147 *e*-log *P* plot for 80% sand-20% B1 mixes compacted at OMC-MDD

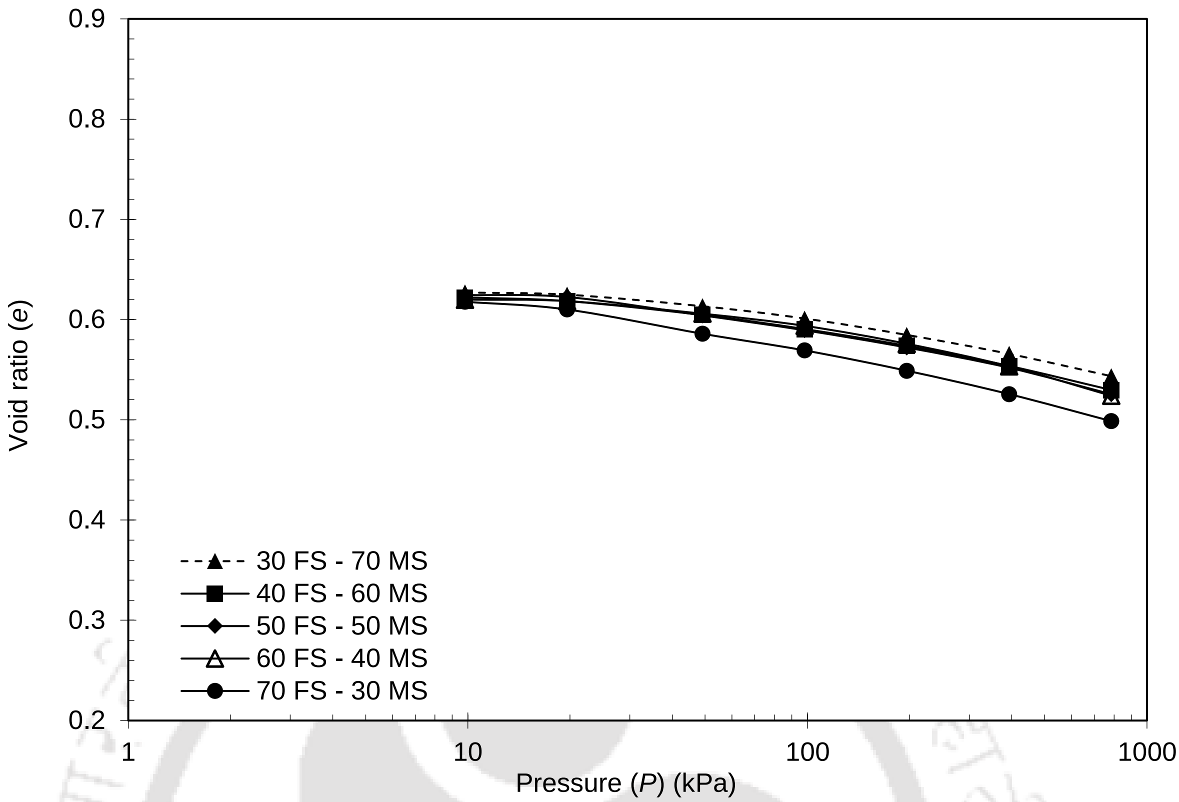


Figure 4.148 *e*-log *P* plot for 90% sand-10% B1 mixes compacted at OMC-MDD

FS-MS-B1 mixes were found to be more compressible than FS-B1 mixes and less compressible than MS-B1 mixes.

4.2.3.5.2 Effect of sand proportioning on *e*-log *P* relationship for FS-MS-B2 mixes

One dimensional consolidation tests were conducted on FS-MS-B2 mixtures on similar lines of FS-MS-B1 mixtures. Void ratio-Pressure relationship exhibited by FS-MS-B2 mixtures statically compacted at OMC-MDD are represented in Figs. 4.149 through Figs. 4.153. Bentonite-2 being a high swelling bentonite, a higher initial void ratio was observed for all the mixtures in comparison to FS-MS-B1 mixtures irrespective of FS-MS proportion. For all proportions of B2, distinct void ratio-Pressure relationships were observed with all FS-MS proportions. FS-MS-B2 mixtures with high bentonite content (50% - 30%) resulted in high swelling and high initial void ratio’s as it has been the case with FS-MS-B1 mixtures. Exhibited final void ratios at final loading revealed a slight dispersion as opposed to close grouping that took place in case of FS-B2 and MS-B2 samples indicating a possible sand proportioning effect. Effect of sand proportioning is more visible in mixes with higher bentonite content (50% - 30%). Mixtures with a bentonite content of 20% and less, with low compressibility, indicate a sand domination in terms of compressibility, initial and final void ratios.

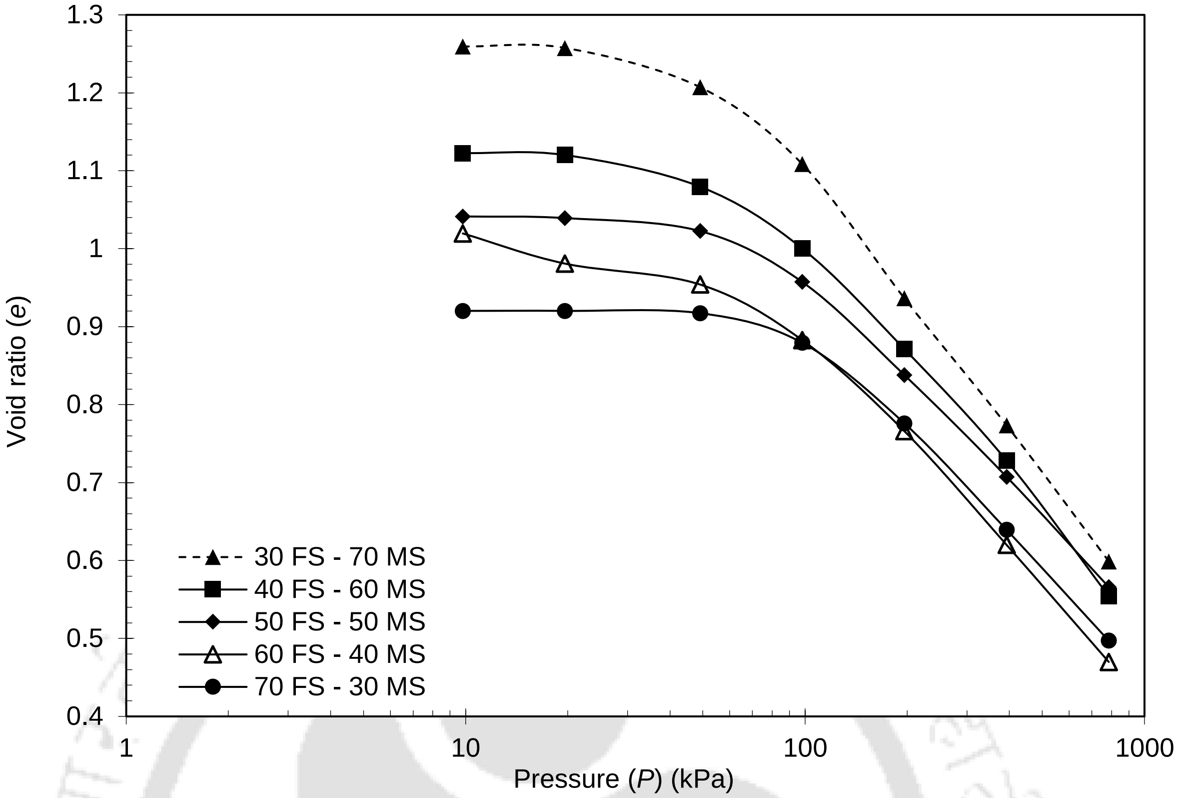


Figure 4.149 *e*-log *P* plot for 50% sand-50% B2 mixes compacted at OMC-MDD

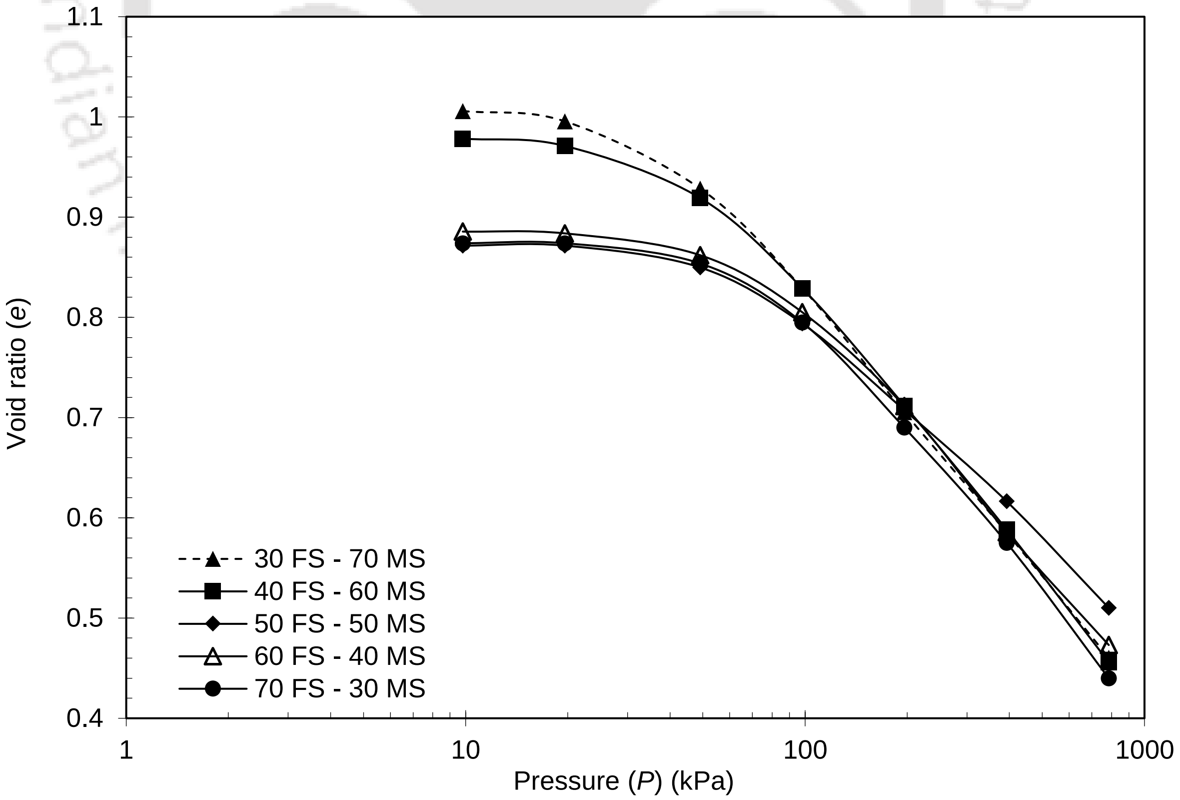


Figure 4.150 *e*-log *P* plot for 60% sand-40% B2 mixes compacted at OMC-MDD

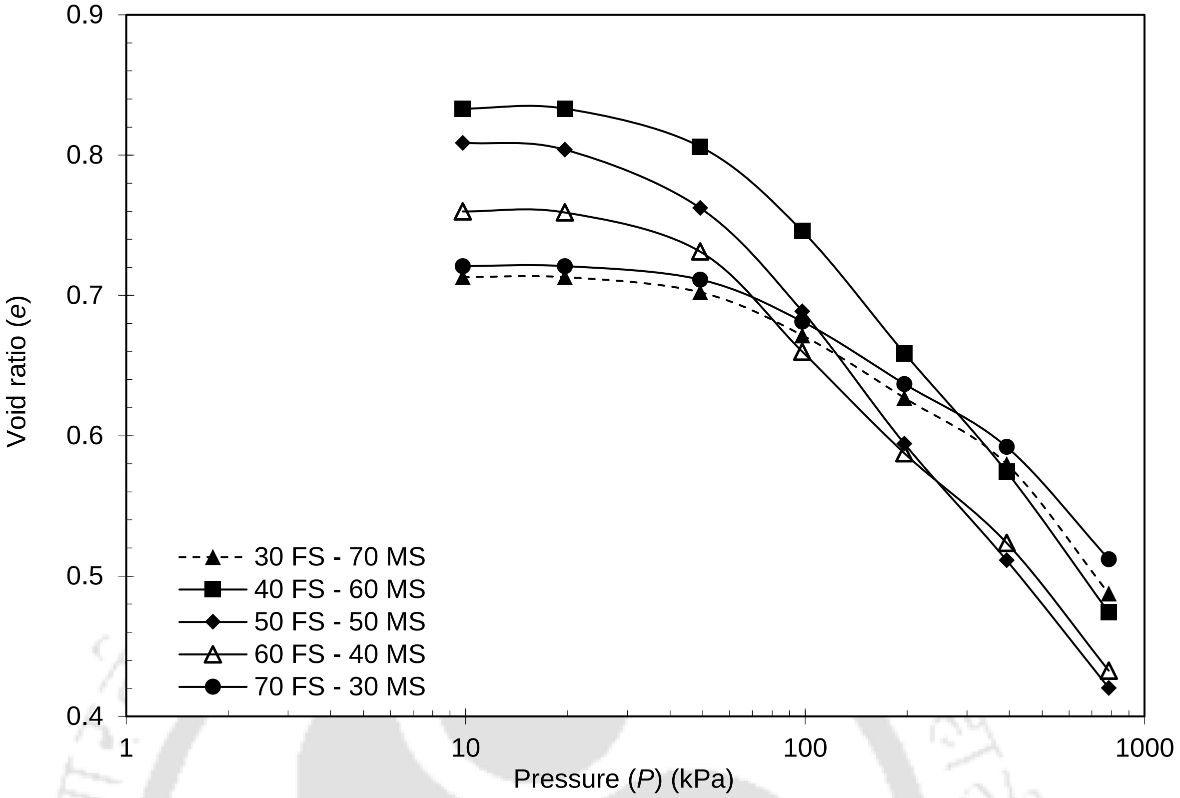


Figure 4.151 *e*-log *P* plot for 70% sand-30% B2 mixes compacted at OMC-MDD

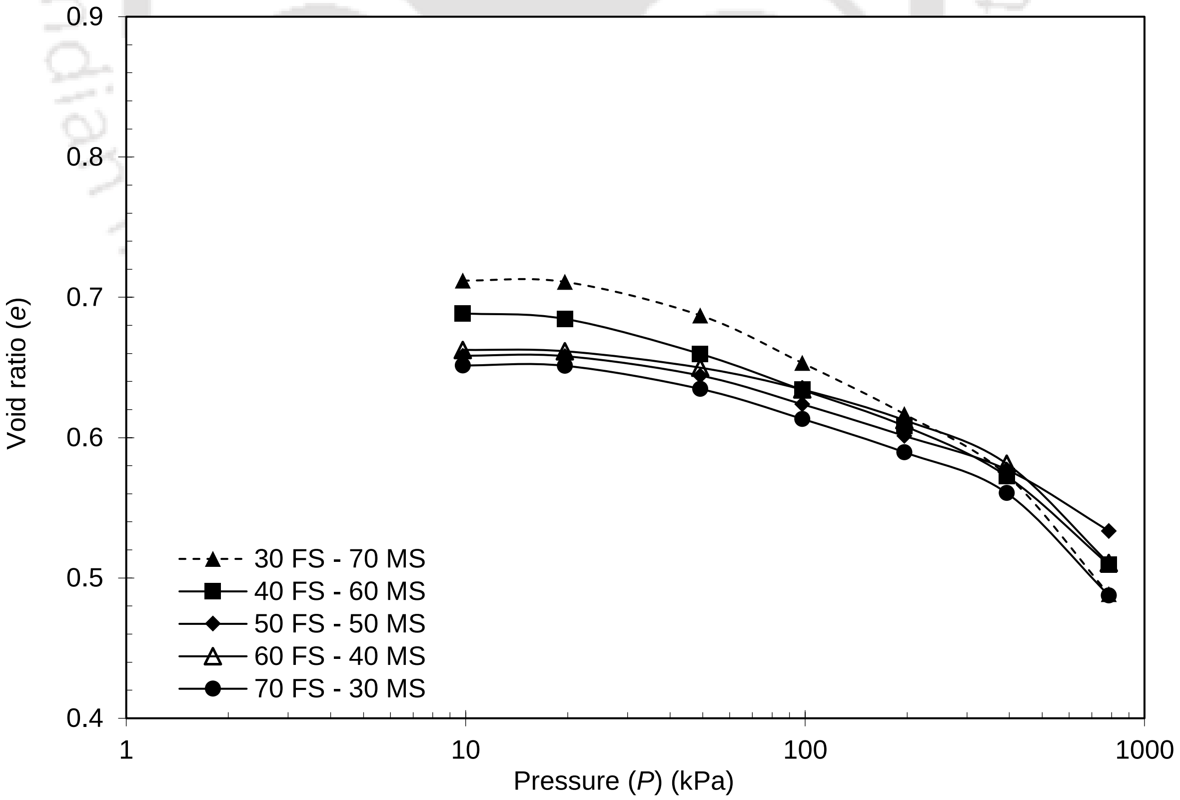


Figure 4.152 *e*-log *P* plot for 80% sand-20% B2 mixes compacted at OMC-MDD

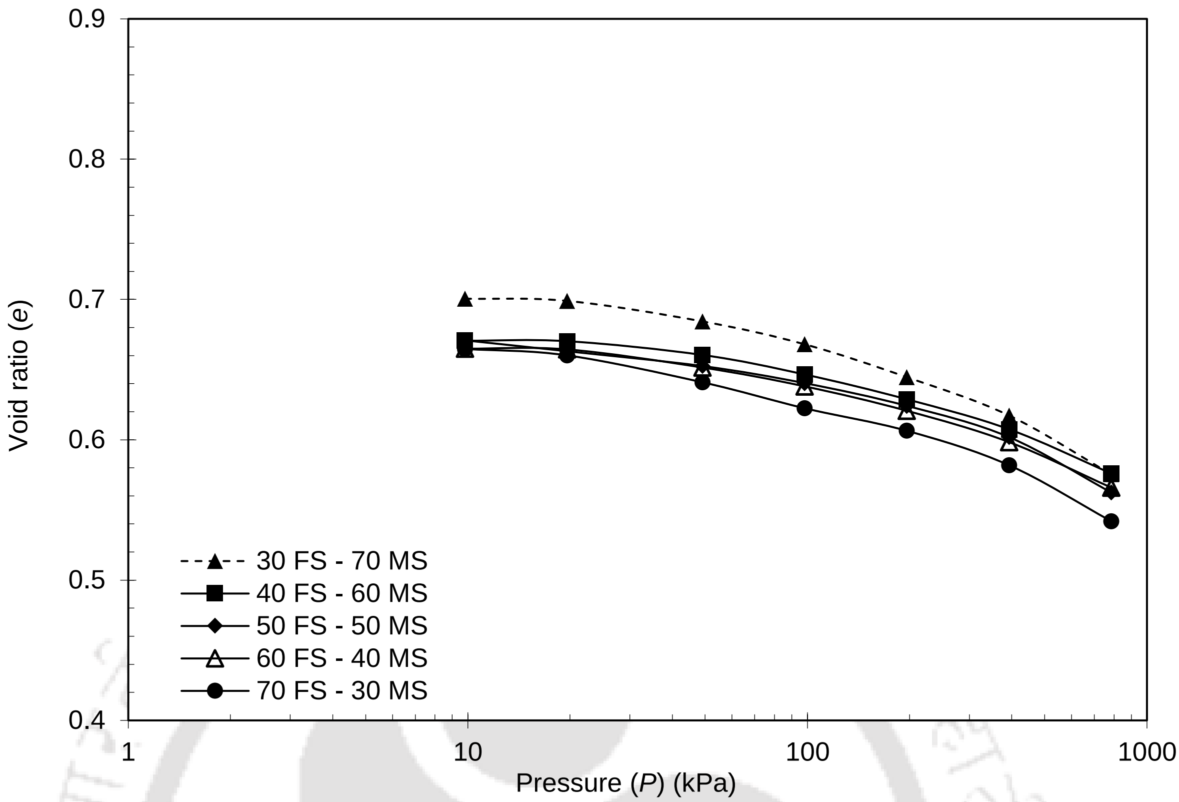


Figure 4.153 *e*-log *P* plot for 90% sand-10% B2 mixes compacted at OMC-MDD

Mixtures with bentonite content less than 20% are clearly sand dependent for their compressibility behavior for all FS-MS proportions. Comparing the void ratio-Pressure relationship for FS-MS-B2 mixes with those of FS-B2 and MS-B2 mixtures compacted at OMC-MDD revealed that the initial void ratio's exhibited by FS-MS-B2 mixes are higher than FS-B2 and MS-B2 mixes, for a given B2 content. FS-MS-B2 mixes were found to be more compressible than FS-B2 mixes and less compressible than MS-B2 mixes.

4.2.3.6 Effect of sand proportioning on Coefficient of consolidation (c_v)-Pressure relationship for various fine sand-medium sand-bentonite mixes

4.2.3.6.1 Effect of sand proportioning on c_v-Pressure relationship for FS-MS-B1 mixes

Coefficient of consolidation (c_v)-Pressure relationship exhibited by FS-MS-B1 mixes compacted at OMC-MDD are presented in Figs. 4.154 through Figs. 4.158. Coefficient of consolidation was found to be increasing with decreasing the bentonite content in the mixture, similar to as observed in case of FS-B1 and MS-B1 mixes. For any given B1 content, distinct c_v-Pressure relationship were observed with each FS-MS proportion. Mixes with 50% bentonite content exhibited c_v values in the range of 3.7x10^{-9} to 3.2x10^{-9} m^2/s. Mixes with 40% bentonite content exhibited c_v values in the range of 1.1x10^{-8} to

$4.1x10^{-9}$ m^2/s. Mixes with 30% bentonite content exhibited c_v values in the range of $1.3x10^{-7}$ to $3.9x10^{-8}$ m^2/s. Mixes with 20% bentonite content exhibited c_v values in the range of $6.9x10^{-7}$ to $1.6x10^{-7}$ m^2/s. Mixes with 10% bentonite content exhibited c_v values in the range of $1.1x10^{-6}$ to $4.1x10^{-7}$ m^2/s. When compared to FS-B1 and MS-B1 mixes, FS-MS-B1 mixes exhibited a much lower c_v, at least 10 times lower for the same load increments. In compacted FS-MS-B1 mixtures, voids formed by MS are filled by FS and voids formed by FS are filled by B1 leading to a much stiffer soil mass with small void spaces for flow to take place and the same is reflected as lower c_v values. For any given bentonite content, increasing the fine sand proportion in the sand mixture is resulting in a soil mass with numerous small voids. Since voids in a soil mass form the flow paths, any reduction in the size of voids may result in reduced flow paths and thereby reflecting as a reduction in hydraulic conductivity. These smaller voids hinder the flow resulting in low hydraulic conductivity and the same resistance to flow is reflected in the relatively lower c_v values being exhibited by FS-MS-B1 mixtures.

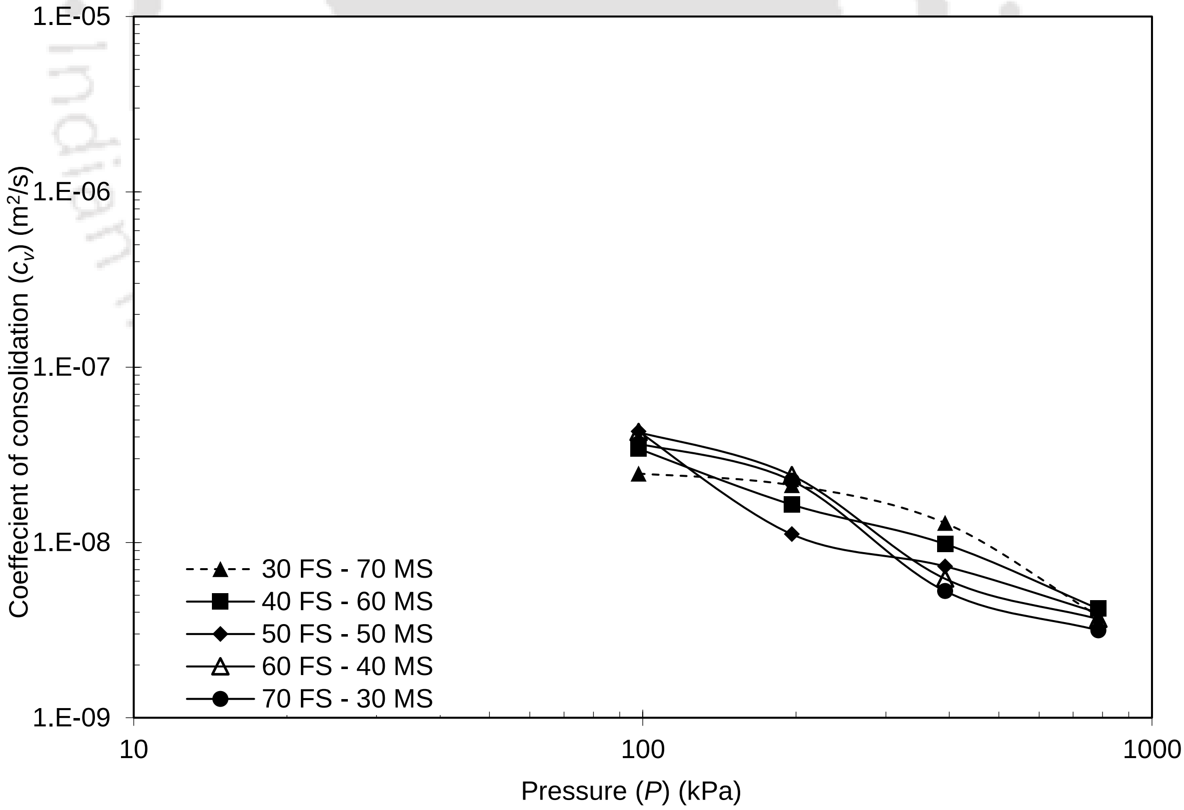


Figure 4.154 c_v-Pressure plot for 50% sand-50% B1 mixes compacted at OMC-MDD

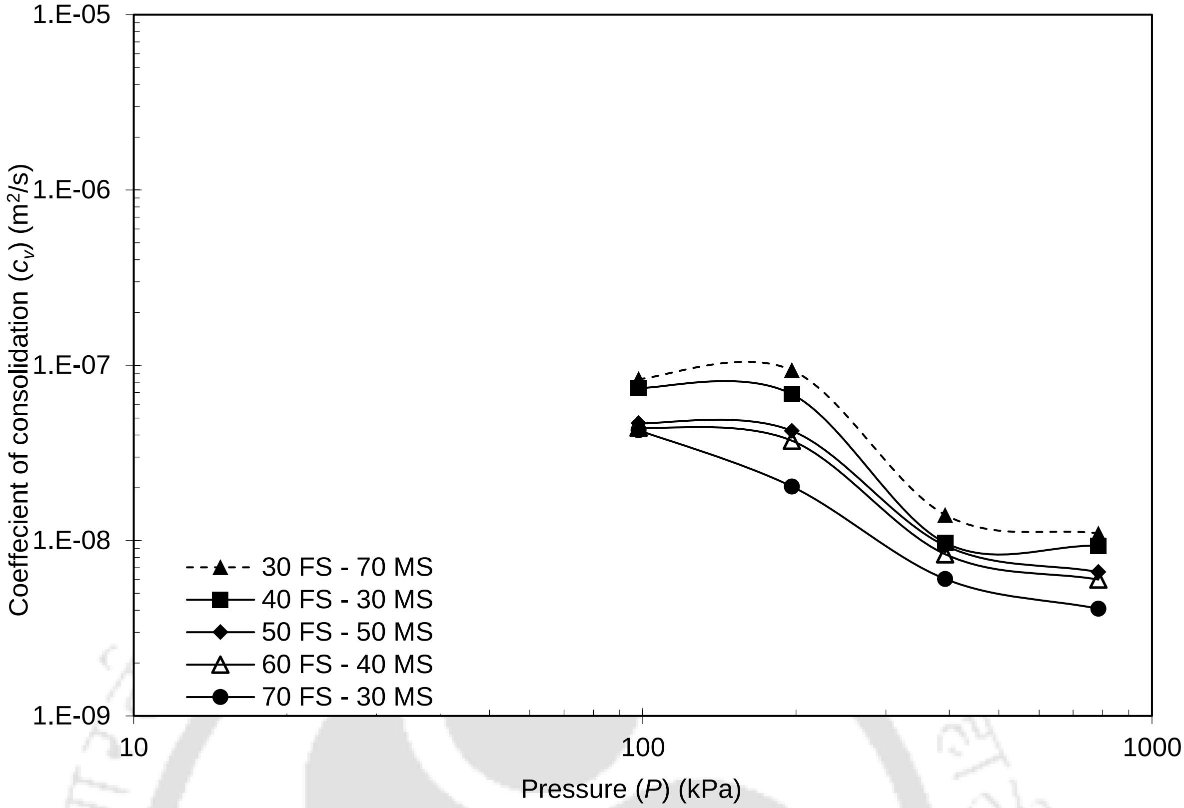


Figure 4.155 c_v-Pressure plot for 60% sand-40% B1 mixes compacted at OMC-MDD

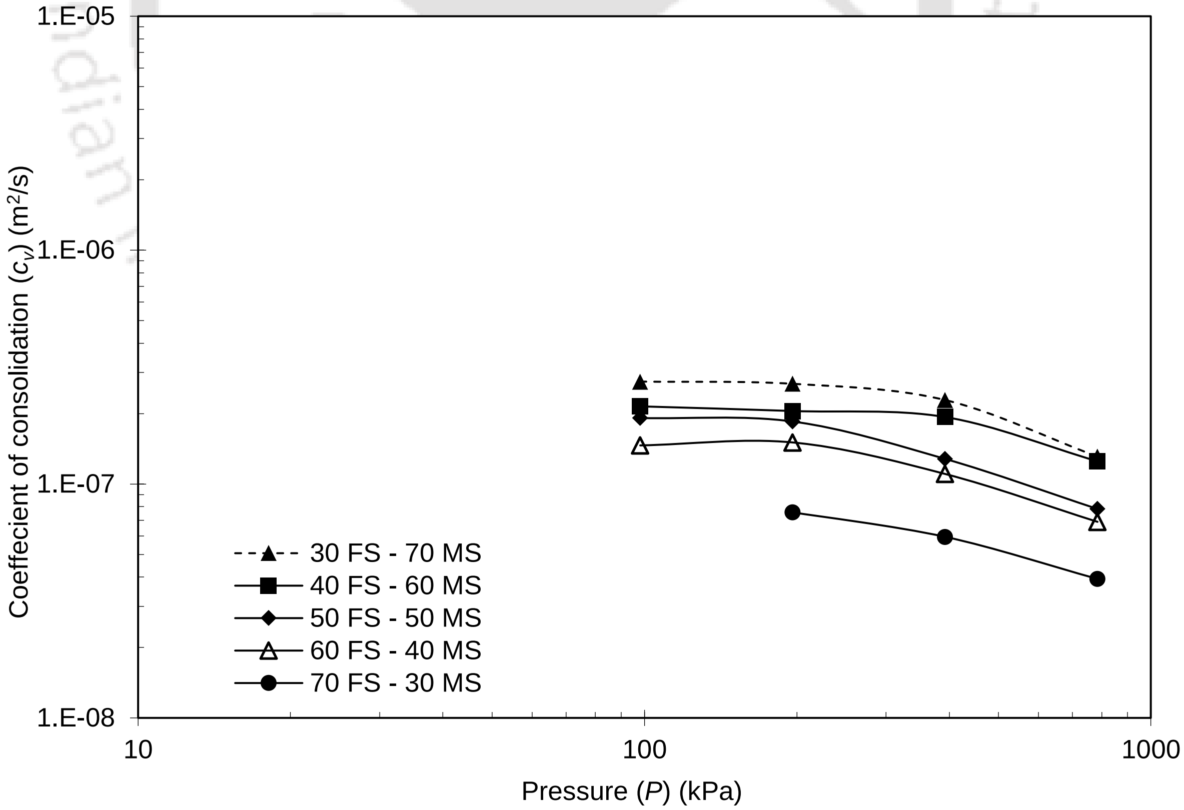


Figure 4.156 c_v-Pressure plot for 70% sand-30% B1 mixes compacted at OMC-MDD

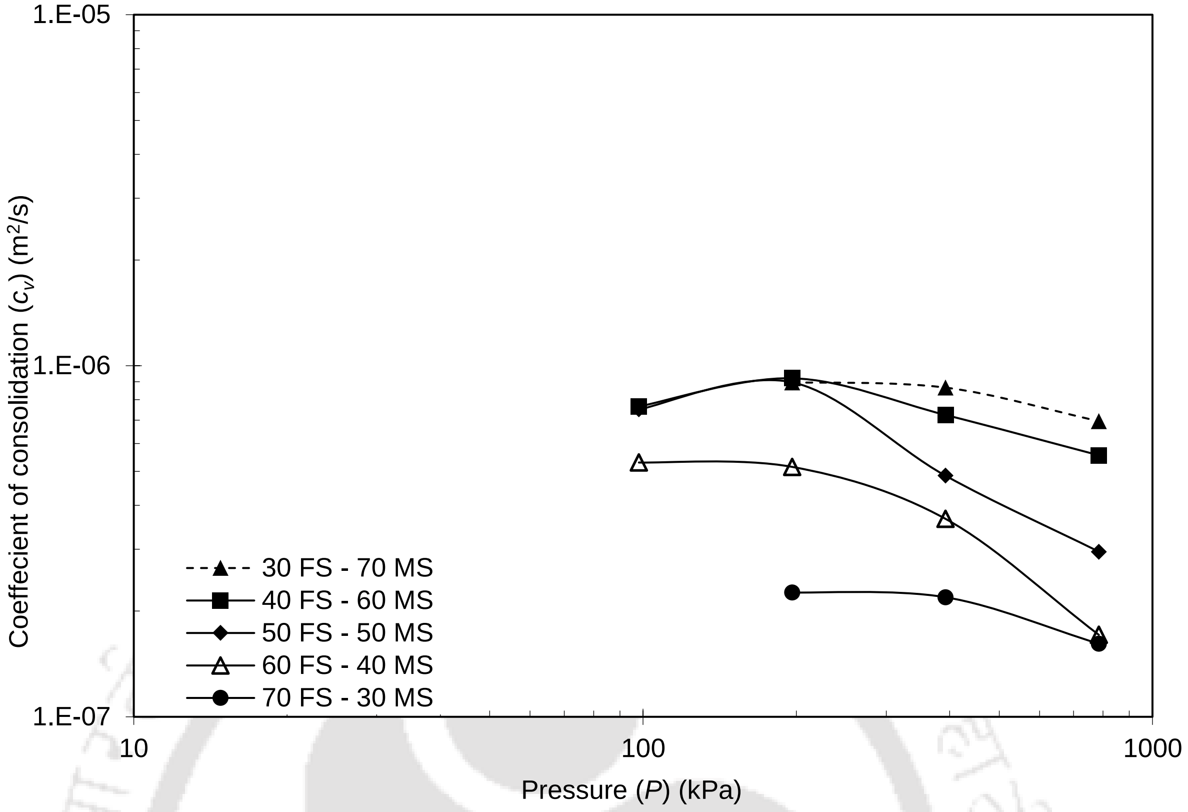


Figure 4.157 c_v-Pressure plot for 80% sand-20% B1 mixes compacted at OMC-MDD

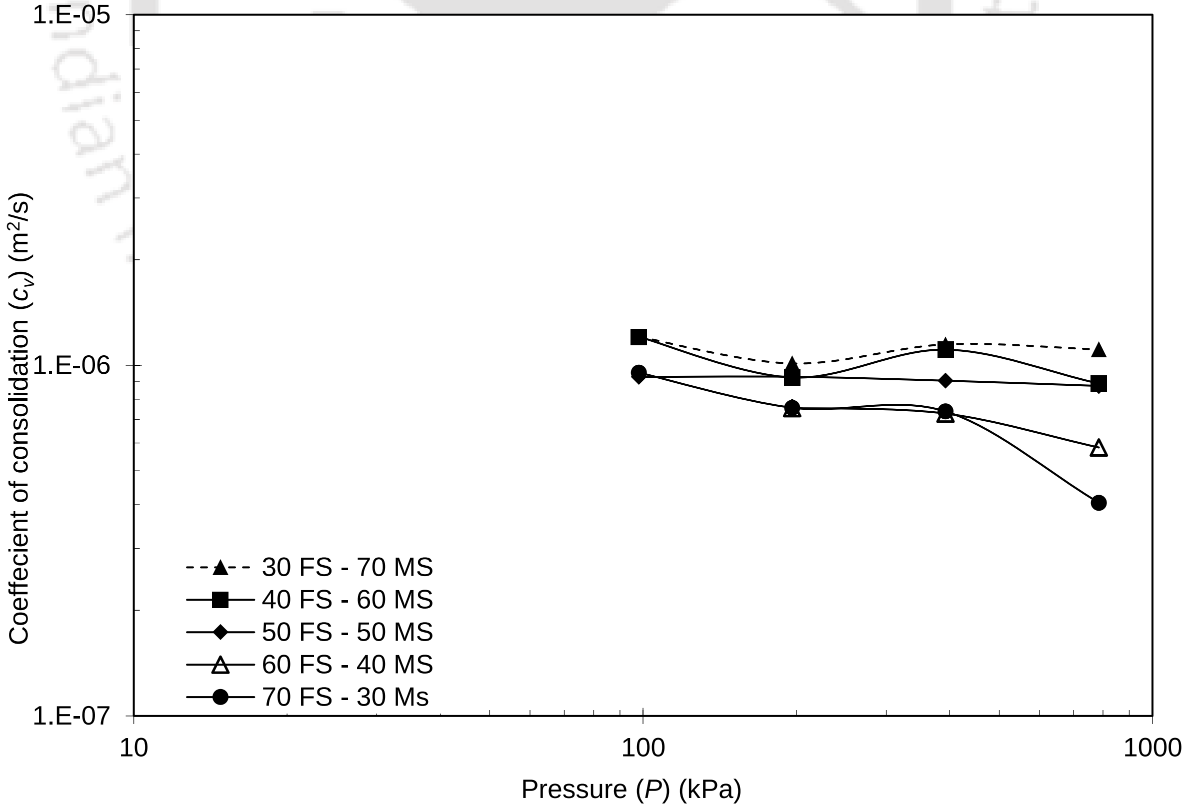


Figure 4.158 c_v-Pressure plot for 90% sand-10% B1 mixes compacted at OMC-MDD

4.2.3.6.2 Effect of sand proportioning on c_v-Pressure relationship for FS-MS-B2 mixes

Coefficient of consolidation (c_v) -Pressure relationship exhibited by FS-MS-B2 mixes compacted at OMC-MDD are presented in Figs. 4.159 through Figs. 4.163. Coefficient of consolidation was found to be increasing with decreasing bentonite content, the same has been observed in case of FS-MS-B1 mixes. For any given B2 content, distinct c_v-Pressure relationship were observed with each FS-MS proportion. Mixes with 50% bentonite content exhibited c_v values in the range of $2.8x10^{-9}$ to $1.6x10^{-9}$ m^2/s. Mixes with 40% bentonite content exhibited c_v values in the range of $5.4x10^{-9}$ to $3.3x10^{-9}$ m^2/s. Mixes with 30% bentonite content exhibited c_v values in the range of $1.8x10^{-8}$ to $6.2x10^{-9}$ m^2/s. Mixes with 20% bentonite content exhibited c_v values in the range of $2.1x10^{-7}$ to $5.4x10^{-8}$ m^2/s. Mixes with 10% bentonite content exhibited c_v values in the range of $3.5x10^{-7}$ to $4.8x10^{-8}$ m^2/s. FS-MS-B2 mixtures exhibited lower c_v values relative to FS-MS-B1 mixtures. The higher swelling nature of B2 present in FS-MS-B2 mixtures helps in filling the voids in a much efficient manner compared to B1 in FS-MS-B1 mixtures. And the better filling of voids is in turn reflected as reduced pathways for water flow to take place leading to a relatively lower c_v values.

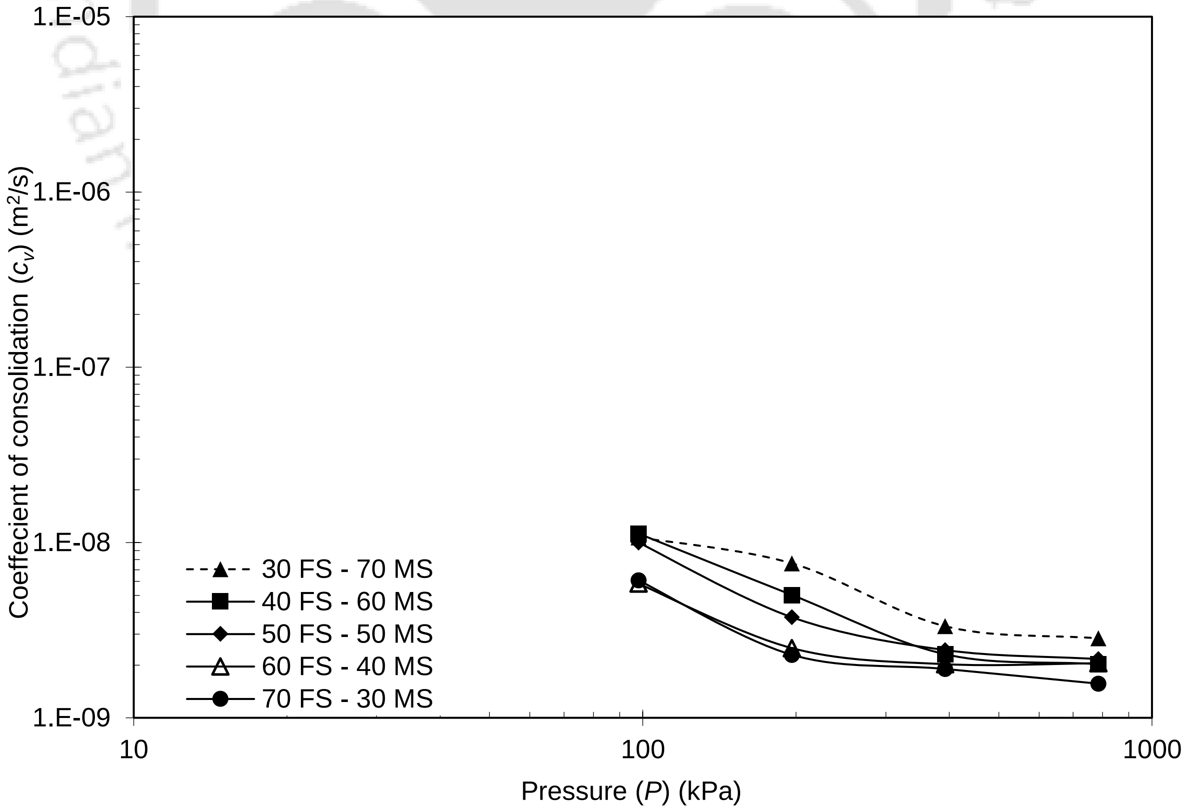


Figure 4.159 c_v-Pressure plot for 50% sand-50% B2 mixes compacted at OMC-MDD

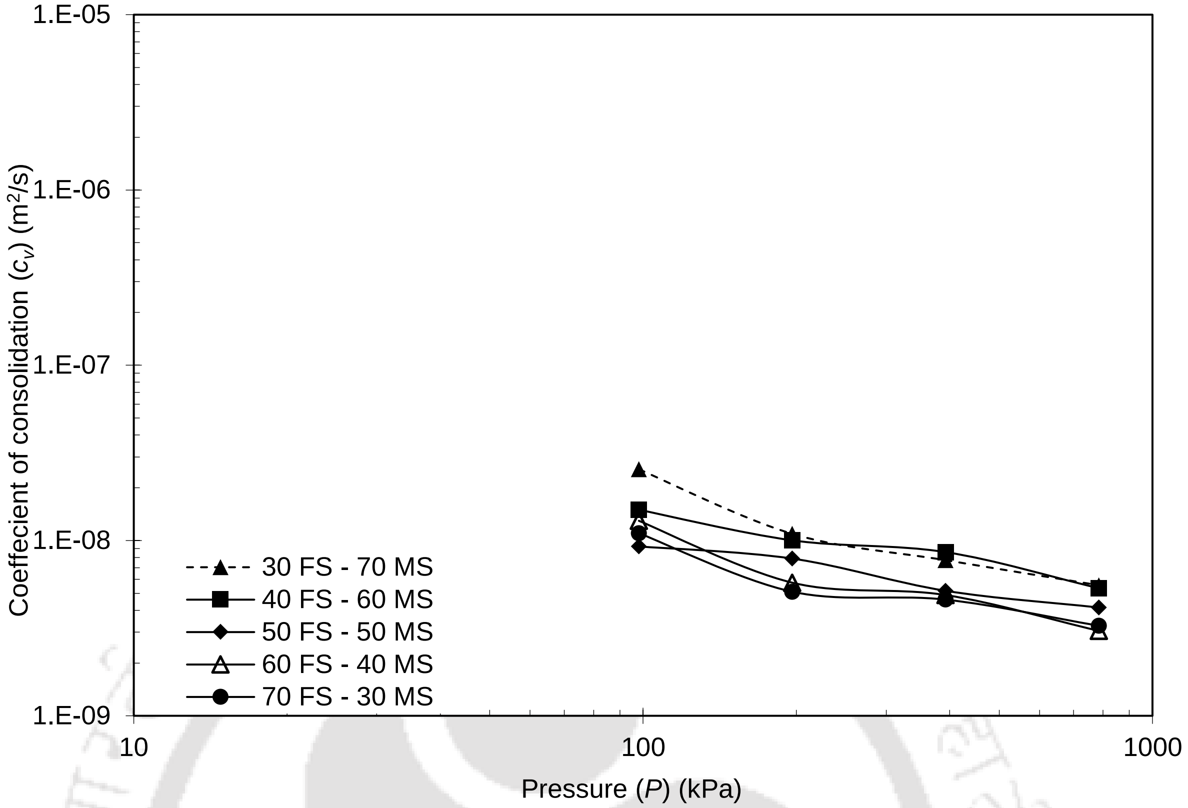


Figure 4.160 c_v-Pressure plot for 60% sand-40% B2 mixes compacted at OMC-MDD

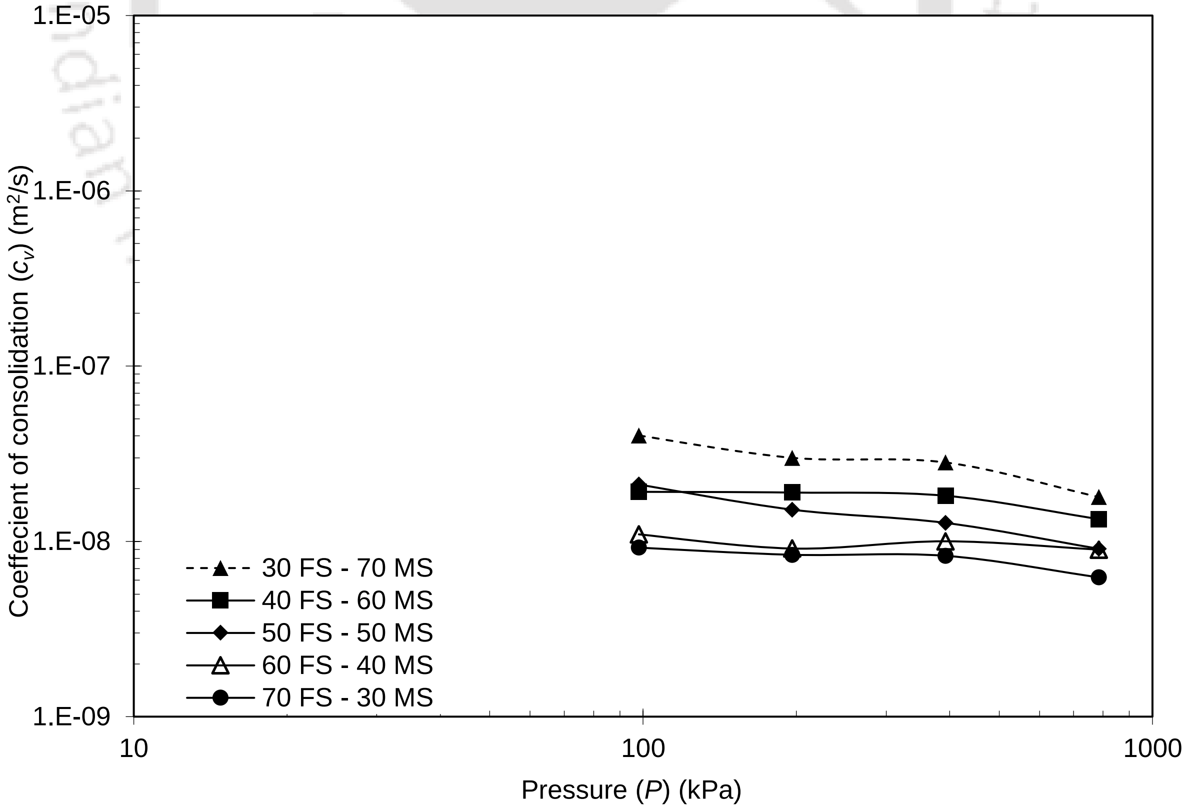


Figure 4.161 c_v-Pressure plot for 70% sand-30% B2 mixes compacted at OMC-MDD

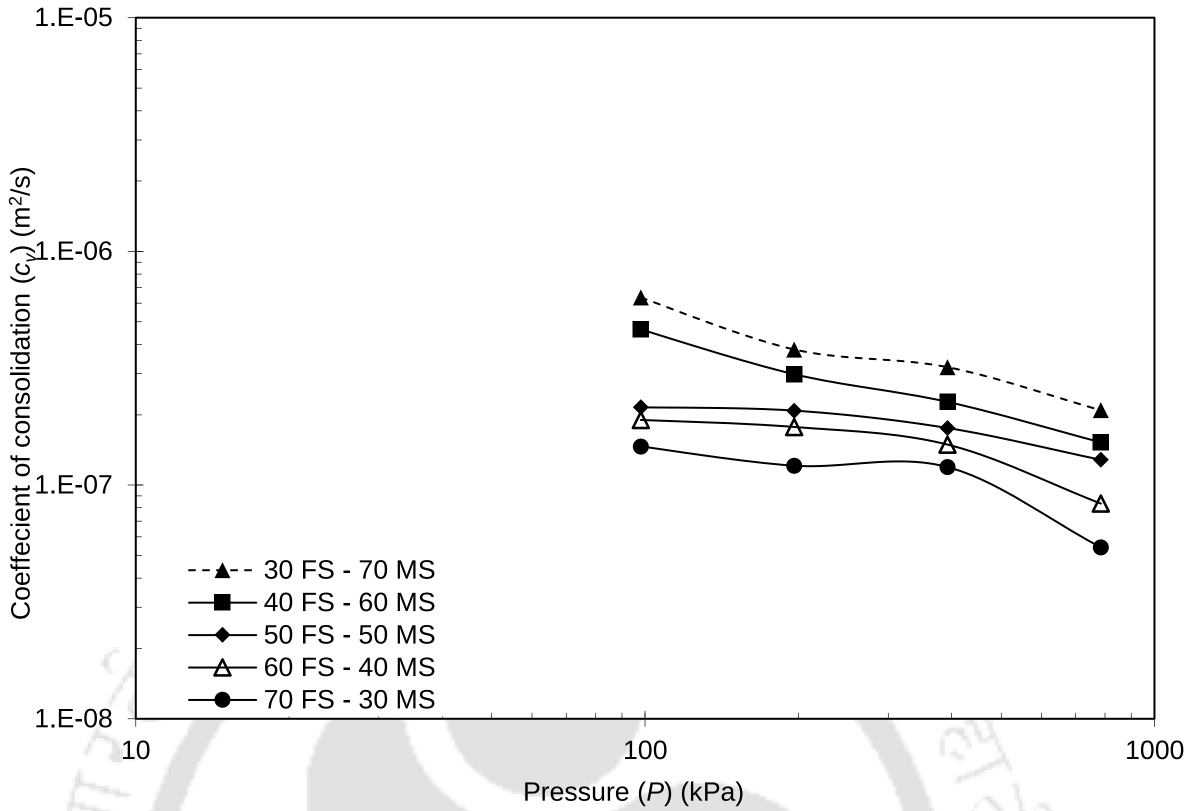


Figure 4.162 c_v-Pressure plot for 80% sand-20% B2 mixes compacted at OMC-MDD

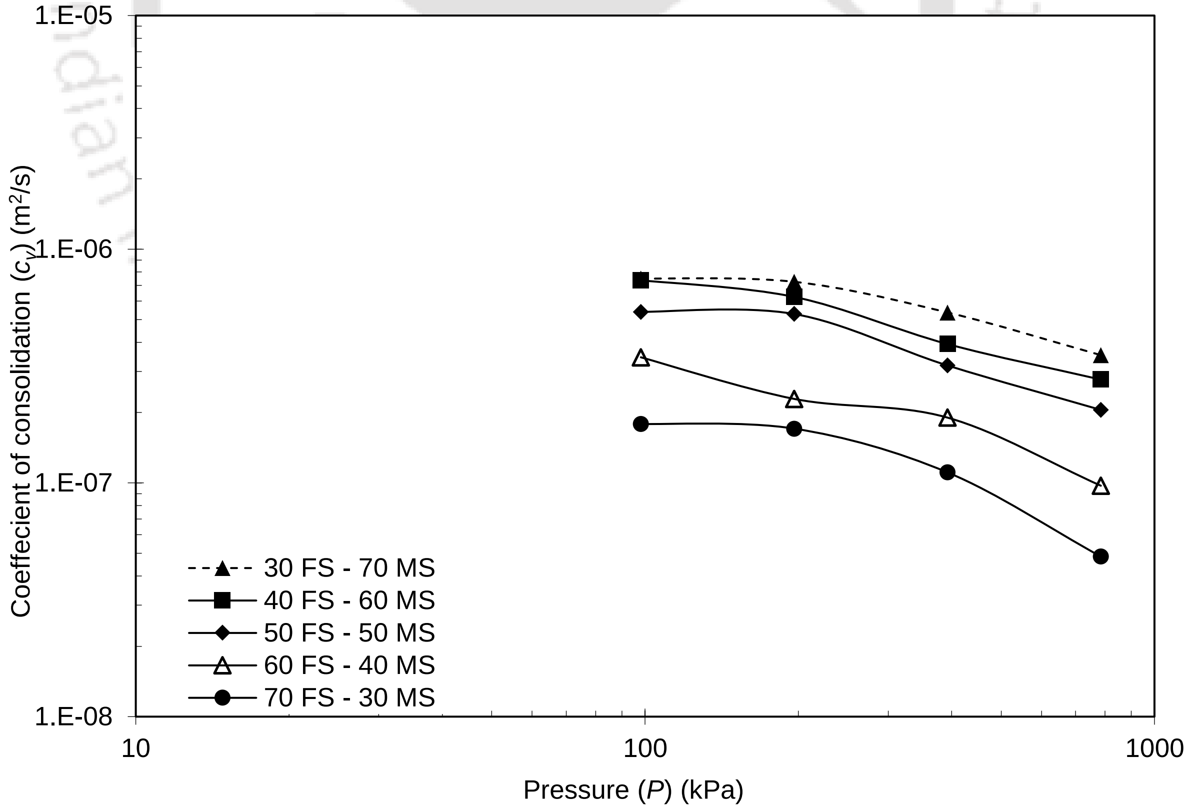


Figure 4.163 c_v-Pressure plot for 90% sand-10% B2 mixes compacted at OMC-MDD

4.2.3.7 Effect of sand proportioning on Coefficient of volume change (m_v)-Pressure relationship of fine sand-medium sand-bentonite mixes

4.2.3.7.1 Effect of sand proportioning on m_v-Pressure relationship of FS-MS-B1 mixes

Influence of bentonite content, initial compaction conditions and sand particle size on the compressibility behavior of sand-bentonite mixtures has been presented in section 4.1.3.7. This part of the study deals with understanding the influence of sand proportioning on the compressibility characteristics of sand-bentonite mixtures. Coefficient of volume change (m_v) – Pressure relationship exhibited by FS-MS-B1 mixtures, compacted at OMC-MDD, is presented in Figs. 4.164 through Figs. 4.168. FS-MS-B1 mixtures exhibited distinct m_v-Pressure relationships for all FS-MS proportions, for any given B1 content. Mixtures with a B1 content of 30% and less exhibited a much lower m_v values compared to mixes with 40% and 50% indicating a shift in load carrying mechanism. Influence of sand proportioning on m_v is low in the mixes with B1 content higher than 40%. With increasing sand content in FS-MS-B1 mixes, m_v values were found to be decreasing, a similar trend was observed with FS-B1 and MS-B1 mixes. Better filling of voids in the soil mass results in a stiffer soil mass. A stiffer soil mass undergoes relatively lower volume changes upon loading. As the stiffness of the soil increases, a reduction in m_v values is observed. Continuing the same, from the observed results, increasing the FS proportion in the sand mixtures is resulting in a similar behavior, for a constant bentonite content. Therefore increasing the FS proportion in sand results in a stiffer soil leading to lower m_v values. The optimum FS proportion in the sand-bentonite mixtures needs to be determined through laboratory testing. With the scope, in the current study, it has been observed that a sand with 70% FS + 30% MS proportions exhibits lowest m_v values for all bentonite proportions considered.

4.2.3.7.2 Effect of sand proportioning on m_v-Pressure relationship of FS-MS-B2 mixes

Coefficient of volume change (m_v) – pressure relationship exhibited by FS-MS-B2 mixtures, compacted at OMC-MDD, is presented in Figs. 4.169 through Figs. 4.173. Bentonite-2 being a relatively high swelling bentonite, FS-MS-B2 mixtures were seen to exhibit a relatively higher m_v values compared to FS-MS-B1 mixtures. Influence of sand proportioning can be seen in the distinct curves exhibited by mixes with different FS-MS proportions, for any B2 content considered in the study.

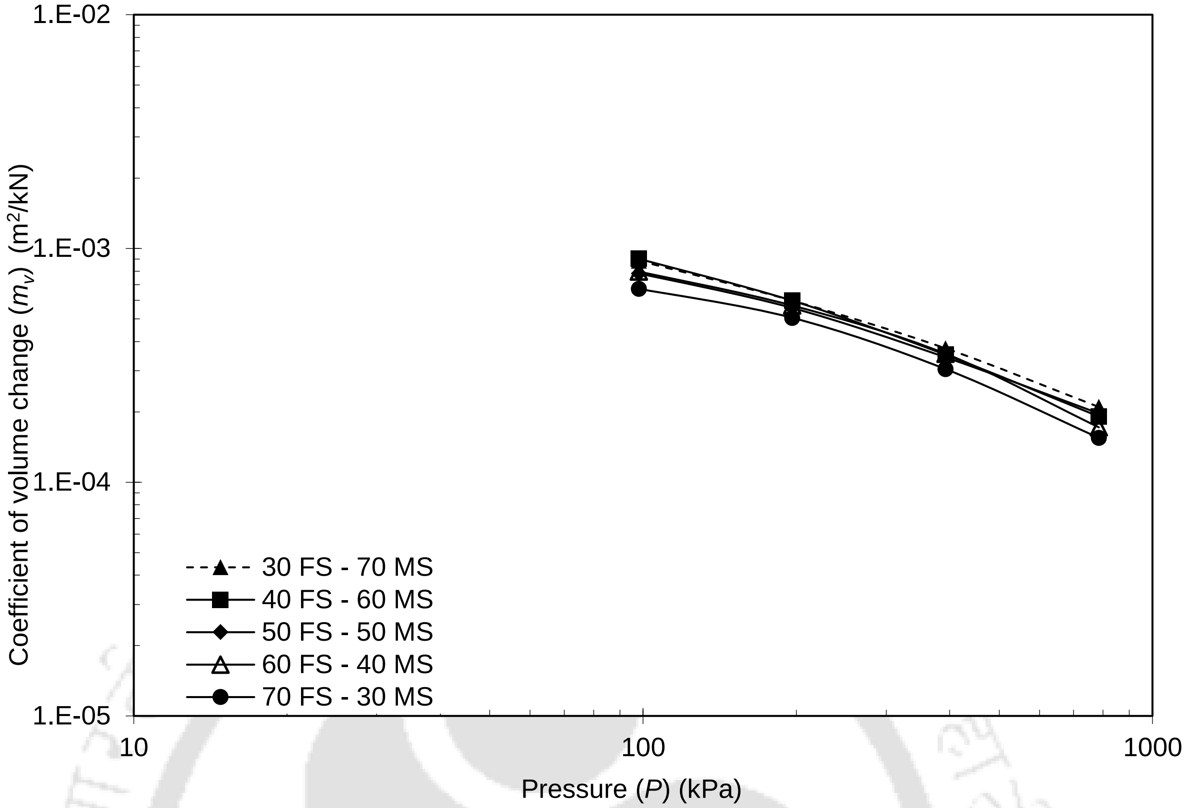


Figure 4.164 m_v-Pressure plot for 50% sand-50% B1 mixes compacted at OMC-MDD

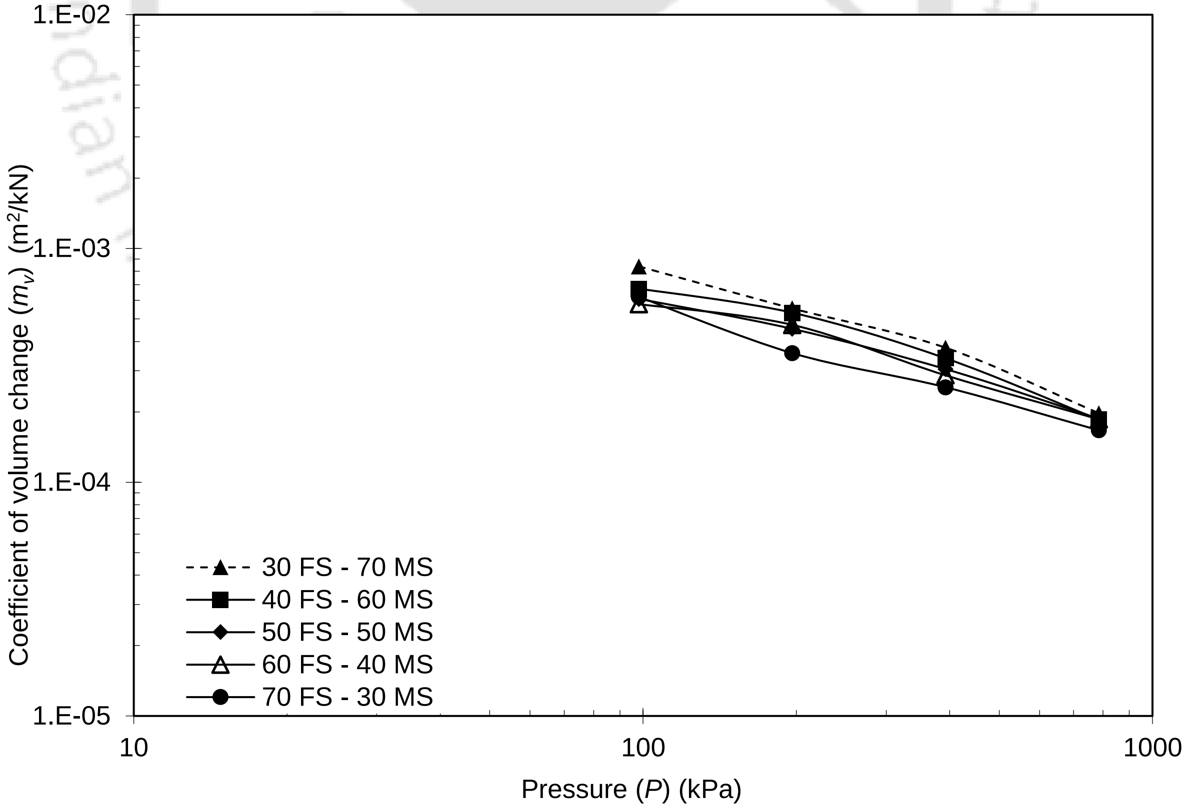


Figure 4.165 m_v-Pressure plot for 60% sand-40% B1 mixes compacted at OMC-MDD

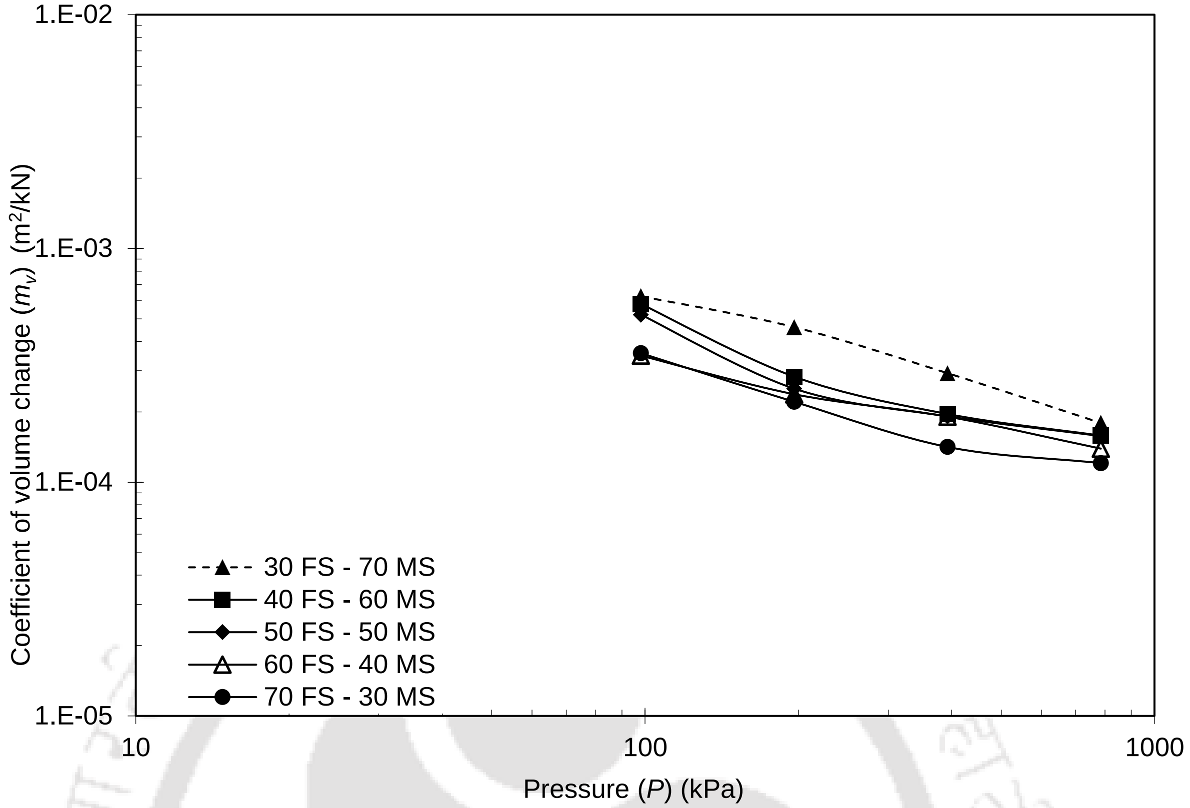


Figure 4.166 m_v-Pressure plot for 70% sand-30% B1 mixes compacted at OMC-MDD

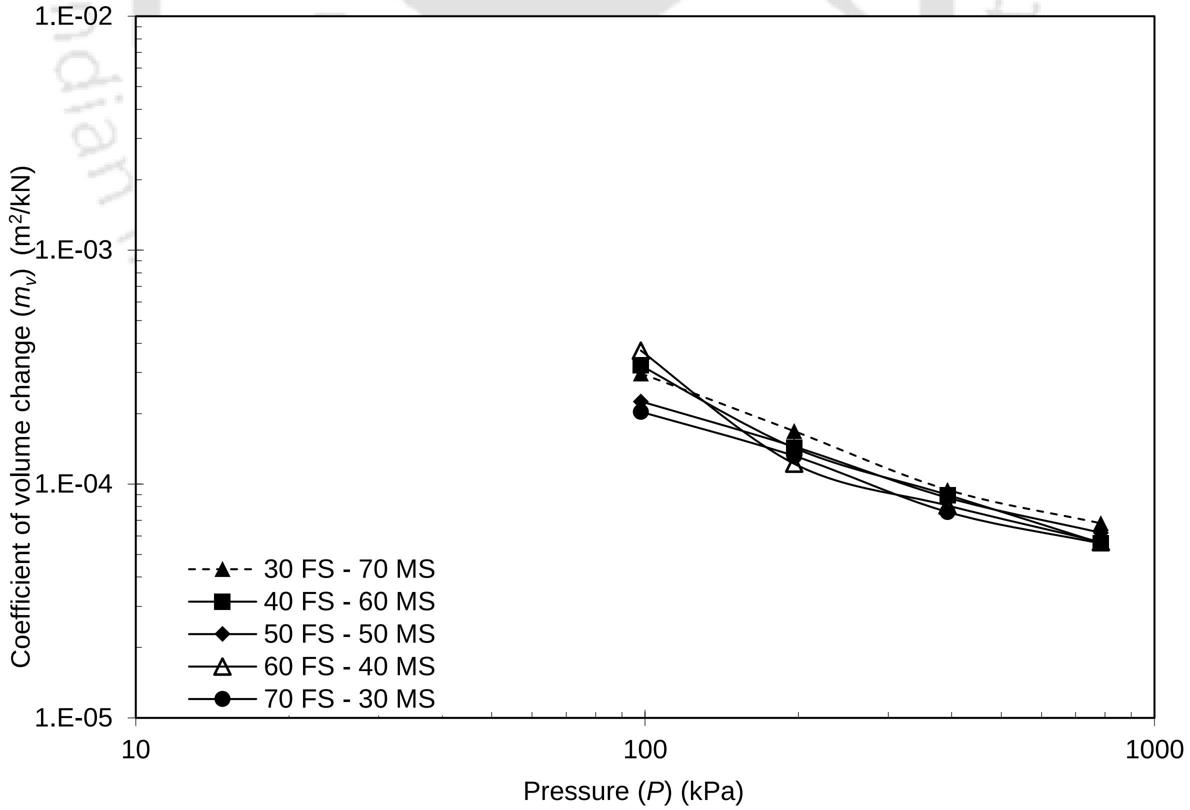


Figure 4.167 m_v-Pressure for 80% sand-20% B1 mixes compacted at OMC-MDD

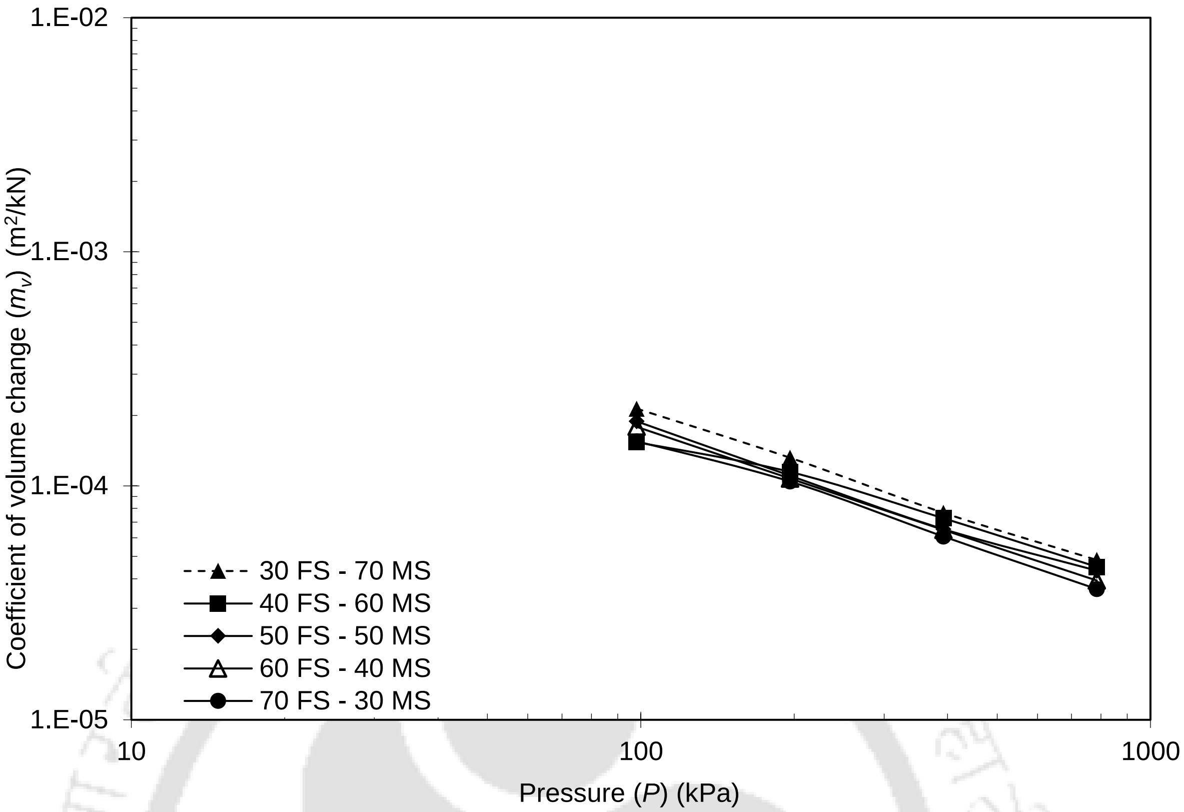


Figure 4.168 m_v-Pressure plot for 90% sand-10% B1 mixes compacted at OMC-MDD

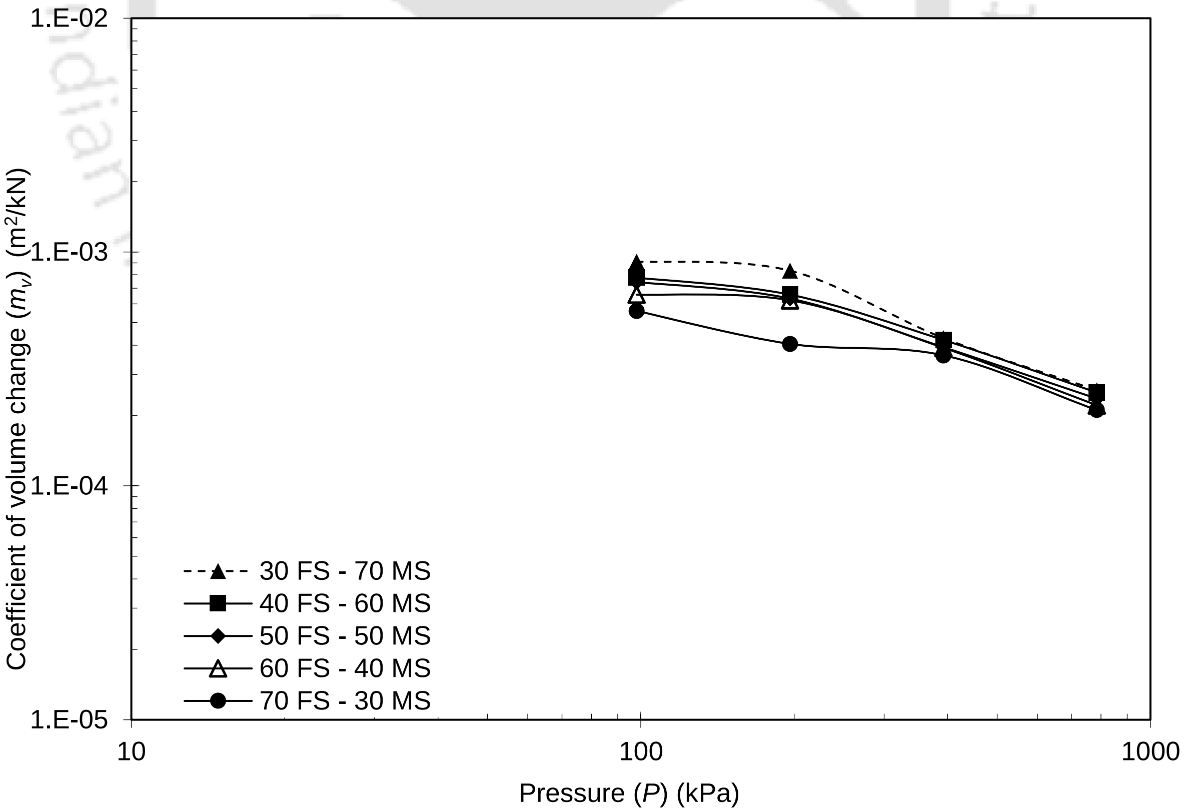


Figure 4.169 m_v-Pressure plot for 50% sand-50% B2 mixes compacted at OMC-MDD

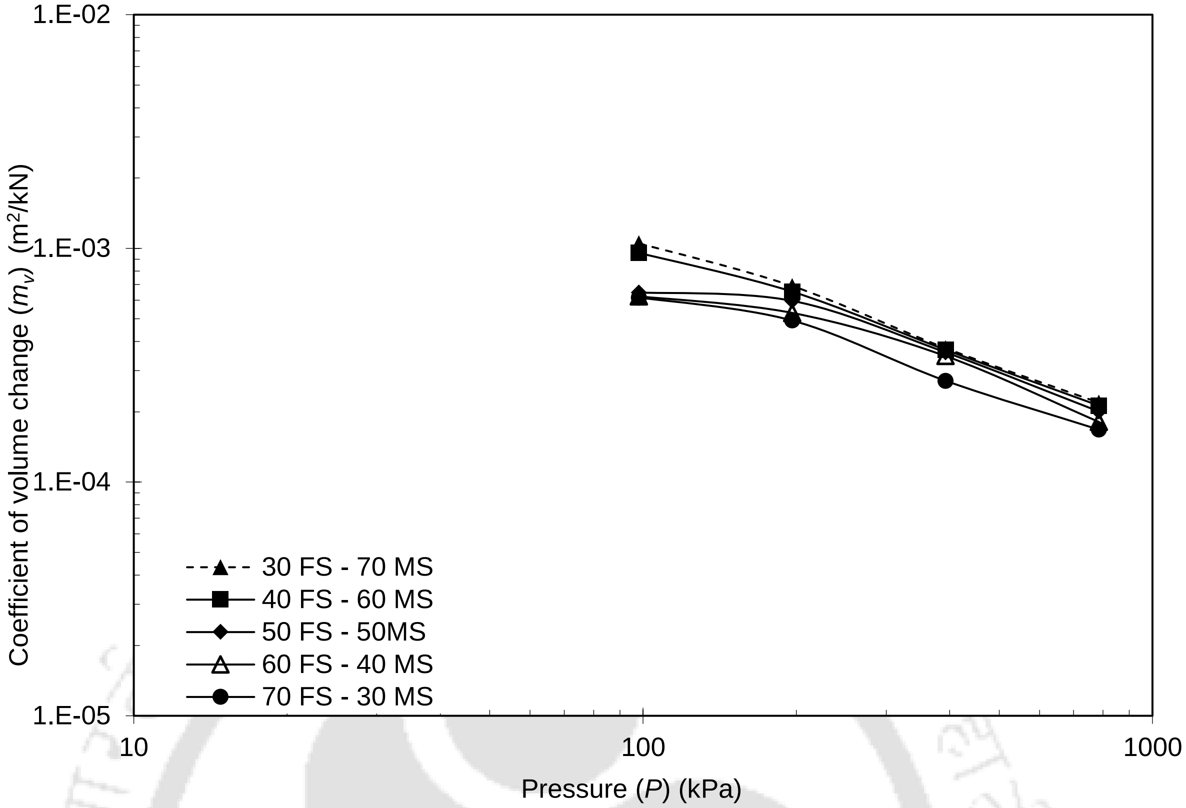


Figure 4.170 m_v-Pressure plot for 60% sand-40% B2 mixes compacted at OMC-MDD

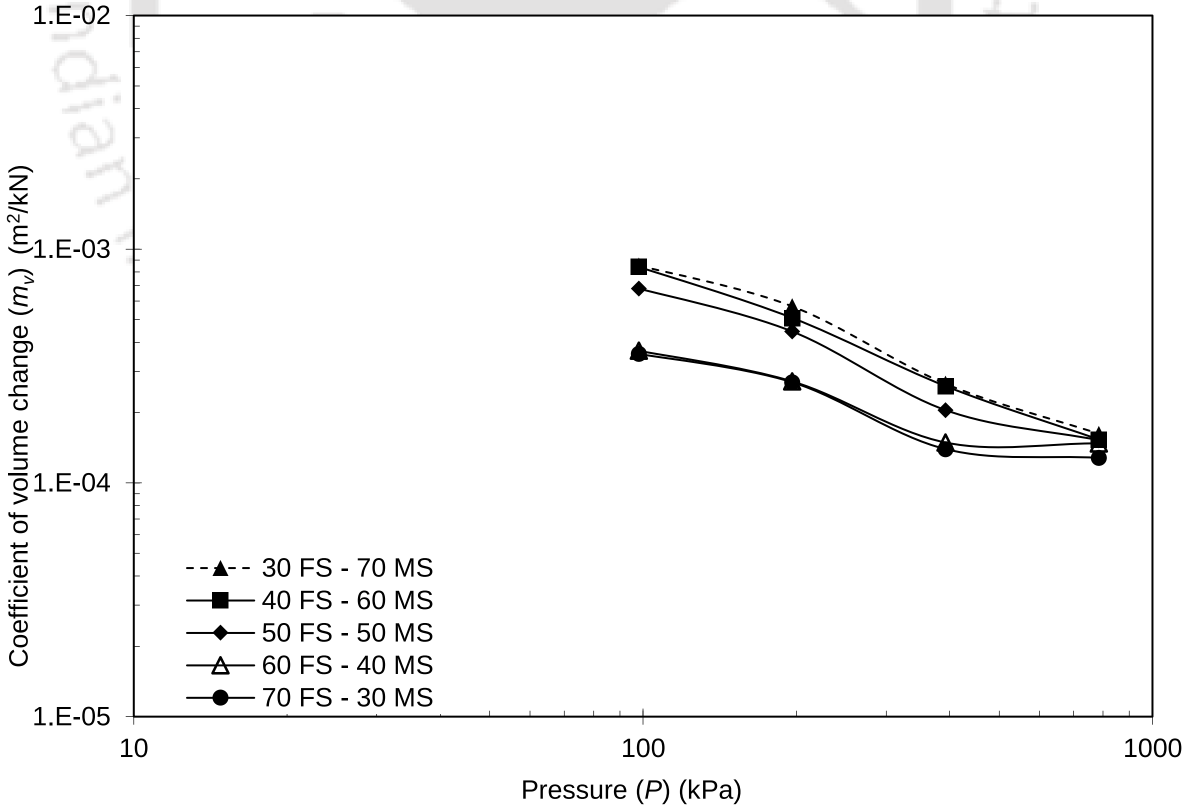


Figure 4.171 m_v-Pressure plot for 70% sand-30% B2 mixes compacted at OMC-MDD

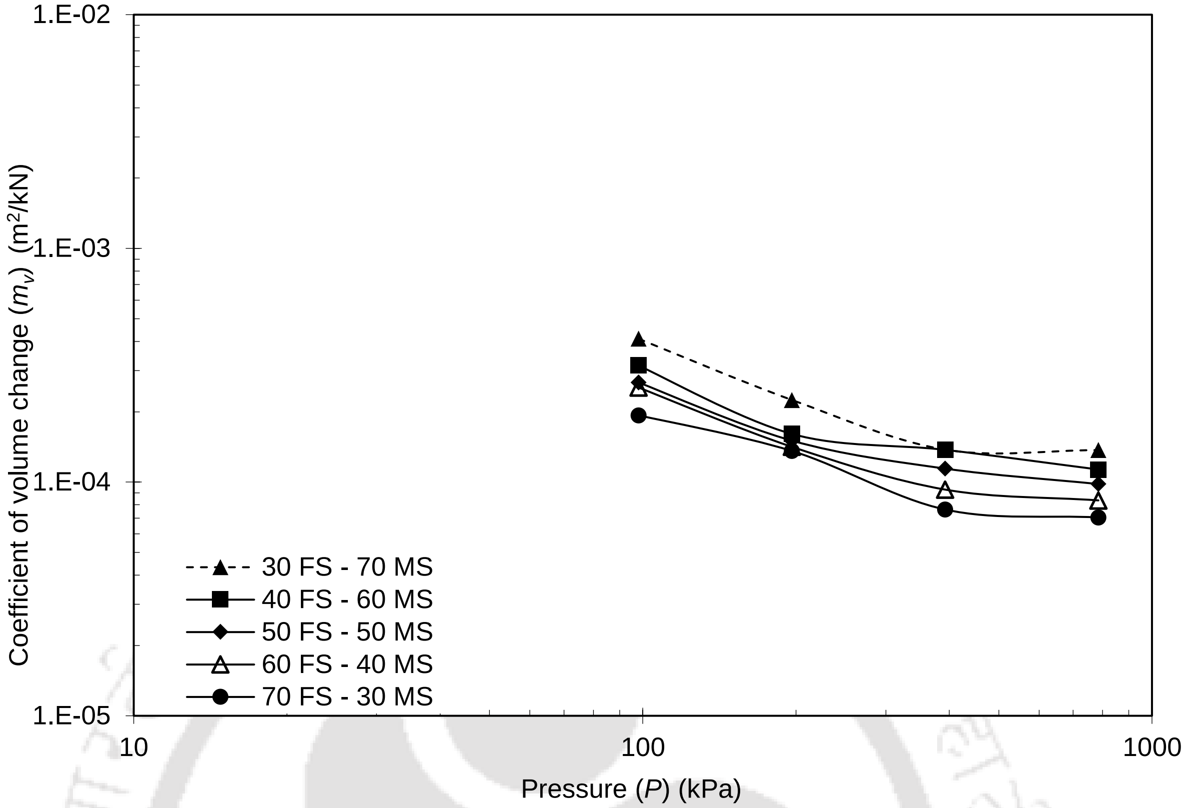


Figure 4.172 m_v-Pressure plot for 80% sand-20% B2 mixes compacted at OMC-MDD

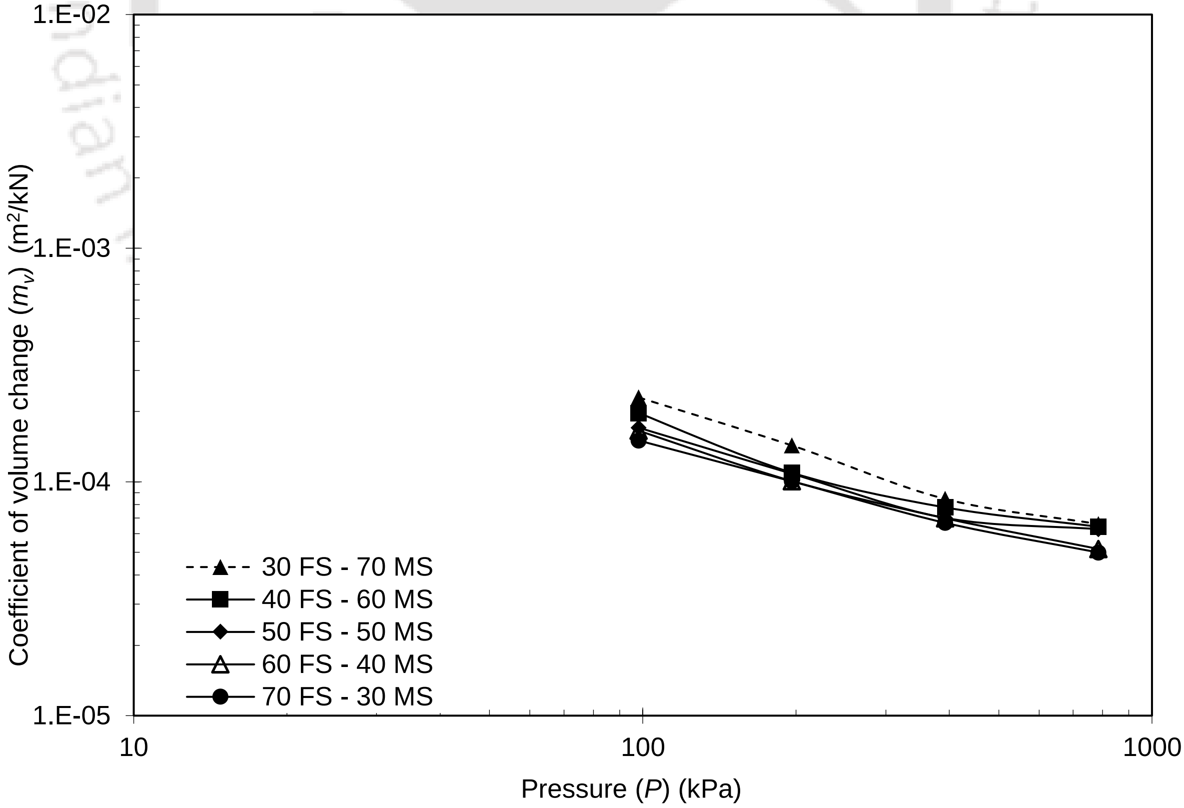


Figure 4.173 m_v-Pressure plot for 90% sand-10% B2 mixes compacted at OMC-MDD

While bentonite content remains the major contributor towards compressibility, with distinct m_v-Pressure curves being exhibited with different FS-MS proportions, it has been seen that by increasing the FS proportion in the sand mixture m_v value can be lowered while the bentonite content remains constant. A similar observation has been made in case of FS-MS-B1 mixtures.

4.2.3.8 Effect of sand proportioning on time required for 90% consolidation (t_{90})-Pressure relationship of fine sand-medium sand-bentonite mixes

4.2.3.8.1 Effect of sand proportioning on t_{90}-Pressure relationship of FS-MS-B1 mixes

Time required for 90% consolidation (t_{90}), exhibited by FS-MS-B1 mixtures compacted at OMC-MDD are presented in Figs. 4.174 through Figs. 4.178. Influence of bentonite content, initial compaction conditions, consolidation pressure and sand particle size on the t_{90} of sand-bentonite mixtures has been presented in section 4.1.3.8. This part of the study presents the influence of sand proportioning on t_{90} of sand-bentonite mixtures, if any. Sand proportioning has a definitive influence on the t_{90}-Pressure relationship of sand-bentonite mixtures. Plots also indicates that compared to FS-B1 and MS-B1 mixtures, a considerable increase in t_{90} values has been observed in case of FS-MS-B1 with increasing consolidation pressure. In case of FS-MS-B1 mixes with B1 content greater than 20%, the increment is almost double and with mixes with 10% B1 content the increment is almost 10 times those of FS-B1 and MS-B1 mixes. The diversity in the particle sizes that were available in case of FS-MS-B1 mixes led to the creation of mixes with relatively smaller voids, which ultimately resulted in an increased duration for the consolidation process to complete. Sand-bentonite-1 mixes with 70% FS + 30% MS were seen to exhibit highest (t_{90}) values for all B1 contents considered in this study.

4.2.3.8.2 Effect of sand proportioning on t_{90}-Pressure relationship of FS-MS-B2 mixes

Influence of sand proportioning on t_{90} of FS-MS-B2 mixtures is presented in Figs. 4.179 through 4.183. For any B2 content, t_{90}-Pressure relationship exhibited by each FS-MS proportion is distinct and the differences between FS-MS proportions is noteworthy. Upon comparison with fine sand-bentonite and medium sand-bentonite mixtures, introduction of sand proportioning resulted in a substantial improvement in t_{90} values exhibited by FS-MS-B1 mixtures for all bentonite contents, while the same cannot be said about FS-MS-B2 mixtures.

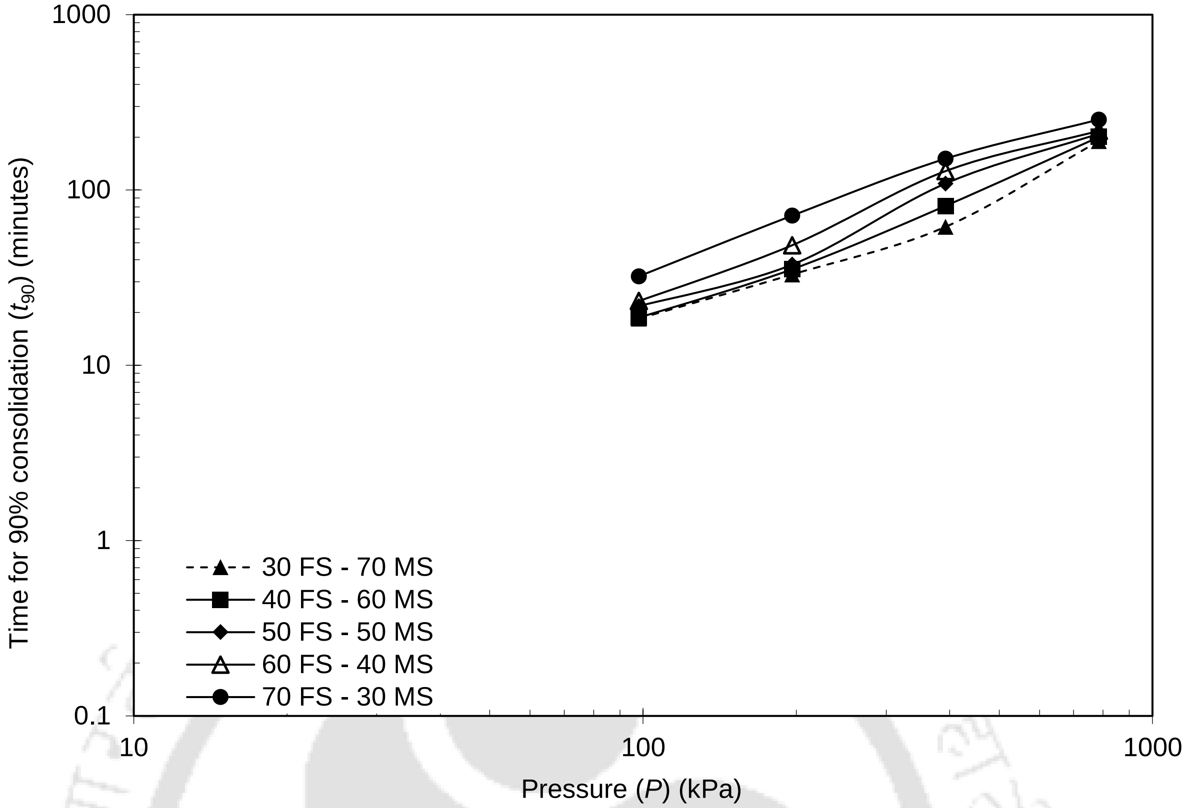


Figure 4.174 t_{90}-Pressure plot for 50% sand-50% B1 mixes compacted at OMC-MDD

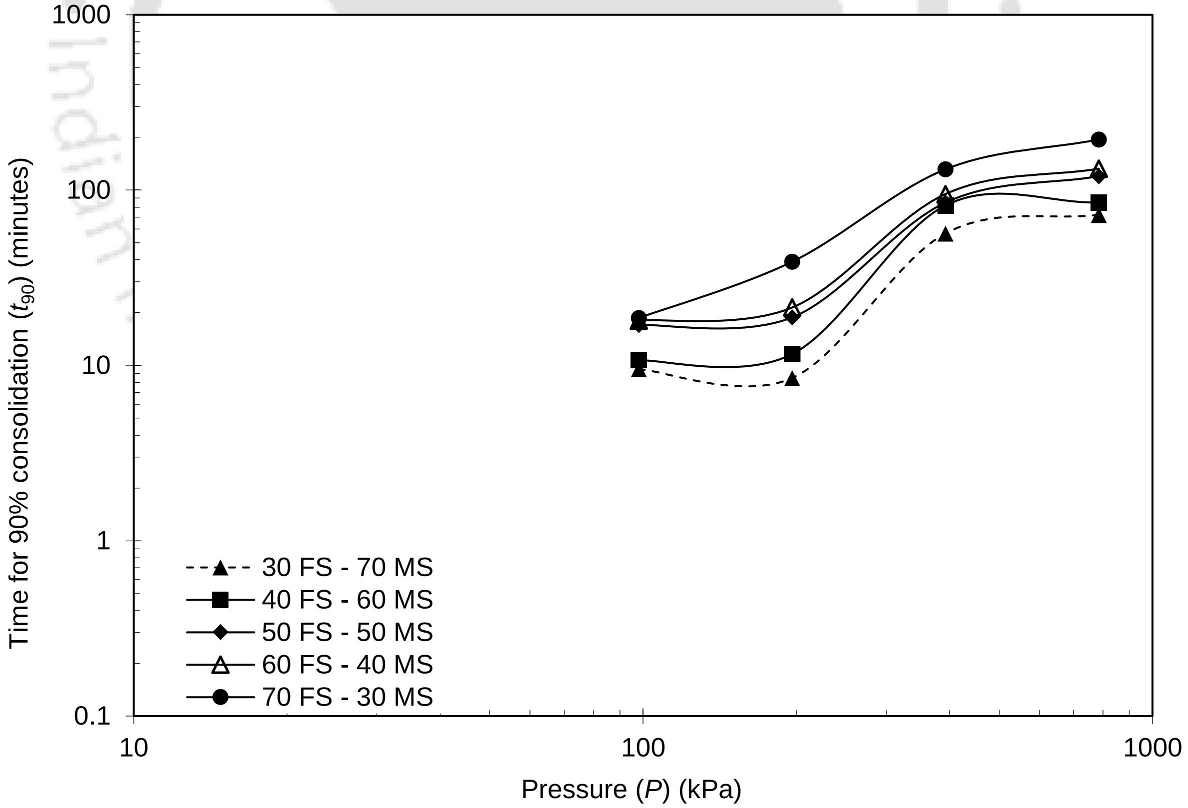


Figure 4.175 t_{90}-Pressure plot for 60% sand-40% B1 mixes compacted at OMC-MDD

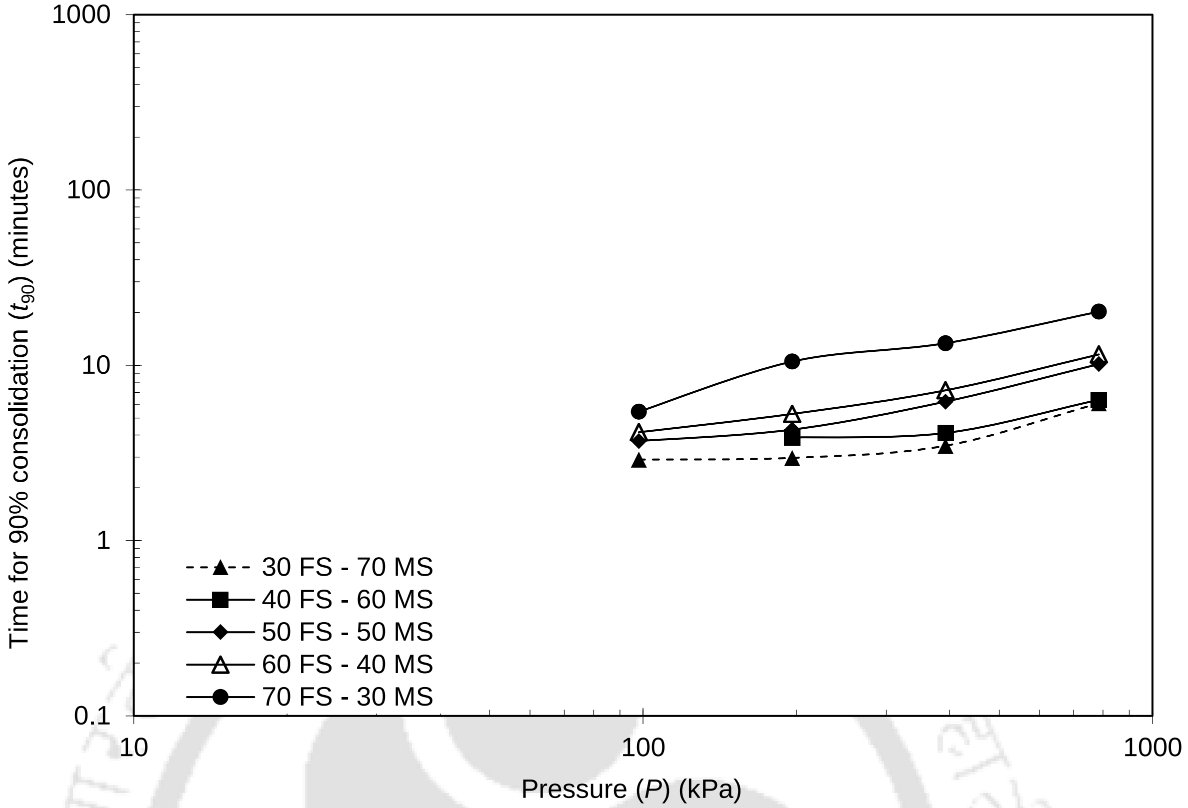


Figure 4.176 t_{90}-Pressure plot for 70% sand-30% B1 mixes compacted at OMC-MDD

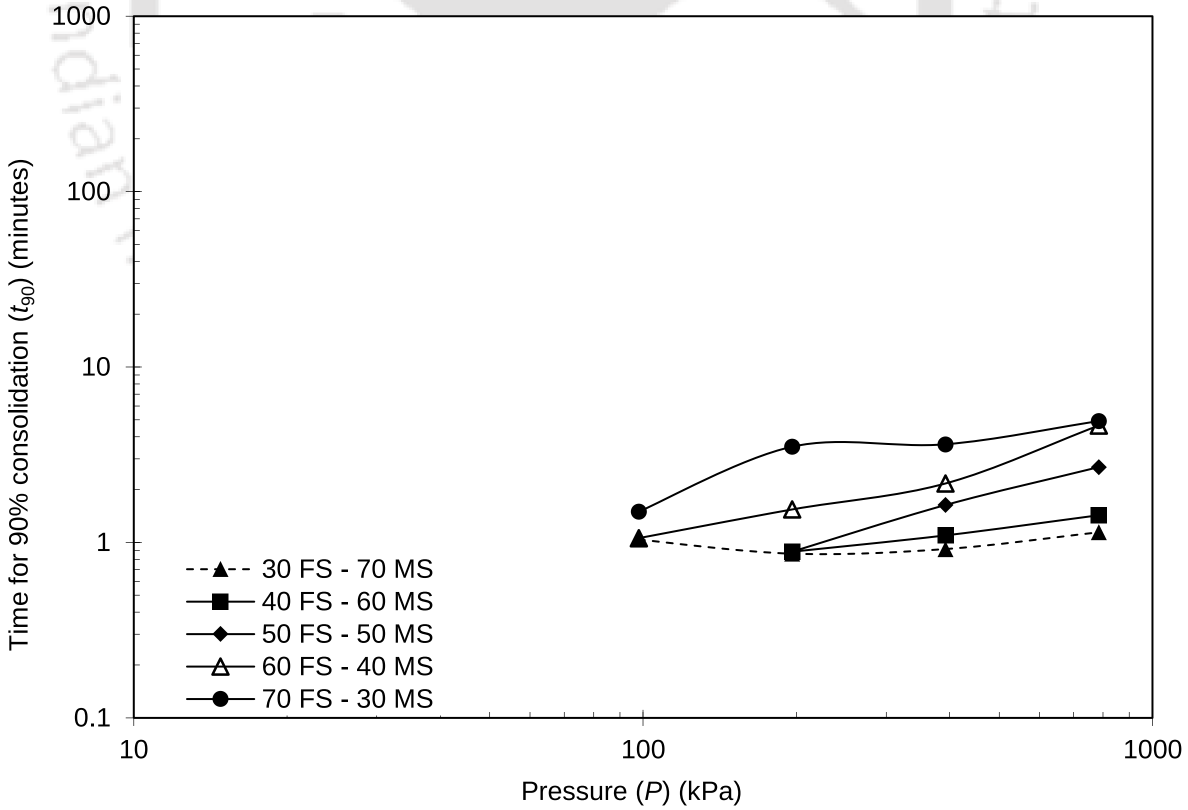


Figure 4.177 t_{90}-Pressure plot for 80% sand-20% B1 mixes compacted at OMC-MDD

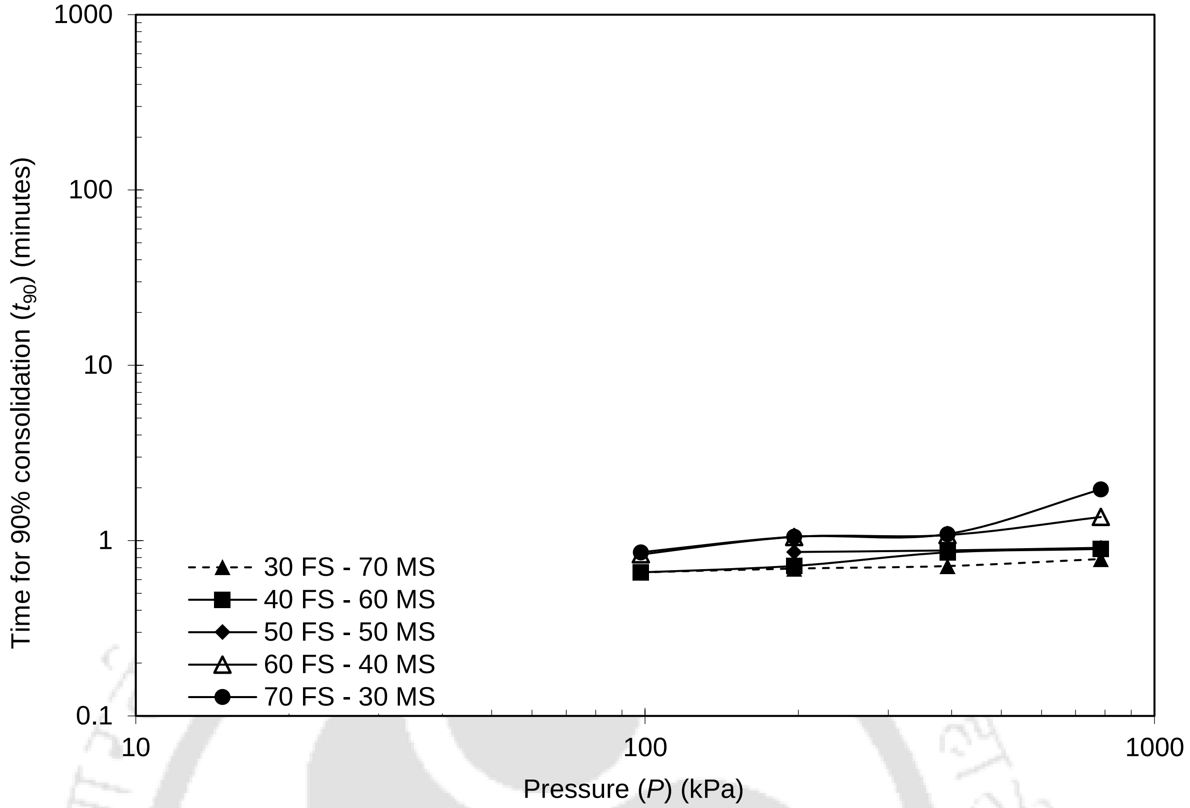


Figure 4.178 t_{90}-Pressure plot for 90% sand-10% B1 mixes compacted at OMC-MDD

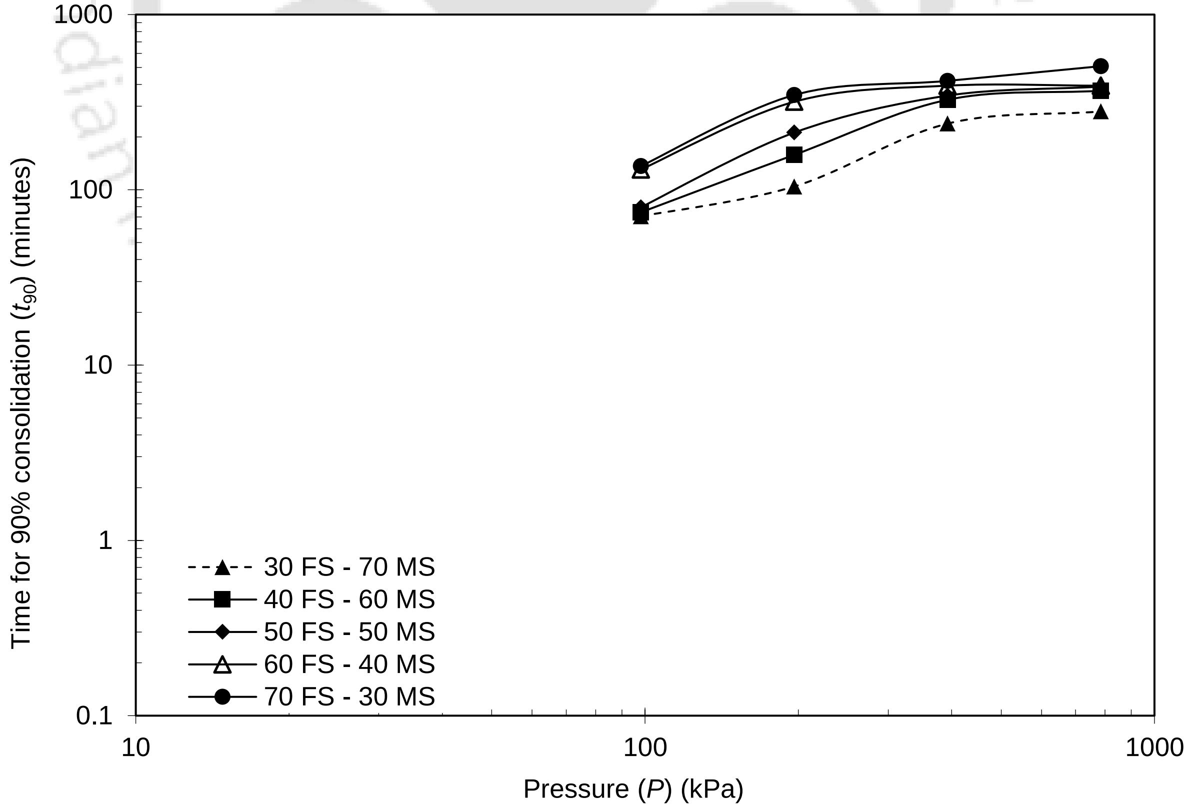


Figure 4.179 t_{90}-Pressure plot for 50% sand-50% B2 mixes compacted at OMC-MDD

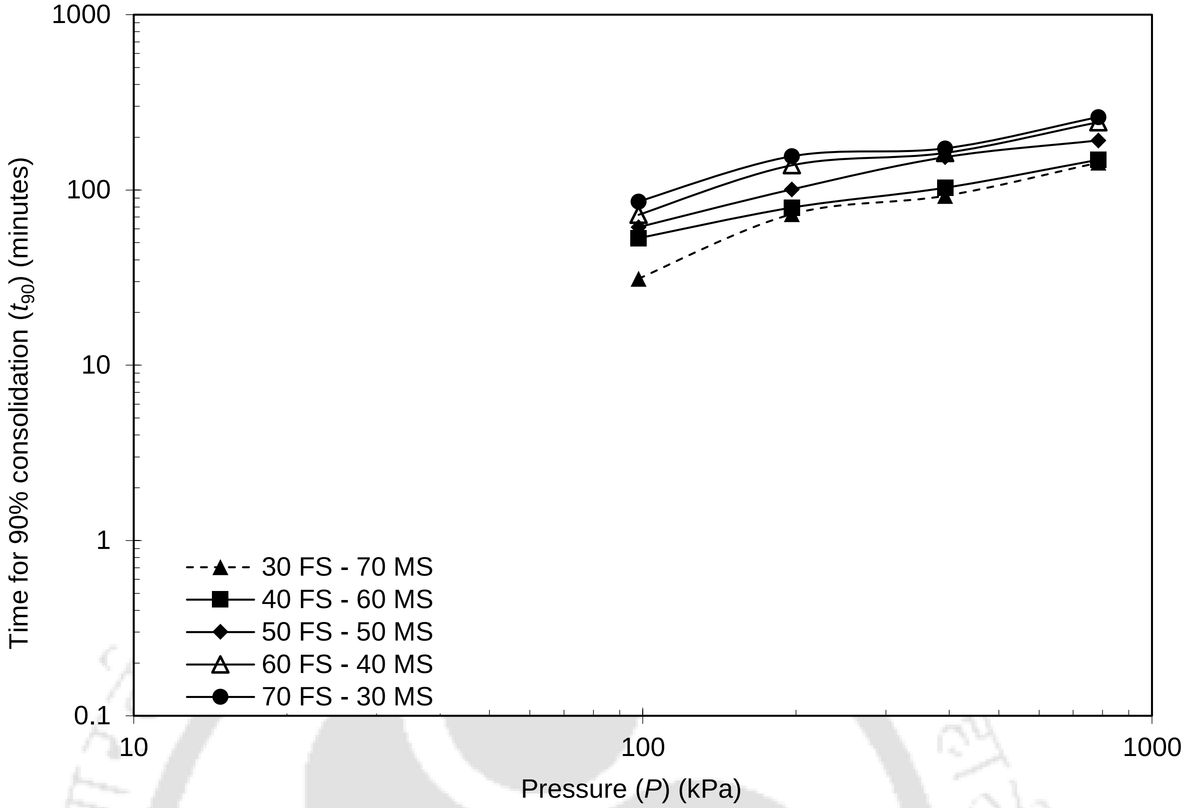


Figure 4.180 t_{90}-Pressure plot for 60% sand-40% B2 mixes compacted at OMC-MDD

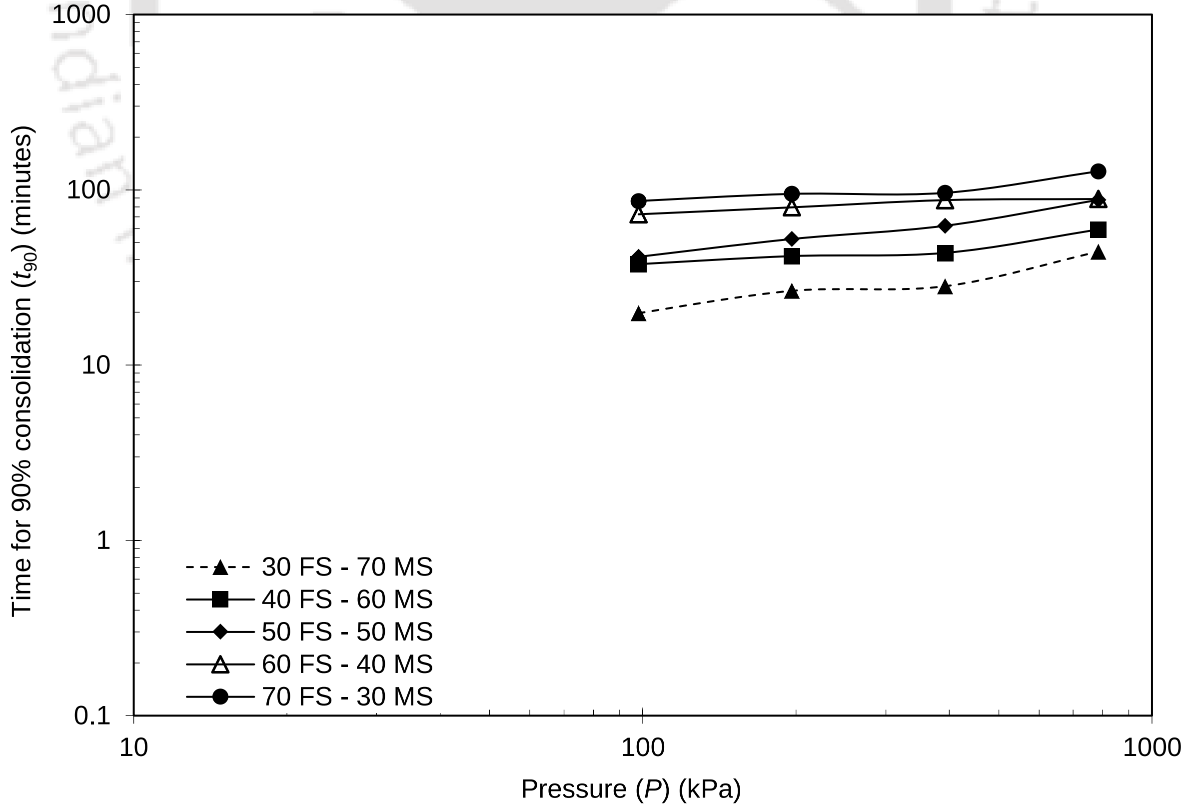


Figure 4.181 t_{90}-Pressure plot for 70% sand-30% B2 mixes compacted at OMC-MDD

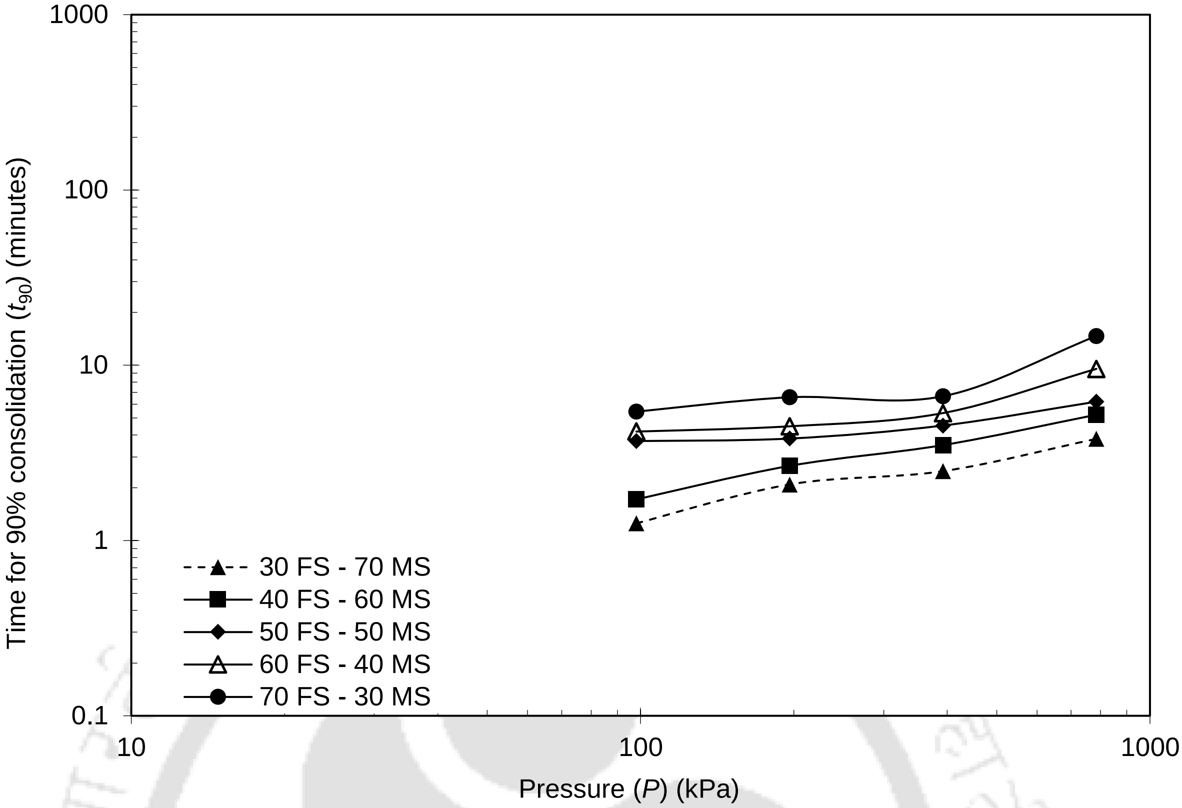


Figure 4.182 t_{90}-Pressure plot for 80% sand-20% B2 mixes compacted at OMC-MDD

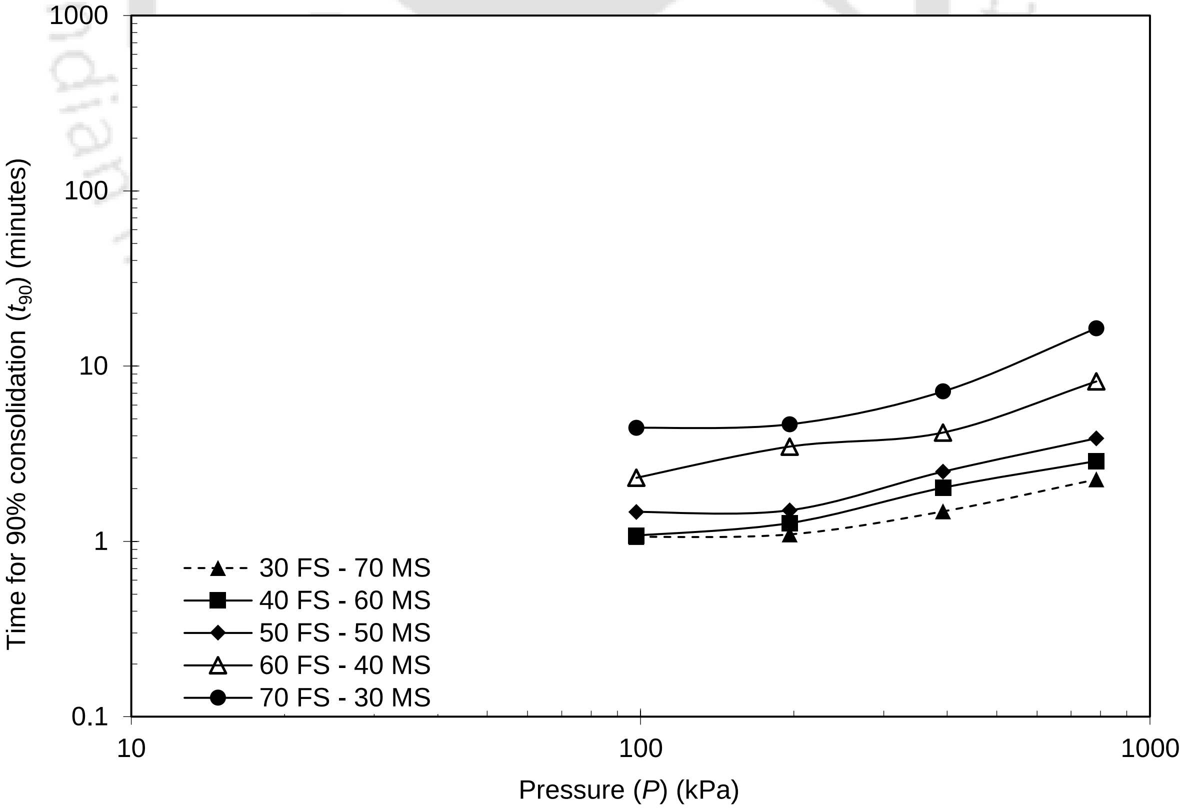


Figure 4.183 t_{90}-Pressure plot for 90% sand-10% B2 mixes compacted at OMC-MDD

The plots indicated that the FS-MS-B2 mixtures with B2 content of 20% and above had little increment in t_{90} values; whereas, mixtures with 10% B2 content indicated about 10-fold increase in t_{90} values when compared with FS-B2 and MS-B2 mixtures. Increasing the FS proportion in the FS-MS mixtures has been seen to deliver lower hydraulic conductivities and higher t_{90} values in case of FS-MS-B1 mixtures and the same holds true in the case FS-MS-B2 mixtures as well.

4.2.3.9 Effect of sand proportioning on compressibility characteristics of fine sand-medium sand-bentonite mixes

Compression index (c_c) of a soil is the slope of the virgin compression line in the e-log P curve and represents the ease of volume change when acted upon by a surcharge load. Compressibility characteristics exhibited by FS-MS-B1 and FS-MS-B2 mixtures are presented in Figs. 4.184 and Figs. 4.185. Observations indicated that c_c is increasing with bentonite content, a trend similar to those exhibited by FS-B1, MS-B1, FS-B2 and MS-B2 mixtures. Though bentonite content and quality is a prime contributor, different c_c values being exhibited by various FS-MS proportions for any bentonite content indicate the undeniable influence of sand proportioning on c_c. Apart from bentonite content, c_c values were seen to be reducing with increasing FS proportion in the FS-MS mixture. For any bentonite content, sand mixtures with 70% FS + 30% MS were seen to exhibit lowest c_c values. Finding the extent of individual contributions of the component soils (FS, MS) forming the sand turned out to be a rather difficult task than anticipated.

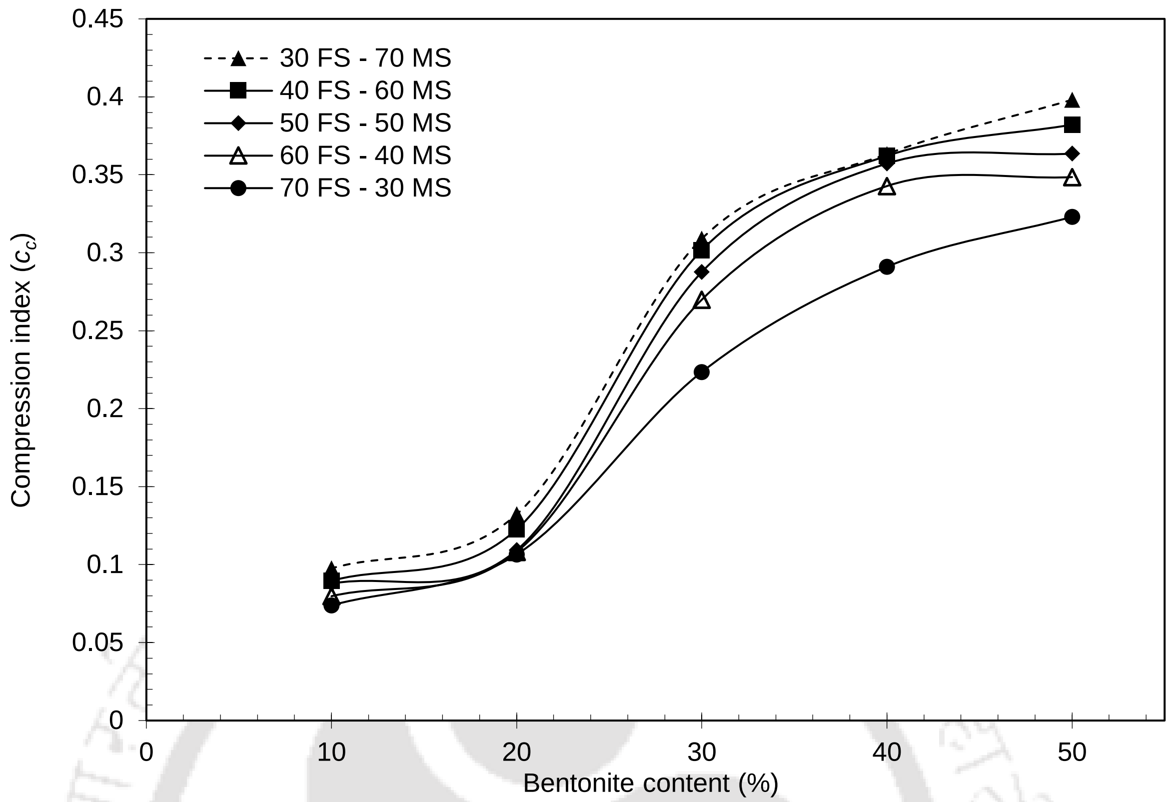


Figure 4.184 c_c-bentonite content plot for FS-MS-B1 mixes compacted at OMC-MDD

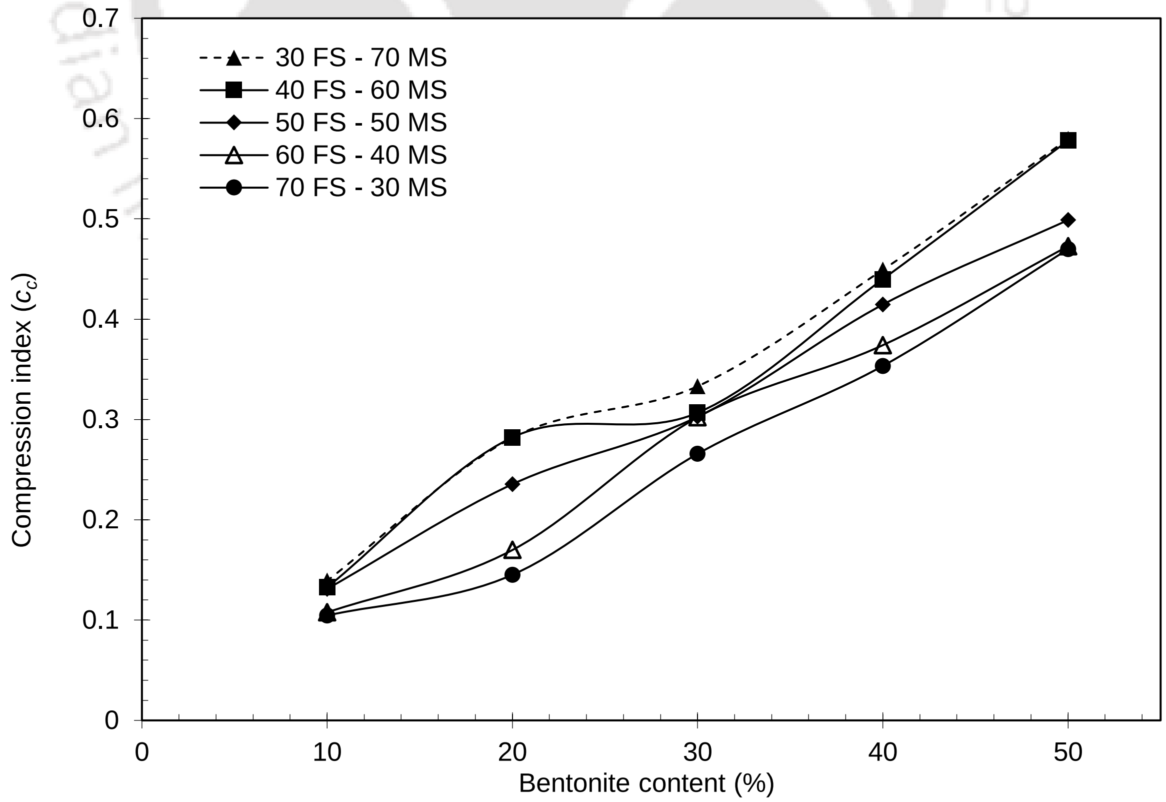


Figure 4.185 c_c-bentonite content plot for FS-MS-B2 mixes compacted at OMC-MDD

4.2.4 SHRINKAGE CHARACTERISTICS OF FINE SAND-MEDIUM SAND-BENTONITE MIXES

4.2.4.1 Shrinkage behaviour of FS-MS-B1 mixes

Shrinkage behaviour upon drying, both linear and radial shrinkage, exhibited by various FS-MS-B1 mixtures compacted at OMC-MDD is presented in Figs. 4.186 and 4.187. In a sand-bentonite mixture, when the initial mixing water content (OMC in this case) is added, bentonite adsorbs the water and undergoes an increase in volume while sand being a chemically inert material does not exhibit any volume changes. When the compacted sand-bentonite mixture is subjected to temperature changes, sand being an inert material does not shrink while bentonite particles loose the adsorbed water and shrink in size resulting in changes in physical dimensions of the previously compacted soil sample. As the amount of bentonite increases in the sand-bentonite mixtures, resulting in an increase in the swelling mineral concentration in the mixture and so does the susceptibility to shrink. The same is reflected as increased shrinkage, both linear and radial, with increasing B1 content in the mixtures. As to the influence of sand proportioning, upon close scrutiny, it can be seen that even for a constant bentonite content each FS-MS proportion has exhibited a unique shrinkage value. No particular trend could be observed as to the role of FS and MS in the mixtures and their contributions towards shrinkage process. Comparing the FS-MS-B1 mixtures with FS-B1 and MS-B1 mixes compacted at OMC-MDD indicated that the shrinkage behavior exhibited the following order

$$\text{FS-B1} < \text{FS-MS-B1} < \text{MS-B1}$$

4.2.4.2 Shrinkage behaviour of FS-MS-B2 mixes

Shrinkage behaviour, both linear and radial shrinkage, exhibited by various FS-MS-B2 mixtures compacted at OMC-MDD is presented in Figs. 4.188 and 4.189. Trends similar to those exhibited by FS-MS-B1 mixtures were observed, i.e. shrinkage increasing with increasing bentonite content and FS-MS proportions delivering distinct shrinkage response even though bentonite content in the mixes is same. Though relatively smaller in magnitude, it can be noticed that as the swelling nature of bentonite improves, the variation in shrinkage is increasingly dependent on FS-MS proportioning.

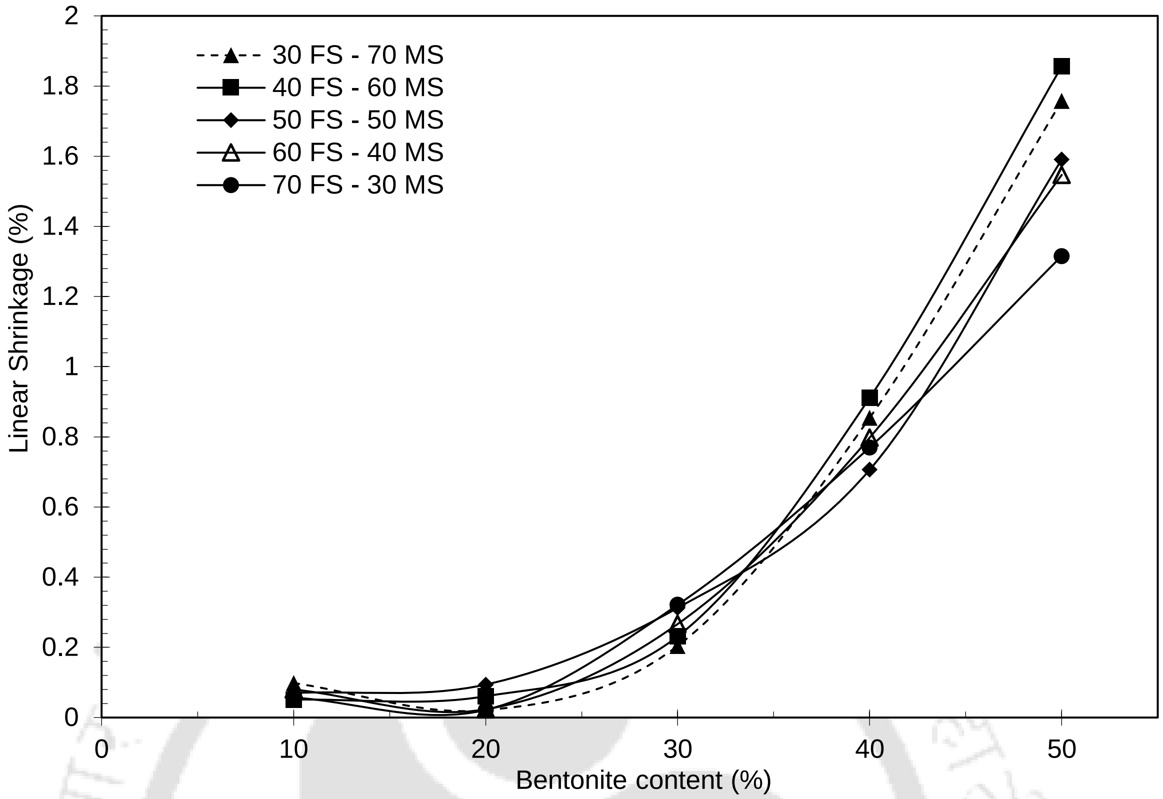


Figure 4.186 Linear shrinkage – bentonite content relationship of FS-MS-B1 mixes compacted at OMC-MDD

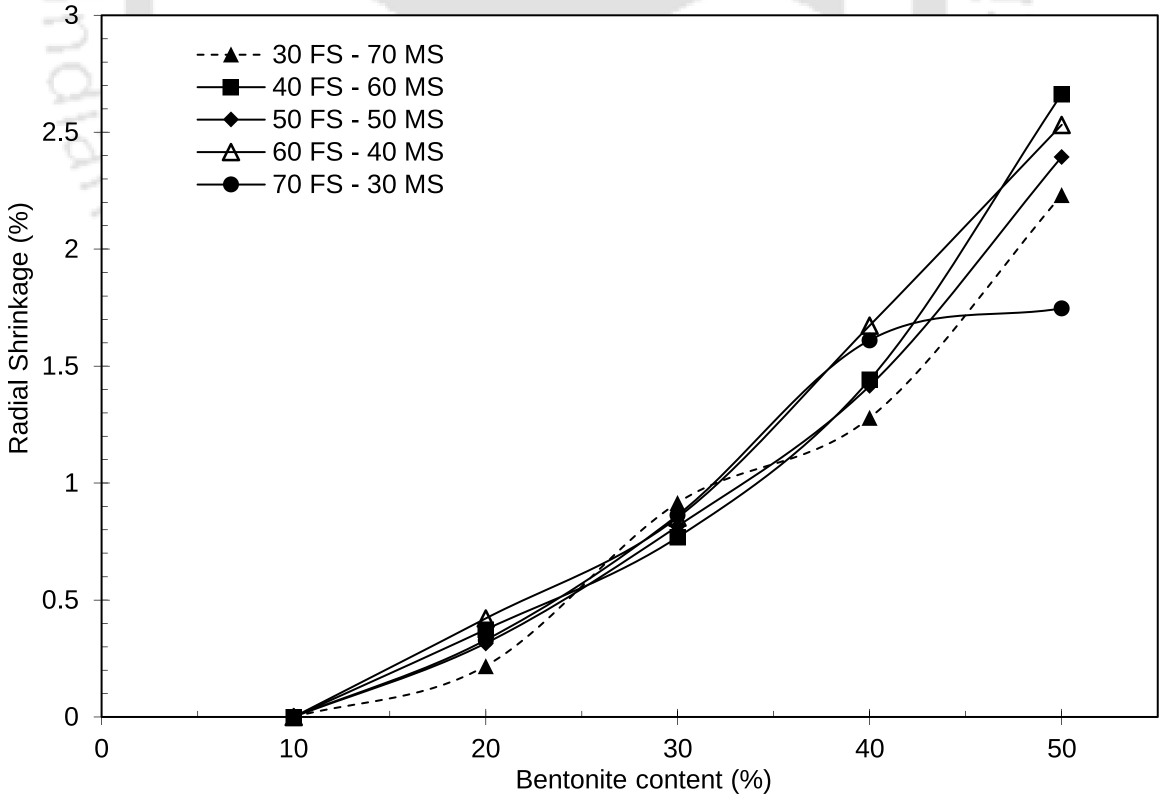


Figure 4.187 Radial shrinkage – bentonite content relationship of FS-MS-B1 mixes compacted at OMC-MDD

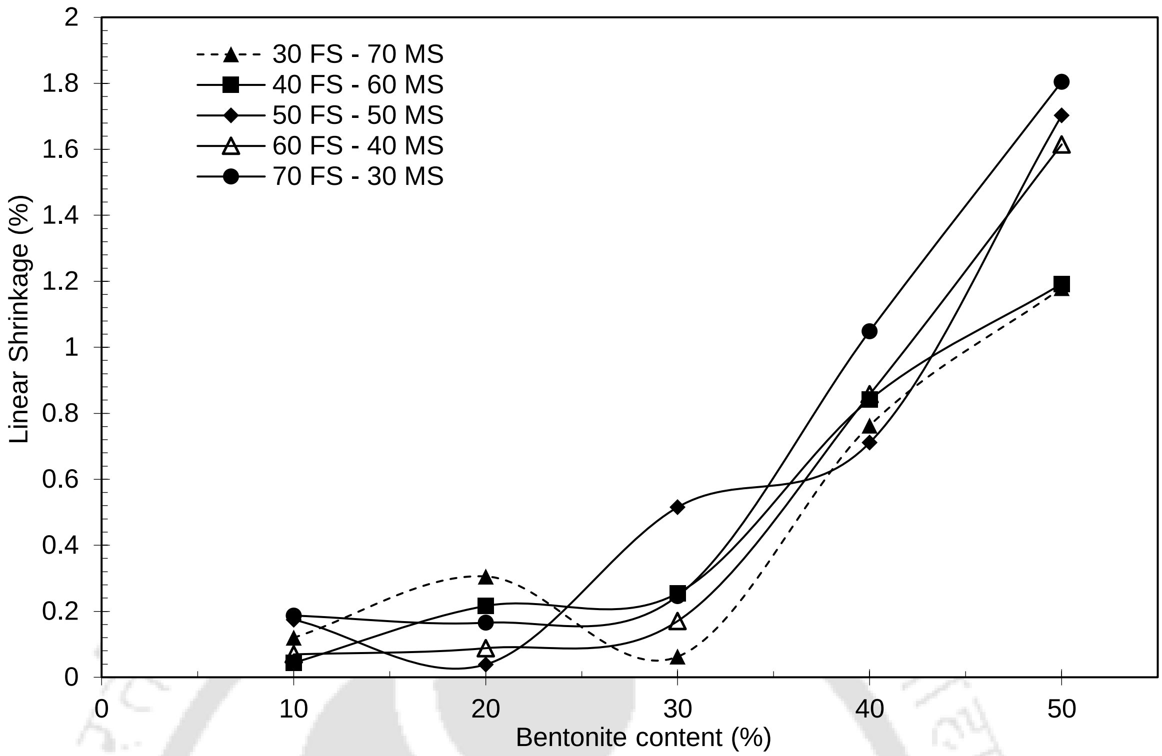


Figure 4.188 Linear shrinkage – bentonite content relationship of FS-MS-B2 mixes compacted at OMC-MDD

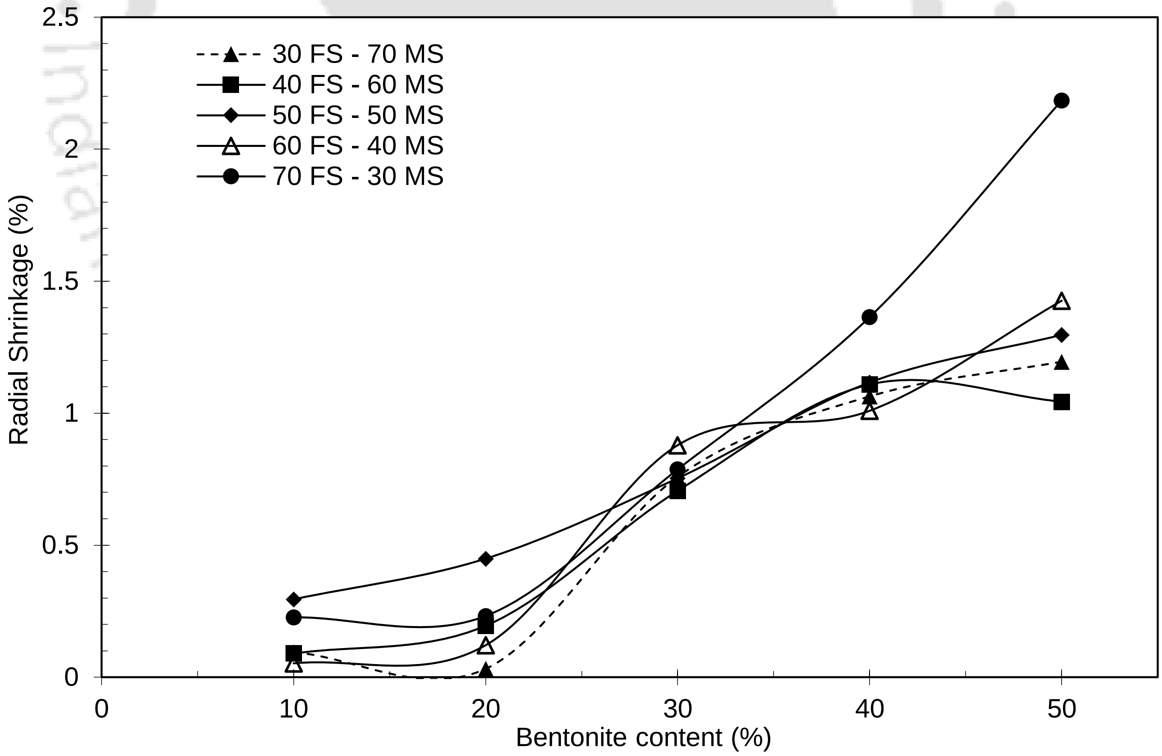


Figure 4.189 Radial shrinkage – bentonite content relationship of FS-MS-B2 mixes compacted at OMC-MDD

Sridharan and Prakash (1998) indicated that shrinkage behaviour is a relative packing phenomenon and is primarily dependent on the particle size distribution of the soil. Even though B1 and B2 are different in terms of swelling ability, given the observed shrinkage behaviour, it seems the idea is being reinforced. Further probe into this issue may yield better insight.

4.2.5 UNCONFINED COMPRESSIVE STRENGTH CHARACTERISTICS OF FINE SAND-MEDIUM SAND-BENTONITE MIXES

4.2.5.1 Unconfined compressive strength (UCS) of FS-MS-B1 mixes

Fine sand-bentonite and medium sand-bentonite mixes were compacted at 3 different compaction conditions to understand the influence of initial compaction state, sand content, bentonite content, bentonite type, water content and sand particle size on the strength characteristics of sand-bentonite mixes. The influence of above said parameters on the strength characteristics of sand-bentonite mixes has been reconfirmed and reported in section 4.1.6. Continuing the study, the second phase of the study, i.e. understanding the influence of sand gradation on the mix characteristics, has been carried out on fine sand-medium sand- bentonite mixes compacted at OMC-MDD. Increasing the sand content in the mixtures resulted in reduction in cohesion binding the particles together and which in turn is reflected as reduction in compressive strength. Unconfined compressive strength exhibited by FS-MS-B1 mixes compacted at OMC-MDD is presented in Fig 4.190. For any given bentonite content, the influence of sand proportioning can be noticed in the variability in UCS results. The variability in UCS data is as high as 75 kPa for mixes with B1 content 30% and above. Increasing the FS proportion in the sand is seen to be resulting in higher UCS values. A general increase in UCS values is seen in case of mixes with 20% and low bentonite content, as compared to FS-B1 and MS-B1 mixes.

4.2.5.2 Unconfined compressive strength of FS-MS-B2 mixes

Unconfined compressive strength exhibited by FS-MS-B2 mixes compacted at OMC-MDD is presented in Fig 4.191. Bentonite-2 with its high cohesion resulted in mixes with relatively higher compressive strength as compared to B1 mixtures. For any given bentonite content, the difference between highest and lowest values observed is around 100 kPa for mixes with bentonite content 40% and above. A general increment in UCS values as compared to FS-B2 and MS-B2 mixtures is observed. A similar trend was observed with FS-MS-B1 mixes in Fig. 4.190, i.e. increasing the FS proportion in the sand resulting in higher UCS values and UCS increasing with increase in bentonite content.

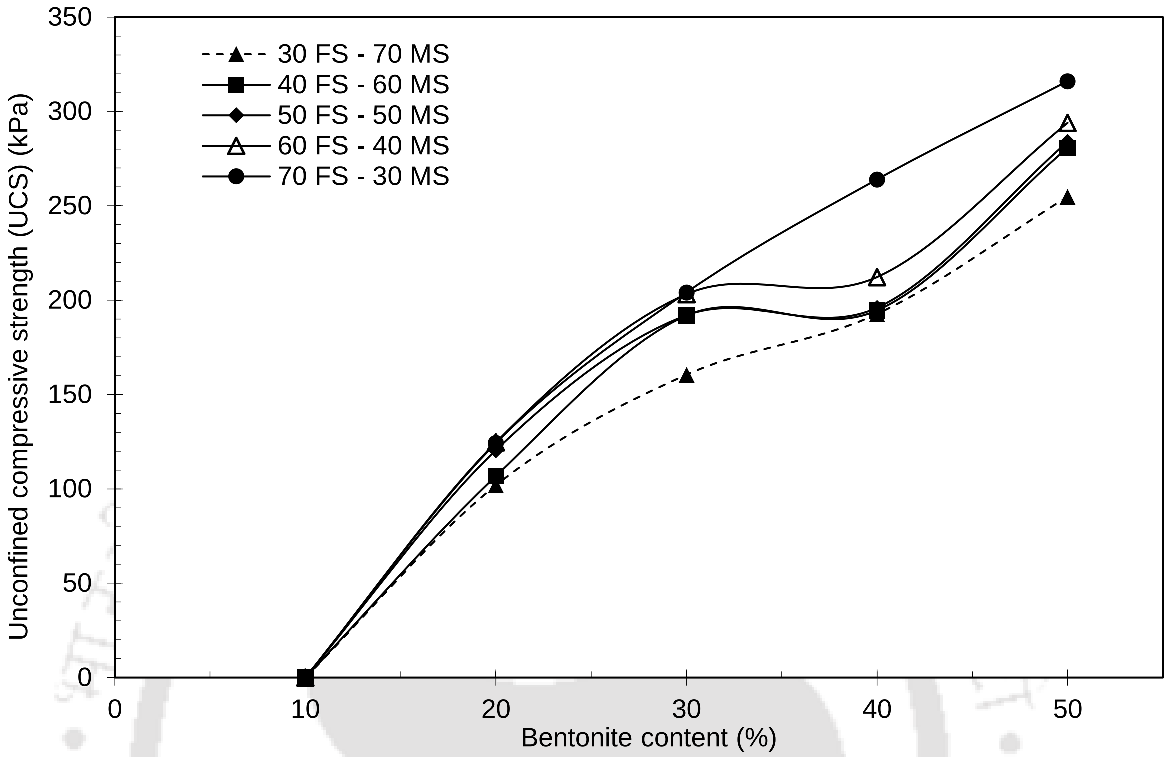


Figure 4.190 Effect of bentonite content and sand proportioning on unconfined compressive strength of FS-MS-B1 mixes

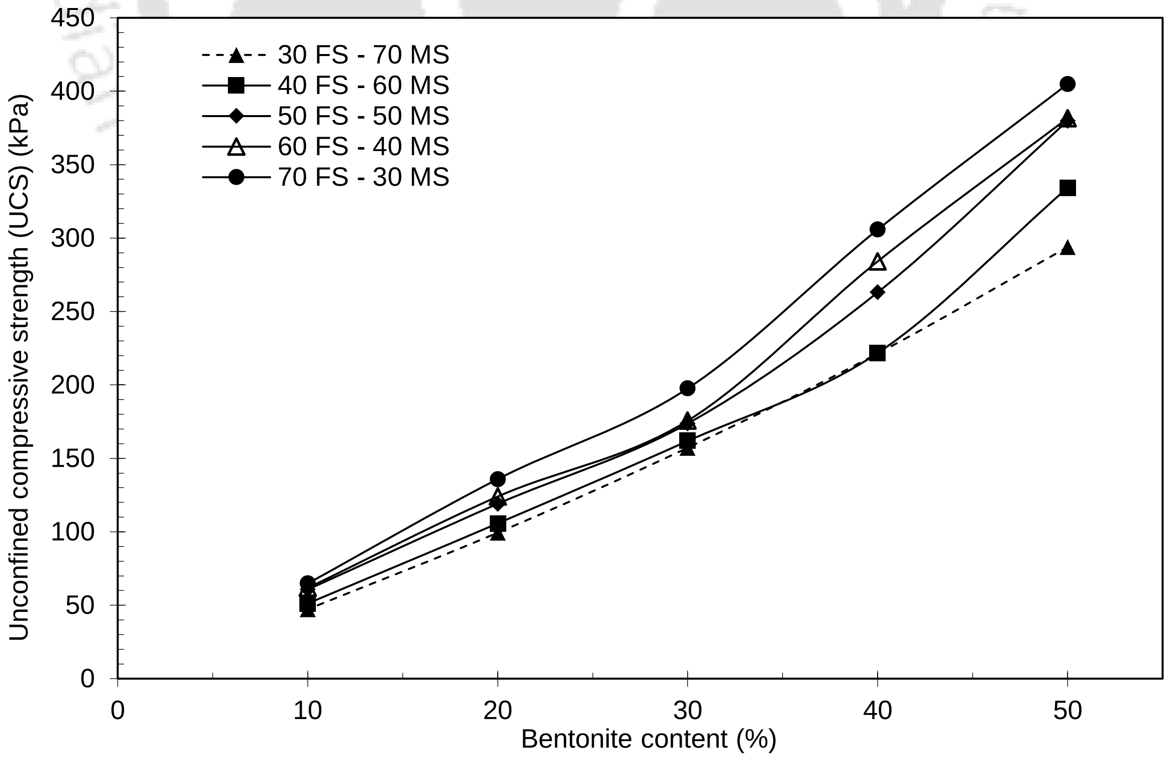


Figure 4.191 Effect of bentonite content and sand proportioning on unconfined compressive strength of FS-MS-B2 mixes

Chapter 5

CONCLUSIONS AND SCOPE FOR FUTURE WORK

Engineering characteristics exhibited by sand-bentonite mixtures and the influence of bentonite content, compaction condition, sand particle size and sand composition on the same has been presented in chapter 4. This chapter summarises the key observations derived from this study.

5.1 CONCLUSIONS

5.1.1 ATTERBERG LIMITS

1. Irrespective of the sand type used, liquid limit was seen to be decreasing with increasing the sand content in sand-bentonite mixtures.

2. Mixtures with fine sand exhibited relatively higher liquid limit compared to those with medium sand for all the bentonite proportions considered in this study.

3. Liquid limit results exhibited by fine sand-medium sand-bentonite mixtures indicated a slight increase in the liquid limit by increasing the fine sand proportion in the mix, with, bentonite content being constant.

4. Though the differences were small, for any particular bentonite content, observed values indicated that liquid limit of soil mixtures exhibited the following order;

   Fine sand-Bentonite > Fine sand-Medium sand-Bentonite > Medium sand-Bentonite

5. Comparing fine sand-bentonite and medium sand-bentonite mixes, shrinkage limit was seen to be increasing with increasing sand content in the mix and fine sand-bentonite mixtures exhibited relatively higher shrinkage limits.

6. Fine sand-medium sand-bentonite mixtures indicated there exists a unique fine sand-medium sand proportion that results in lowest shrinkage limit, for a bentonite content.

5.1.2 COMPACTION CHARACTERISTICS

1. Fine sand-bentonite and medium sand-bentonite mixtures exhibited different optimum moisture contents and maximum dry densities, bentonite content being constant.

2. Medium sand-bentonite mixtures exhibited higher dry density while fine sand-bentonite mixtures exhibited higher optimum moisture content, for the same bentonite content.

3. Sand-bentonite mixtures exhibited highest dry density with 70-80% sand content in the mixtures.

4. Though the differences are small, fine sand-medium sand-bentonite mixtures exhibited highest densities with sand containing 30% fine sand + 70% medium sand.

5.1.3 CONSOLIDATION CHARACTERISTICS

1. Fine sand-bentonite-1 and medium sand-bentonite-1 mixtures took about 96 hours for swelling process to seize, while fine sand-bentonite-2 and medium sand-bentonite-2 mixtures took about 192 hours.

2. Fine sand-medium sand-bentonite-1 mixtures took about 210 hours for swelling to complete and fine sand-medium sand-bentonite-2 mixtures took 275 hours for the same.

3. Though medium sand-bentonite mixes exhibited relatively higher dry densities during compaction testing, fine sand mixtures exhibited considerably higher swelling potential and swelling pressure for the same bentonite content. Emphasizing the need to understand the role of voids being formed in the sand-bentonite matrix.

4. For mixtures with bentonite content greater than 20%, swelling pressure exhibited by fine sand-medium sand-bentonite mixtures is less than fine sand-bentonite mixes and greater than medium sand-bentonite.

5. Sand proportioning resulted in an improvement in the swelling potential and swelling pressures of the mixtures with a bentonite content of 20% and lower, as compared to fine sand-bentonite and medium sand-bentonite mixtures.

6. Fine sand-bentonite mixes exhibited relatively higher initial void ratio's compared to medium sand mixes with similar bentonite content.

7. Initial void ratio's exhibited by fine sand-medium sand-bentonite mixes are lower than fine sand-bentonite mixes and higher than medium sand-bentonite mixes, for a given bentonite content.

8. Fine sand-medium sand-bentonite mixes are more compressible than fine sand-bentonite mixes and less compressible than medium sand-bentonite mixes, for a given bentonite content.

9. Fine sand-bentonite mixes exhibited lower coefficient of consolidation compared to medium sand mixes. Influence of sand particle size on the c_v characteristics was predominantly observed in mixes with low swelling bentonite and that too in the mixes with bentonite content lower than 30%.

10. Fine sand-medium sand-bentonite mixes exhibited almost 10 times lower coefficient of consolidation values compared to fine sand-bentonite and medium sand-bentonite mixes. Increasing the fine sand proportion in the sand mixture is resulting in a soil mass with numerous small voids and these smaller voids hinder the flow resulting in low hydraulic conductivity. The same resistance to flow is reflected as relatively lower c_v values being exhibited by fine sand-medium sand-bentonite mixes.

11. Irrespective of sand type, mixes with bentonite content less than 20% indicated a sand domination in terms of load carrying mechanism, compressibility, initial and final void ratios.

12. Coefficient of volume change (m_v) was increasing with increasing bentonite content in the mixtures, mixes with bentonite content less than or equal to 30% exhibited much lower m_v values compared to mixes with 40% and 50% indicating a shift in load carrying mechanism.

13. Medium sand mixes were exhibiting higher m_v values compared to fine sand-bentonite mixes.

14. In fine sand-medium sand-bentonite mixtures, increasing the fine sand proportion in sand resulted in a stiffer soil leading to lower m_v values. In the current study, sand

with 70% FS + 30% MS proportions exhibited lowest m_v values for all bentonite proportions considered.

15. As the swelling nature of bentonite improved an increment in m_v values has been observed, i.e. bentonite-2 mixes exhibited relatively higher coefficient of volume change.

16. Comparing fine sand-bentonite and medium sand-bentonite mixtures, fine sand-bentonite mixes with their relatively smaller voids exhibited higher t_{90} values for all compaction conditions and bentonite contents.

17. Introduction of sand proportioning resulted in higher t_{90} values compared to fine sand-bentonite and medium sand-bentonite mixtures, for the same bentonite content.

18. Fine sand-medium sand-bentonite mixes with 70% FS + 30% MS were seen to exhibit highest (t_{90}) values for all bentonite contents.

19. Sand-bentonite-2 mixes exhibited higher t_{90} values indicating a clear influence of bentonite swelling nature on consolidation characteristics of sand-bentonite mixtures.

20. Compression index (c_c) was seen to be increasing with bentonite content and quality.

21. Comparing fine sand-bentonite and medium sand-bentonite mixtures, medium sand mixes were seen to exhibit relatively higher c_c values, indicating the ease of breakdown of relatively larger voids in the medium sand skeleton

22. Apart from bentonite content, c_c values were seen to be reducing with increasing FS proportion in the FS-MS mixture. For any bentonite content, sand mixtures with 70% FS + 30% MS were seen to exhibit lowest c_c values.

5.1.4 HYDRAULIC CHARACTERISTICS

1. Fine sand-bentonite mixtures were exhibiting lower hydraulic conductivities compared to their medium sand counterparts for all the bentonite contents and initial compaction conditions considered in the study.

2. A relatively higher bentonite content was found to be necessary in case of medium sand mixes to achieve a similar level of water tightness compared to their fine sand counterparts.

3. As the swelling nature of bentonite is improved and with bentonite content greater than 40% the influence of sand particle size on hydraulic characteristics is seen to be of little importance.
4. Sand proportioning resulted in 1-5 fold reduction in hydraulic conductivity in case of fine sand-medium sand-bentonite-1 mixtures with bentonite content greater than 30% and 10-100 fold reduction in case of mixtures with bentonite content lesser than 30%.
5. As compared to fine sand-bentonite-2 and medium sand-bentonite-2 mixes, no notable reduction in hydraulic conductivity of fine sand-medium sand-bentonite-2 mixtures has been observed in case of mixtures with bentonite content greater than 20%, a 2-8 fold reduction was seen in mixes with bentonite content lower than 20%.

5.1.5 SHRINKAGE CHARACTERISTICS

1. Linear shrinkage and radial shrinkage data of fine sand-bentonite and medium sand-bentonite mixtures indicated that bentonite content plays a major role in the shrinkage process followed by initial compaction condition.
2. Medium sand-bentonite mixes exhibited higher shrinkage compared to fine sand mixes for all bentonite contents.
3. For any bentonite content, observed values indicated that shrinkage behaviour of soil mixtures exhibited the following order;

   Fine sand-Bentonite < Fine sand-Medium sand-Bentonite < Medium sand -Bentonite
4. Though Bentonite-1 and Bentonite-2 are two different bentonites with distinct swelling capabilities the shrinkage behavior exhibited is almost similar, indicating that shrinkage is more of a particle size dependent phenomenon.

5.1.6 UNCONFINED COMPRESSIVE STRENGTH CHARACTERISTICS

1. Compressive strength increased with increasing bentonite content, while increasing the initial mixing water content resulted in a reduction in strength for all sand-bentonite mixes.
2. Fine sand-bentonite exhibited higher UCS value compared to medium sand mixes.

3. Bentonite content being constant, sand proportioning resulted in a noticeable variability with difference between highest and lowest value exhibited in the range of 75-100 kPa.

4. Increasing the fine sand proportion in the fine sand-medium sand-bentonite mixtures indicated an improvement in UCS values.

5. Compared to fine sand-bentonite and medium sand-bentonite mixes, fine sand-medium sand-bentonite mixtures exhibited an improvement in UCS in the mixes with a bentonite content of 20% and less.

6. As the swelling nature of bentonite improved an increment in UCS has been observed, i.e. bentonite-2 mixes exhibited relatively higher UCS.

5.2 SCOPE FOR THE FUTURE WORK

Further work can be taken up in the following direction:

1. Sand proportioning has been seen to improve the hydraulic characteristics of sand-bentonite mixtures in the bentonite contents less than 30%. Further studies can include the other fine sand:medium sand proportions that were beyond the scope of this study, i.e. 10% FS+ 90% MS, 20% FS+ 80% MS, 80% FS+ 20% MS, 90% FS+ 10% MS.

2. With the variation in sand composition, variability in shrinkage behaviour has been observed. Further studies can include the above mentioned sand compositions and probe further into improving the desiccation susceptibility of sand-bentonite mixtures.

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LIST OF PUBLICATIONS FROM THIS RESEARCH WORK

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