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The factors controlling the engineering properties of bentonite-enhanced sand

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ABSTRACT: This paper considers the engineering behaviour of bentonite-enhanced sand (BES) mixtures in relation to their performance as environmental barriers. Data on the swelling and hydraulic conductivity are presented. At low effective stresses the bentonite within BES mixtures swells sufficiently to separate the sand particles. In such states two factors affect the void ratio reached by the bentonite after swelling, the ionic concentration of the pore solution and the bentonite fabric after compaction. Bentonite swelling is very sensitive to the pore solution concentration because increasing concentration suppresses the diffuse double layer component of swelling. Remoulding during compaction can result in a slight reduction in bentonite swelling, probably because of disruption to the cluster-based fabric of bentonite. At high effective stresses the bentonite has insufficient swelling capacity to force the sand particles apart, and the sand pore volume thus limits swelling.

A model to predict the swelling and hydraulic conductivity of BES in distilled water and various salt solutions is described. This model requires the swelling behaviour and hydraulic conductivity of the bentonite in the relevant solution, and the compressibility and porosity of the sand component as input parameters. Soil tortuosity is used as a fitting parameter, and is estimated from Archie's equation. Application of this model to the swelling of compacted mixtures is shown to produce a good fit with the experimental data.

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1. INTRODUCTION

Bentonite-enhanced sand (BES) mixtures are widely used as barriers to control the movement of liquid from waste disposal facilities because BES can combine relatively high strength and low compressibility with very low hydraulic conductivity. This is achieved by using a mixture that contains sufficient sand to ensure the stability of the compacted mixture and enough bentonite to seal the voids between the sand particles. Other benefits are that compacted BES containing modest amounts of bentonite is fairly resistant to the effects of desiccation (Tay et al. 2001), and the bentonite in BES has a high chemical buffering capacity (Yong, 1999b).

The aim of this paper is to review the factors affecting the performance of BES as a landfill liner, to report data from tests investigating the influence of compaction on the properties of BES mixtures and make recommendations about the design of compacted BES landfill liners.

2. BACKGROUND

2.1 The structure and engineering properties of bentonite

Commercially available processed bentonites are principally montmorillonite with impurities such as fine quartz particles. Those used in the construction of BES landfill liners usually contain sodium montmorillonite. Montmorillonite is an alumino-silicate mineral with a 2:1 unit layer structure. Individual layers (or lamellae) are about 10Å (1nm) thick, but up to several orders of magnitude larger in the other directions (Grim, 1968; Mitchell, 1993).

Stable montmorillonite unit particles are stacks of 1 to 16 lamellae (Sposito, 1984), although 2-3 lamellae is typical of sodium montmorillonite (van Olphen, 1991). These unit particles can aggregate together to form clusters which, due to the tendency of the platy unit particles to align, are anisotropic (Pusch, 1999). Pusch (op. cit.) suggests that bentonite clusters can consist of many unit particles (possibly 10^7 to 10^9). Thus, structural elements exist at several scales and can be arranged in the size order:

Unit layers (Lamellae) < Unit particles < Particle clusters

A representative volume of bentonite consists of particles and voids which, arranged in size order, comprise:

Interlayer pores < Interparticle pores (or micropores) < Intercluster pores (macropores)

(after Pusch, 1999; Yong, 1999b).

Exposure of bentonite powder to water, or even water vapour, results initially in surface hydration due to the attraction of water molecules to the clay surfaces. This is primarily an interlayer process due to the relative amounts of interlayer and external surface. Water uptake beyond that needed to give an interlayer separation of about 1.2 nm (3-4 layers of water) results from diffuse double layer forces between the hydrated montmorillonite unit layers (Yong, 1999a). In a sodium montmorillonite unrestrained double layer swelling can result in the dispersion of the unit layers and the formation of a gel phase, where the plate-like unit layers form a “house-of-cards” structure which, on a macroscale, is a homogeneous system with some rigidity and elasticity (van Olphen, 1991). However, complete dispersion of lamellae is sometimes prevented by the formation of tactoids (possibly due to Van der Waals forces or edge-face bonding of occasional non-aligned layers), which are stable regions where the lamellae are orientated essentially parallel to one another at a distance of about 100Å.

When swelling is constrained, the density of the bentonite varies spatially in a manner that suggests that some aspects of the cluster structure are preserved after swelling (Pusch and Schomburg, 1999). However, stacks of lamellae can become exfoliated from the expanding clusters and reorganise to form gels that can invade the macroporosity (Alonso et al., 1999; Pusch, 1999). Thus, Pusch (1999) proposed that swollen bentonite can be conceptualised as consisting of stacks of individual 10Å montmorillonite lamellae (hydrated unit particles), stack aggregates (particle clusters), and non-montmorillonite grains (as bentonite is not pure montmorillonite), and gel-filled and unfilled voids. Gens and Alonso (1992) relate different aspects of the mechanical behaviour of swollen bentonite to the behaviour of structural elements at two different scales; the microstructural level at which swelling of active minerals takes place, and the macrostructural level at which major structural changes take place. Similarly, Graham et al. (1992) suggest that in a dense state bentonite supports applied loading both by direct contact between the clusters of hydrated unit particles and by diffuse double layer phenomena in the pore spaces between the clusters.

Studds et al. (1998) report the behaviour of air-dried bentonite powder (SPV200 Wyoming bentonite supplied by Volclay) swelling one-dimensionally against a surcharge (see figure 1a). At vertical effective stresses below about 200kPa the bentonite void ratio is very sensitive to the applied stress, decreasing approximately linearly with the logarithm of vertical stress. Above about 200kPa the void ratio is less sensitive to changes in stress, but still appears to decrease linearly with the logarithm of vertical stress.

Studds et al. (1998) also report similar tests where the same air-dried bentonite is allowed to swell with various chloride salt solutions. In such tests there is always concern that the bentonite can act as a semi-permeable membrane once it is partially hydrated (drawing the water in more readily than the salt). This may result in a lower salt concentration in the bentonite pores than in the bulk solution. Malusis and Shackelford (2002) measured the rate of aqueous potassium chloride diffusion through a geosynthetic clay liner containing bentonite. Their specimens had a similar thickness to those used by Studds et al. (about 10mm). Malusis and Shackelford found that it took about 2 days to establish steady state diffusion of the conservative Cl^- specie, but between 10 and 30 days to establish steady state diffusion of the K^+ because of retardation by sorption on the clay (lower solution strengths being retarded more strongly). The tests reported by Studds et al. were conducted for periods of up to 45days, and were not ended until all swelling had ceased. It is therefore thought that the semi-permeable membrane effect did not adversely affect these tests, and the final salt concentration in the bentonite macro-pores will have been similar to that in the bulk solution.

Studds et al. (1998) found that at surcharges less than 200kPa the amount of swelling in the salt solutions decreased with increasing solution concentration, and for each concentration the void ratio decreases approximately linearly with increasing vertical stress (see figure 1b). All the data converge at about 200kPa, when the bentonite void ratio was approximately 1.5. Data for different chloride salts at the same concentration produced broadly similar trends in swelling behaviour, so the cation type has not been shown on Figure 1b. However, Studds et al. (1996) report that in salt concentrations of 0.01M and 0.1M the amount of bentonite swelling decreased with increasing valance of the solution cation, but in 1M salt solutions the amount of swelling increased slightly with the valance of the solution cation. The trend in the 0.01M and 0.1M solutions is predicted by diffuse double layer theory, whereas the trend in the 1M solutions suggests that such a concentration is sufficient to suppress the diffuse double layer, and that the amount of swelling is related to the hydrated radius of the solution cation. Interestingly, the relatively small differences in swelling at a given solution concentration suggests that cation type does not have a significant influence on cluster-based microstructure of the bentonite when it swells against a surcharge from a dry state.

The insensitivity of bentonite void ratio to the pore solution composition and concentration above a stress of 200kPa suggests that void ratio is not controlled by diffuse double layer interactions in this range. A void ratio of 1.5 is not much greater than that of a hypothetical system of perfectly aligned basic units separated by 4 layers of hydration water (which would be about 1.2). However, soil-water characteristic curves for BES containing the same bentonite presented by Tay (2000) indicate that the stress between unit layers when there are four layers of hydration water absorbed into the interlayer space is of the order of 2MPa[2]. This is an order of magnitude higher than the “averaged” applied stress.

Bentonite specimens that are prepared from powder will consist of clusters of hydrated unit particles separated by gel-filled and unfilled macropores, and it is suggest that an applied stress of about 200kPa is sufficient to produce a network of particle clusters in close contact. Compression of such a network must involve deformation of the particle clusters. Thus it is suggested that, when bentonite powder swells one-dimensionally from an air-dried state, there is a change in the dominant process at an applied stress of about 200kPa. At lower stresses the dominant process is diffuse double layer interaction between particle clusters, which (with exfoliation of unit layers) will eventually produce a fabric of isolated clusters separated by gel. At higher stresses the clusters are in close contact, and volume change involves deformation of the clusters.

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[2] An estimate of this stress can be obtained from a soil water characteristic curve if it is assumed that water will occupy only the interlayer space at low water contents, and that this space must be saturated with four layers of hydration water before water can occupy other pore spaces.

Mollins (1996) determined the one-dimensional swelling behaviour of air-dried bentonite powder (Conquest Wyoming bentonite supplied by Colin Stewart MinChem) placed in an oedometer and allowed access to water, and compared it with the one-dimensional consolidation behaviour of the same bentonite mixed with water at a moisture content just above its liquid limit (LL) of 407% (see figure 2). It can be observed that the swelling behaviour of initially air-dry Conquest bentonite is very similar to that of SPV200 under the same conditions (Figure 1a). During consolidation the void ratio of the LL specimen was significantly above the trend-line for swelling. Mollins (*op. cit.*) reports that an initially air-dried specimen that had swollen against a small surcharge exhibited very similar behaviour to the LL specimen upon subsequent consolidation. On unloading the expansion (or rebound) index of the LL specimen was significantly smaller than the compression index, indicating that the consolidation results in a change in bentonite fabric. It is suggested that the fabric of specimens prepared as air-dried powders (randomly orientated clusters of aligned unit particles) is only preserved during swelling if the bentonite is confined, and the structure becomes dispersed (i.e. essentially a system of hydrated unit particles) if sufficient swelling is permitted (either by mixing at the LL or if the confining stress during swelling is sufficiently small). Subsequent consolidation results in realignment of the bentonite unit particles, but not the formation of particle clusters.

Studds et al. (1998) measured the “hydraulic” conductivity to various chloride salt solutions of bentonite specimens that were initially prepared in an air-dry state, then allowed to swell in the selected solution against a surcharge stress (Figure 3). For each strength of solution, there is a linear trend between the logarithm of hydraulic conductivity and the logarithm of void ratio (different chloride salts at the same concentration produced broadly similar trends; see Studds, 1997, for more details). Also, at a given void ratio, the hydraulic conductivity of the bentonite increases as the solution strength increases. This later trend probably results from the influence of the permeant on the effective porosity. Dixon et al (1985) suggested that the effective porosity of a clay is less than would be expected considering the total pore space per unit volume because some of the pore space is occupied by bound water which has a greater viscosity than free water. Diffuse double layer theory predicts that the diffuse double layer thickness decreases with increasing pore-solution concentration. Therefore, at a given void ratio the effective porosity of the bentonite will increase as the solution strength increases.

2.2 The engineering properties of BES

Studds et al. (1998) report the swelling behaviour of initially air-dried BES with distilled water (see figure 4). When the surcharge stress is low, mixtures containing 20% bentonite (by dry weight) swell in water to higher overall void ratios than do those containing 10% bentonite, whereas at high surcharge stresses the two mixtures swelled to similar void ratios. The response of the bentonite in the mixtures (expressed as a bentonite void ratio, e_b = volume of water/volume of dry bentonite) is shown in Figure 4b, together with the swelling behaviour of bentonite powder for comparison (the broken lines were generated by the proposed model). At low surcharge stresses e_b within the mixtures is similar to that of bentonite alone, whereas at high surcharge stresses e_b within the mixtures is higher than that of the bentonite under the same surcharge.

Mollins et al. (1996) idealised such behaviour by proposing that BES containing modest amounts of bentonite can be characterised by a threshold stress that is a function of the bentonite content. Below the threshold stress the clay in the mixture is able to swell against the surcharge and separate the sand particles to reach the same void ratio, for a given surcharge, as the bentonite alone. Above the threshold stress the e_b value, upon filling the sand pores, is greater than the void ratio of bentonite alone that would be in equilibrium with the surcharge stress, and the sand particles remain in contact.

Studds et al. also report the swelling behaviour of initially air-dry BES with 0.1 mol/l chloride salt solutions (see figure 5). Mixtures containing 10 and 20% bentonite swelled to similar overall void ratios when subjected to the same surcharge (Figure 5a). However the bentonite in these mixtures responded differently (Figure 5b). Mixtures containing 10% bentonite exhibit an e_b that is consistently higher than that of the 20% mixtures mixture which, in turn is consistently higher than that of bentonite alone. This suggests that in both mixtures the sand matrix supports a proportion of the surcharge stress over the entire stress range investigated.

Studds et al. measured the hydraulic conductivity of bentonite-Knapton Quarry sand mixtures (Figure 6a and b, where the solid lines represent the best-fit line for the relevant bentonite data presented in Figure 3 and the broken lines were generated by the model proposed later). Despite some scatter in the data, the main trends are:

(a) at a given e_b the hydraulic conductivity of the 10% mixtures is lower than that of the 20% mixtures, which in turn is lower that that of the bentonite alone;

(b) the hydraulic conductivity of each mixture increases as e_b increases.

These results suggest that flow through the mixtures is through the bentonite phase occupying the pores of the coarse soil matrix. The reason why the 10% mixtures appear to have a lower hydraulic conductivity than the 20% mixtures is that the data is presented in terms of the clay void ratio, and at the same e_b the sand particles in the 10% mixtures must be more tightly packed together (resulting in reduced cross-sectional area for flow and longer flow-paths though the mixture). The ratio of the mixture to bentonite hydraulic conductivity which can be determined from Figure 6 is generally low indicating good filling of the pores in the sand matrix. The difference in hydraulic conductivities is generally more than can be explained by considering the effects of sand porosity and tortuosity, which may indicate a difference between the bentonite fabric in the mixtures and that of bentonite alone.

Borgesson et al. (2002) report a very different trend in the hydraulic conductivity of BES. They found that the hydraulic conductivity of the bentonite in the pores of BES mixtures was frequently higher than that of the bentonite alone. They attributed this effect to an uneven bentonite distribution in the mixtures. The most obvious difference between the mixtures report by Borgesson et al. and those of Studds et al. is that the former used Volclay MX-80 bentonite, which has a granular structure with a particle size (0.06 to 0.6mm) similar to the effective size of their ballast (D_{10}<0.1mm), whereas the latter used SPV200 bentonite, which had an average particle size (2μm) more than an order of magnitude smaller than the effective size of their sand (D_{10}<0.07mm). Thus it appears that problems associated with an uneven bentonite distribution can occur when the bentonite granule size is similar to the typical pore size of the ballast material.

Studds et al. proposed a model to predict the swelling behaviour of BES from the swelling response of the bentonite alone and the load-deformation characteristics of the coarse soil. It assumes that the overall vertical effective stress applied to the mixture is equal to the sum of the stress components supported by the coarse soil and the bentonite (Graham et al. 1986). Also, as the load deformation characteristics of the coarse soil within a mixture cannot be directly measured, it is assumed that the change in coarse soil porosity, n_{cs}, with logarithm of vertical effective stress is independent of the initial value of n_{cs} (which is similar to the assumption of parallel elastic rebound lines made in critical state soil mechanics).

The relationship between bentonite void ratio and vertical effective stress of a particular BES mixture can then be generated by repeated application of the following procedure:

1. For a given σ'_v in the coarse soil matrix, calculate n_{cs} using the load-deformation relationship for that soil.
2. For the desired bentonite content, calculate e_b for complete filling of the soil pores.
3. From the bentonite swelling data, estimate σ'_v required to confine the hydrated bentonite at the calculated e_b.
4. Calculate the overall σ'_v supported by the mixture by summing the components supported by the coarse soil matrix and the bentonite.

Studds et al. used this model to generate the broken lines shown in Figs 4 and 5. They also used their model to estimate the hydraulic conductivity, k, of BES (the broken lines on Figures 6a and b) from the calculated n_{cs}, an estimate of the coarse soil tortuosity, and k-e_b data for the bentonite. It should be noted that soil tortuosity, τ, is essentially unmeasurable (Clennell, 1997), and the value of the coarse soil tortuosity is estimated from Archie's equation, $\tau_{cs}=n_{cs}^{(m-1)}$ (Archie, 1942), where m is used within the model as a fitting parameter.

In summary, the microstructure of bentonite has a significant effect on its swelling behaviour, a property that is important to the performance of BES as an environmental barrier. Field compaction methods are not replicated in the research work to date. Compaction in the field is likely to be conducted at a moisture close to the optimum (the moisture content at which the maximum dry density is achieved for a given compactive effort). Optimum moisture content for heavy manual compaction (BS 1377: Part 4: 1990, Method 3.5) is around 10% moisture content (Tay et al. 2001). As most of the water in a BES is associated with the clay minerals this is equivalent to a bentonite moisture content of around 100% in a 10% mixture. At high bentonite moisture contents, mechanical reworking of a BES during mixing and compaction is likely to cause significant disruption to the microstructure. At present it is unknown whether this will affect the subsequent swelling behaviour after compaction.

3. MATERIALS

The materials used were SPV 200 Wyoming bentonite supplied by Cetco Europe Ltd (formerly Volclay), and Sherburn yellow building sand supplied by Tom Langton and Sons, Leeds, UK. SPV 200 bentonite originates from Lovell, Wyoming, USA, and is a well ordered sodium montmorillonite with minor quartz and cristobolite impurities (Studds et al., 1998). Sherburn sand is predominantly a quartz sand (suppliers specification). Other properties of these materials are given in Table 1.

4. METHODS

BES containing either 10 or 20% bentonite was mixed at the desired moisture content for 20 to 25 minutes in a Hobart bench mounted mixer. Immediately after mixing, BES specimens were compacted into specially designed oedometer rings. These rings have the same internal diameter (105mm) as a standard compaction mould, but are 20mm high. The original mild steel rings were chrome plated to prevent corrosion, but when the plating became chipped they were replace by stainless steel rings. The compaction moisture contents were within ±1% of optimum for heavy manual compaction (which are 9.5% and 11.5% for the mixtures containing 10 and 20% bentonite, respectively; Tay et al., 2001). The one exception was a specimen containing 20% bentonite, and later surcharged by a stress of 190kPa, which was compacted at a moisture content 1.5% below optimum. The BES was compacted in a single layer by 27 blows of the heavy manual compaction drop-hammer (heavy manual compaction in a standard mould is undertaken in five layers of about 23mm final thickness, with each layer subjected to 27 blows of the drop-hammer). The final dry densities achieved were on average 96% and 95% of the maximum dry densities for these mixtures. The compacted specimens were trimmed, subjected to a surcharge load, inundated with water, and monitored until swelling ceased.

5. RESULTS

The one-dimensional swelling behaviour of BES containing 10 and 20% bentonite compacted by heavy manual compaction at optimum moisture content is shown in Figure 7a and 7b, respectively, expressed in terms of the void ratio of the bentonite in the mixture (e_b). The trend-lines from figure 1a, showing the swelling behaviour of the bentonite prepared as a dry powder, are also shown on these figures. Trend-lines presented by Studds (1997), for the swelling behaviour of BES containing 10 and 20% bentonite prepared in a dry state, are shown as heavy dashed lines on figure 7 (Studds tested BES containing Knapton Quarry sand, which is a fine quartz sand). At low surcharge stresses, Studds found that the behaviour of the BES mixtures was indistinguishable from that of the bentonite prepared as a dry powder.

Compacted mixtures containing 10% bentonite (Figure 7a) swell against a nominal surcharge (≈1kPa) to reach a bentonite void ratio that is slightly greater than that achieved by the bentonite swelling from a dry powder. Under low surcharges (≤25kPa) compacted mixtures containing 10% bentonite reached void ratios slightly lower than that of bentonite powder. However, at higher surcharge stresses (>25kPa), compacted mixtures containing 10% bentonite reached higher bentonite void ratios than the bentonite powder. A straight line (in e_b-$\log\sigma_v'$ space) has been fitted to the data over the range of surcharge stresses from 1 to 25kPa ($r^2=0.97$). A second straight line has been fitted for surcharge stresses greater than or equal to 25kPa ($r^2=0.91$).

Compacted mixtures containing 20% bentonite (Figure 7b) swell against a nominal surcharge to a bentonite void ratio that is similar to that achieved by the bentonite swelling from a dry powder. However, under low surcharges (≤25kPa) these mixtures reached void ratios significantly lower than did bentonite powder. At higher stresses (>25kPa) e_b is significantly less sensitive to stress, such that the BES specimen subjected to a surcharge of 190kPa reached an e_b larger than that of bentonite powder specimens. A straight line (in e_b-$\log\sigma_v'$ space) has been fitted to the data over the range of surcharge stresses from 1 to 25kPa (r^2=0.97). A second straight line has been fitted for surcharge stresses greater than or equal to 25 kPa (r^2=0.99).

6. DISCUSSION

It has been proposed that BES containing modest amounts of bentonite can exist in two characteristic states: below a threshold applied stress the bentonite separates the sand particles and must support the whole of the applied stress, whereas above the threshold stress there is a matrix of sand particles that support most of the stress. The swelling behaviour of compacted BES containing 20% bentonite (Figure 7b) is distinctly bilinear on a graph of e_b against $\log\sigma_v'$, with a threshold stress of about 20kPa. This behaviour supports the proposition that BES exhibits two characteristic states.

The swelling behaviour of compacted BES containing 10% bentonite (Figure 7a) is less clearly bilinear, partly because there is more scatter in the data, but also there is less difference in gradient above and below the assumed threshold stress. However, there is clearly a change in the relationship between e_b and $\log\sigma_v'$ in the stress range 10 to 30kPa, with the gradient at higher stresses very similar to that measured by Studds (1997) for 10% mixtures in the stress range where the sand is supporting most of the applied stress. It is therefore suggested that two straight lines on a graph of e_b against $\log\sigma_v'$, with a threshold stress of about 20kPa, is a good characterisation of the experimental data, which again supports the proposition that BES exhibits two characteristic states.

Below the threshold stress, it is thought that any stress applied to BES is supported entirely by the bentonite in the mixture. Thus it can be inferred from Figures 7a and 7b that compaction at optimum moisture content has only a slight effect on the swelling properties of the bentonite powder within the 10% mixtures (although it does seem to increase the threshold stress), but a marked effect on that within the 20% mixtures. In the background section air-dried bentonite powder was described as consisting primarily of randomly orientated clusters of aligned unit particles, and it was reported that this cluster-based fabric is preserved during swelling if the bentonite is confined. It is proposed that during compaction at optimum moisture content the cluster-based fabric of the wet bentonite within a mixture is partially disrupted by the mechanical action of the sand particles during the shearing induced by compaction. The difference in behaviour between the two compacted mixtures is attributed to the relative amounts of remoulding undergone by sandy and clayey soils during compaction, with less effect on the bentonite in the mixtures with the higher amount of sand. The convergence of the swelling behaviour of both compacted mixtures with that of bentonite powder at very low surcharges indicates that sufficient swelling can occur under very low stresses for the bentonite fabric to become dispersed.

Above the threshold stress the relationships between e_b and $\log\sigma_v'$ for the compacted mixtures have similar gradients to those measured by Studds (1997) for initially dry mixtures containing the same proportion of bentonite and a similar sand. However there is a significant difference in the magnitude of e_b, for the 10% mixture. Mollins (1996) reports the swelling behaviour of Conquest Wyoming bentonite/Knapton Quarry sand mixtures containing 10 and 20% bentonite prepared both dry and by heavy manual compaction at optimum moisture content. Above the appropriate threshold stresses dry prepared BES had similar bentonite void ratios to those represented reported by Studds (1997), whereas compacted BES achieved void ratios similar to those of the compacted mixtures reported here. The observed difference between the dry-placed and compacted mixtures above the threshold stress is therefore thought to be associated with the higher density (i.e. closer packing of the sand particles) that can be achieved when compacting at optimum moisture content, rather than the difference in the sands used.

The threshold stress for the compacted 10% mixture corresponds to a sand void ratio of 0.69, whereas the threshold stress for the 20% mixture corresponds to a sand void ratio of 1.12. The maximum void ratio of Sherburn sand measured by the method recommended by Head (1980) is 0.82. Thus compaction resulted in a dense packing of the sand within the 10% mixture, whereas the larger volume of clay in the 20% mixture prevented such a dense sand packing being achieved. Indeed it may initially appear unlikely that that there is a contiguous matrix of sand particles in the 20% mixtures when the sand void ratio is 1.12. However, it should be recognised that the “standard” test that has been used to find the maximum void ratio of a sand is intended to obtain an “index value” to be used primarily for comparative purposes. For illustration, a void ratio for Sherburn sand of 0.93 has been achieved by a non-standard preparation method (careful pouring of the sand down the side of an inclined measuring cylinder). Secondly, it ignores the role of the clay in stabilising the columns of contiguous sand particles that support the applied loading. Thirdly, there is an abrupt change in BES compressibility at the threshold stress, and above the threshold stress it is significantly less compressible than the bentonite it contains implying a contiguous sand matrix.

The data reported in this paper came from specimens compacted at a moisture content very close to optimum for the compaction method used. Also all specimens were compacted as soon as practicable after mixing (typically about 30 minutes after the start of mixing) to replicate the typical field situation where compaction takes place shortly after mixing. As clayey soils tend to undergo more remoulding when compacted wet of optimum than they do at optimum moisture content, compacting BES wet of optimum, common for clay barrier materials, may further suppress the swelling of bentonite in BES due to the increased disruption to the cluster based fabric. Delaying the compaction of BES after mixing may also affect the subsequent bentonite swelling behaviour, as it will allow better penetration of water into the bentonite particle clusters which may affect their stability during compaction.

The model proposed by Studds et al. (1998) for predicting the swelling behaviour of BES requires data on the swelling properties of the bentonite, and data on the variation in coarse soil porosity with the stress that it supports and the proportion of bentonite in the mixture. Thus application of the model in engineering design will require a limited experimental programme to calibrate the model to the specific materials and compaction method being used. As a minimum, this would involve;

(i) a number of low surcharge stress swelling tests to establish the swelling behaviour of the bentonite within a compacted mixture,

(ii) high surcharge stress swelling tests to establish the sand porosity when a particular stress is supported by the sand matrix (if the surcharge stress is sufficiently high, the stress supported by the bentonite can be ignored),

(iii) measurement of the sand porosity, n_{cs}, with stress.

Tests required under (ii) and (iii) above will be relatively rapid, as those required under (ii) will exhibit very little volume change because the sand is supporting most of the applied stress, and those required under (iii) can be conducted on the sand alone if it is assumed that the change in n_{cs} with $\log\sigma_v'$ is independent of the initial value of n_{cs} (as previously proposed). Use of the model calibrated in this way produced the curved lines on Figure 8.

It is not possible to measure the hydraulic conductivity of the bentonite that has exactly the same fabric as the bentonite within a compacted mixture. This would appear to make it impossible to predict the hydraulic conductivity of BES from that of the bentonite. However, the tortuosity relationship that is used within the model is essentially a calibration factor that must be determined by experimental measurements on BES. Thus, provided the fabric produced by compaction has only a modest effect on the hydraulic conductivity of the bentonite, the effect will be accommodated within the tortuosity factor.

7. CONCLUSIONS

- The swelling behaviour of BES compacted at optimum moisture content can be characterised by a threshold stress. Below the threshold stress the bentonite in the mixture has sufficient swelling capacity to separate the sand particles, and supports the entire applied stress. Above the threshold stress there is a contiguous matrix of sand particles that supports a proportion of the applied stress.
- The swelling potential of the bentonite within BES can be reduced by the disruption of its cluster-based fabric by the mechanical action of the sand particles during compaction. The swelling potential of the bentonite within a 10% mixture compacted at optimum moisture content was only slightly reduced in comparison with that of initially dry bentonite powder, but the swelling potential of the bentonite within a 20% mixture was

significantly affected. The difference between the two mixtures is due to the larger amount of remoulding undergone by the mixture containing sufficient hydrated bentonite to prevent a tightly packed sand matrix forming.

- The model proposed by Studds et al. (1998) for predicting the swelling behaviour of dry-prepared BES can be applied to compacted mixtures provided account is taken of the impact of compaction on both the bentonite swelling behaviour and the initial sand porosity.

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LIST OF TABLES AND FIGURES

Table 1: Properties(1) of SPV200 Wyoming bentonite and Sherburn yellow building sand

SPV200 Wyoming Bentonite(2)	Sherburn yellow Building Sand(3)
Average particle size = 2 µm	Effective size (D_{10}) = 212µm
Specific gravity = 2.751	Fines = 0.36%
Liquid limit = 354%	Coefficient of Uniformity = 2
Plastic limit = 27%	Specific gravity = 2.68
Moisture content = 13% (as supplied)	Max & min void ratio (4) = 0.82 & 0.38
	Moisture content ~ 4% (as supplied)
	Angle of repose (5) = 34°

(1) Tests performed in accordance with B.S. 1377: Part2: 1990 unless otherwise indicated

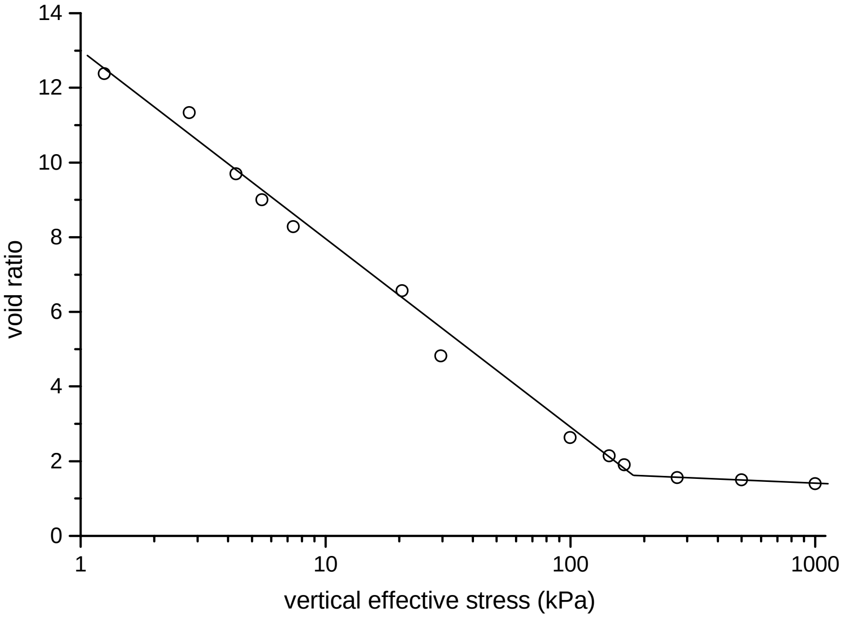
(2) Data from Studds (1997)

(3) Data from Tay (2000)

(4) Determined by methods described in Head (1980)

(5) Determined by method recommended by Cornforth (1973)

(a)



(b)

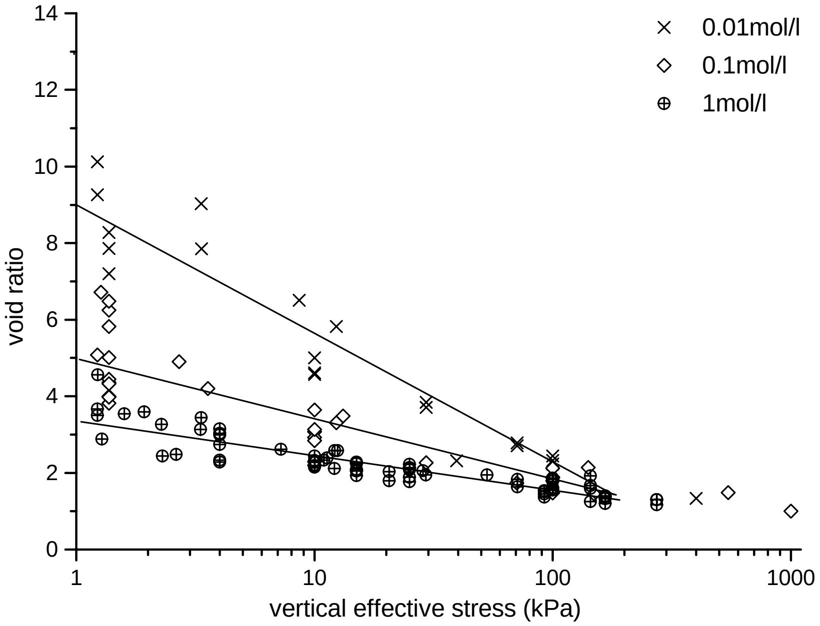


Figure 1: One-dimensional swelling behaviour of SPV200 bentonite in (a) distilled water and (b) various chloride salt solutions (after Studds et al., 1998).

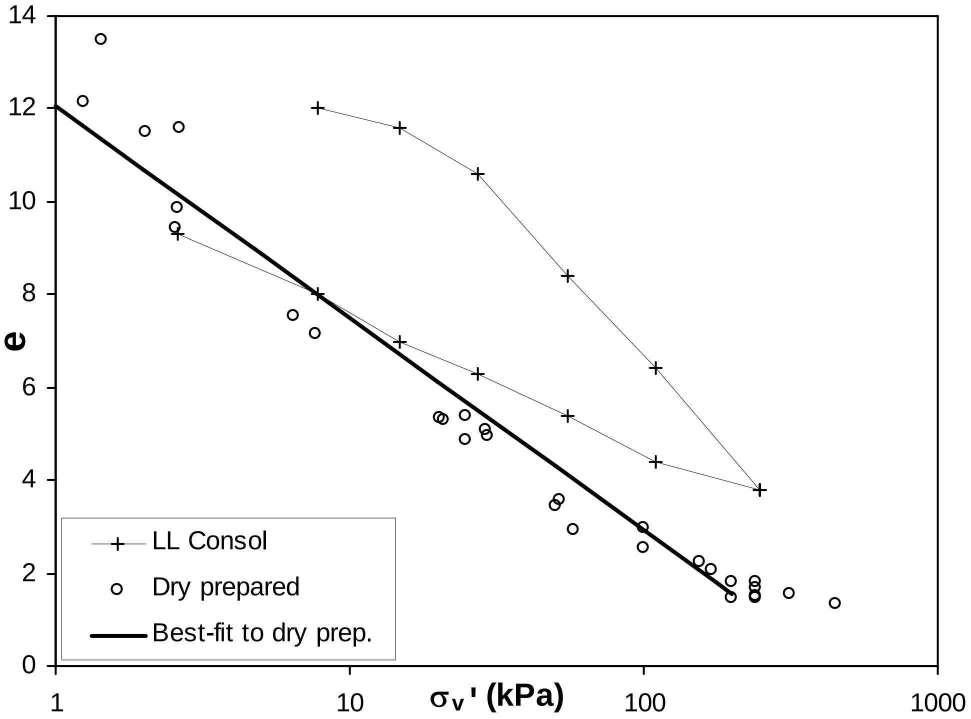


Figure 2: Comparison between the one-dimensional swelling behaviour and consolidation behaviour of Conquest Wyoming bentonite (after Mollins, 1996)

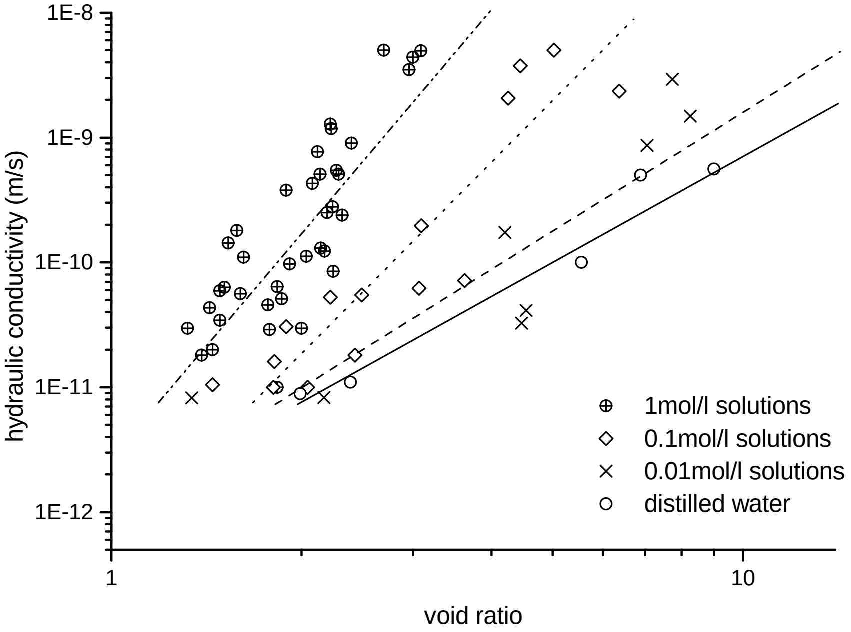


Figure 3: Hydraulic conductivity of SPV200 bentonite prepared in an air-dry state with distilled water and various chloride salt solutions (Studds et al., 1998).

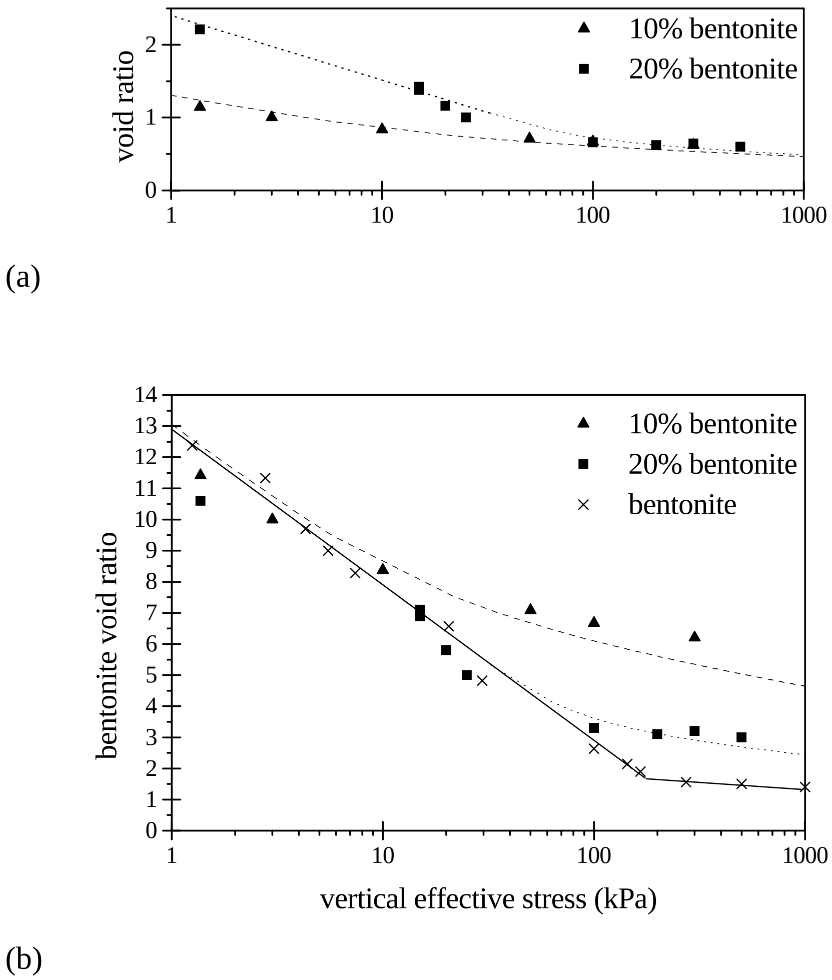
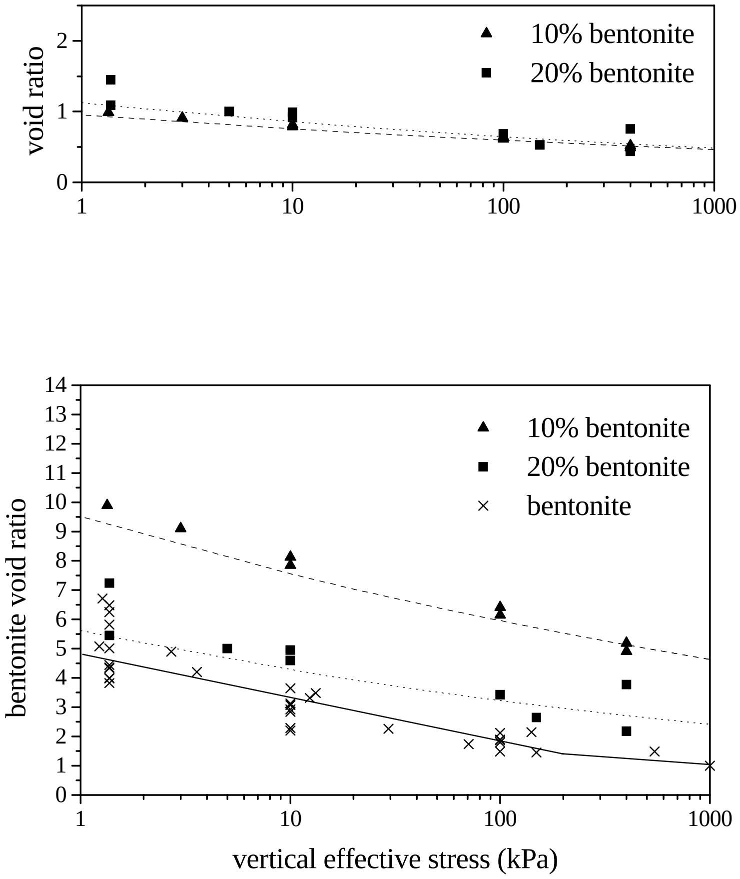


Figure 4: One-dimensional swelling behaviour of dry prepared BES with distilled water (Studds et al., 1998).

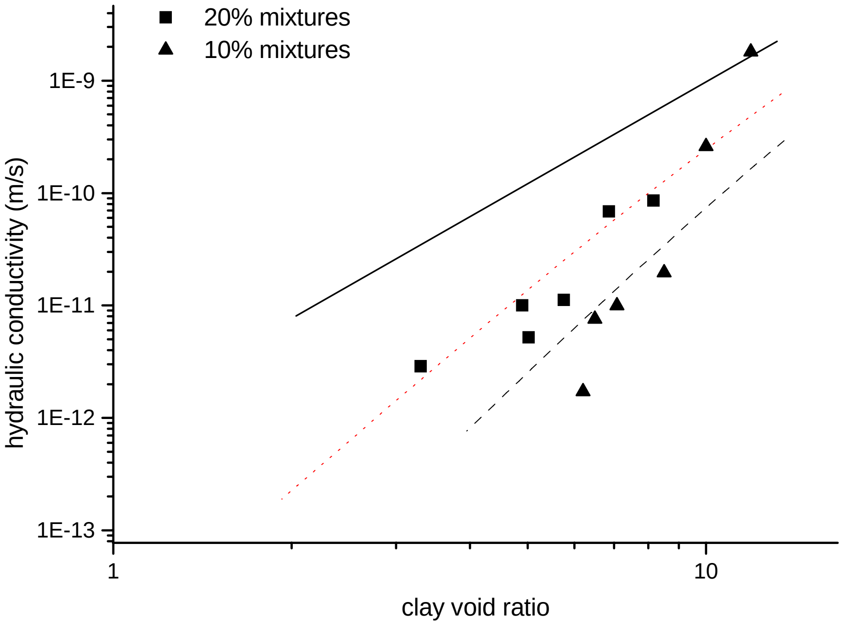


(a)

(b)

Figure 5: One-dimensional swelling behaviour of dry prepared BES with various 0.1 mol/l chloride salt solutions (Studds et al., 1998).

a)



b)

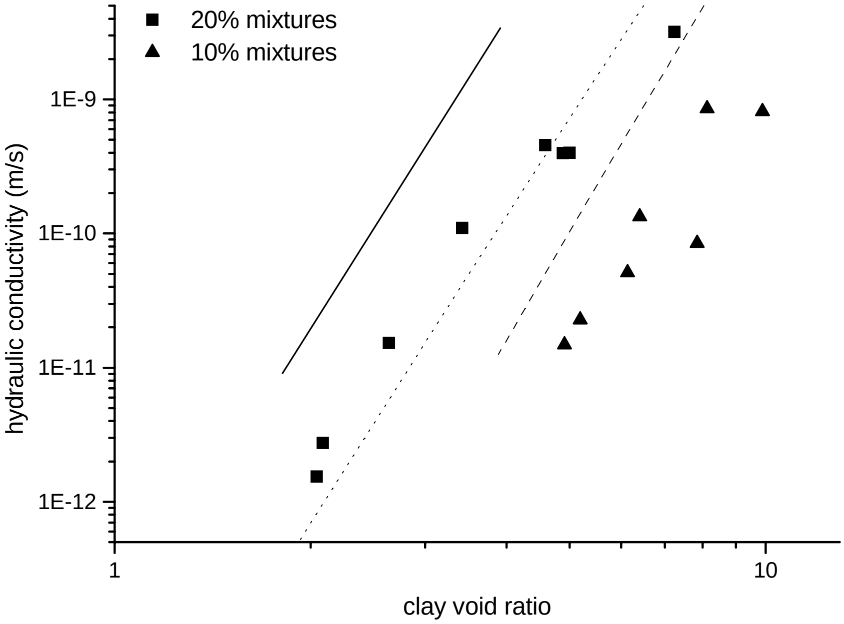
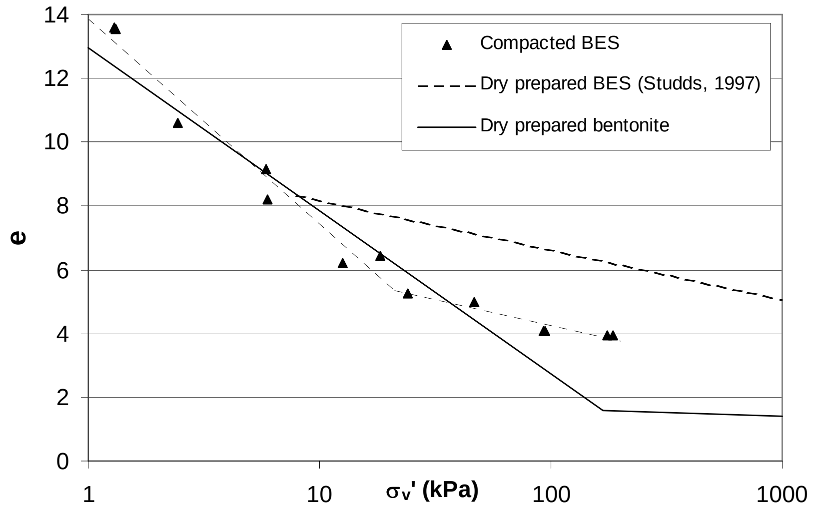


Figure 6: Hydraulic conductivity of dry prepared BES with (a) distilled water and (b) various 0.1 mol/l chloride salt solutions (Studds et al., 1998).

(a) BES containing 10% bentonite



(b) BES containing 20% bentonite

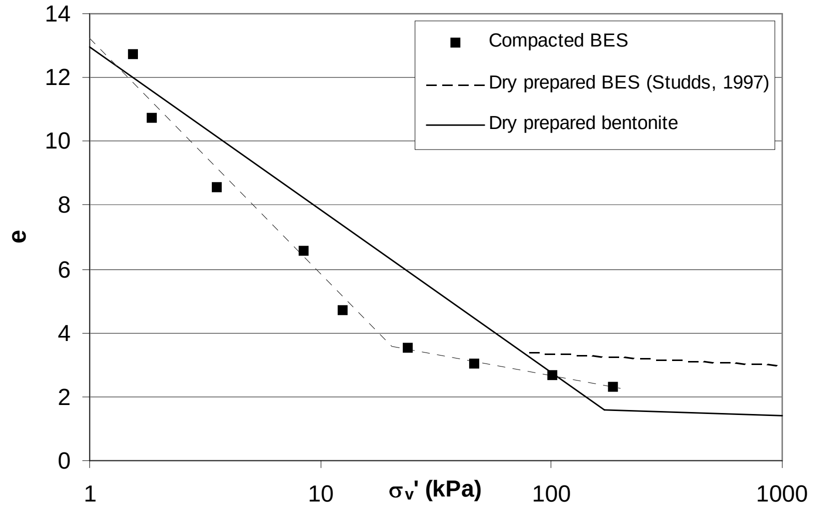


Figure 7: One-dimensional swelling behaviour of BES compacted at optimum moisture content.

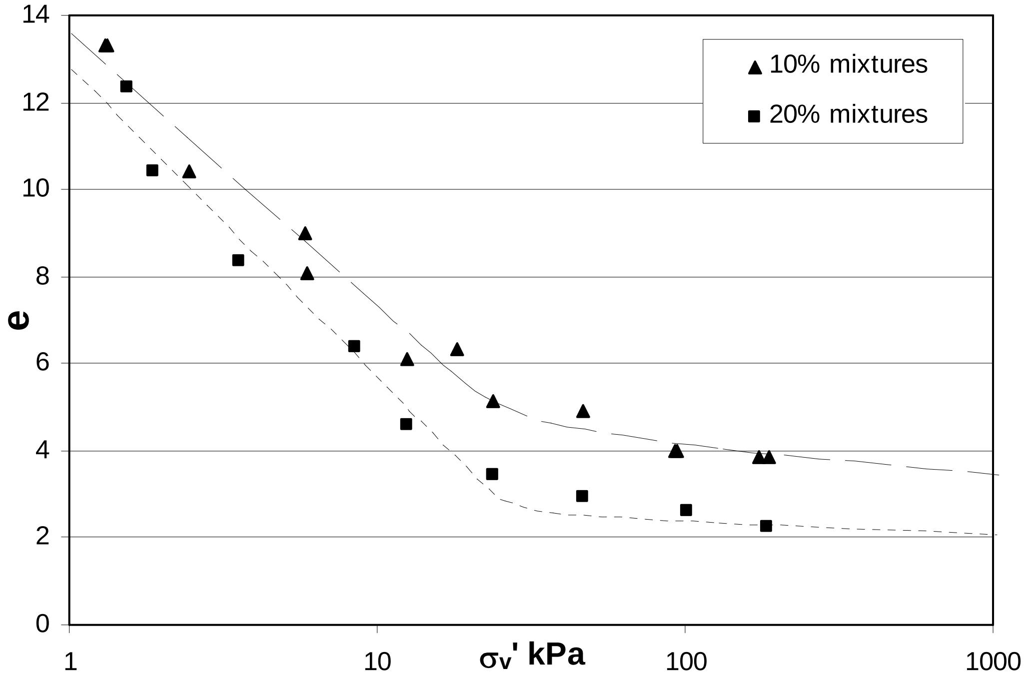


Figure 8: Comparison of the swelling behaviour of BES compacted at optimum moisture content with model predictions.