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INFUENCE OF SALINITY ON THE CONSISTENCY AND SWELLING CHARACTERISTICS OF BENTONITE

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Abstract: Bentonite clay liners are used as a barrier material for water, chemicals and gas in civil engineering structures such as engineered landfills and in structural water proofing. Bentonite clays absorb water and expand greater than any other ordinary plastic clay. The expansiveness of the clay is characterised by the absorbed cation in the clay and the geochemical environment. This paper critically investigates factors that contribute to the swelling characteristics of bentonite clay and its products. It takes particular view on different types of bentonite used in clay liners and their interaction with saline ground water conditions. The swelling pressure of sodium bentonite in deionised water is demonstrated to be very high. However when it is in a saline environment the magnitude of swelling pressure can be less than halved. A parallel observation is noted under conditions of free swell. These are explained as being a consequence of reduction in the double layer thickness which is further reflected in the reduction of cation-exchange capacity when the bentonite is in a saline environment. Variations in cation exchange capacity, consistency limit and free swell of the bentonite products in different saline environment are observed and its significance discussed.

1. Introduction:

The geotechnical behaviour of clays and in particular that of fine grained active clays is strongly influenced by the pore fluid chemistry. Bentonite is widely used in the industry during construction of slurry trenches and for the protection of foundations and tunnels from the detrimental effects of adverse moisture movement. As the bentonite expands it turns into a thixotropic gel, impairing any fluid movement through it. The hydrogen bonding which holds the soil layers and water together does not permit ready drainage, and consequently the consolidation time is lengthened.

GCLs are an innovative construction material that has been developed over the last three decades and is being widely used

commercially as hydraulic barriers in structural water proofing or as a leachate barrier in landfill design. These liners encapsulate bentonite clay and its activity depends on the water balance between the sealing element and the surrounding soil layers. Quantitative clay mineralogical analyses and the ground water chemistry are desired in site appraisal. The differences between sodium and calcium montmorillonite are presented in the paper.

2. Bentonite:

2.1. General information:

The term bentonite was first given to a plastic clay deposit found in the upper cretaceous tuff near Fort Benton, Wyoming. Bentonite is generally formed by the alteration of volcanic ash. Dry bentonites

range in colour; from cream to olive green, in specific gravity; from 2.4-2.8, and in refractive index; from 1.547-1.557, Fusion points; range from about 1,330° to 1,430°C. It is characterised chiefly by its potential to absorb water to a very great extent. It can absorb up to 5 times its weight of water and increase in volume up to 15 times its dry bulk volume. An important characteristic of clay minerals is that they carry a net negative charge that is expressed as the number of deficient electrons / unit cell of ten oxygens with respect to charge neutrality. If there are no fixed cations between the sheets, the negative charge deficiency correlates directly with the cation exchange capacity (CEC) which is a measure of the number of positive cations in milliequivalents that will neutralize 100g of clay. These clays also have a much greater cation exchange capacity than that possessed by the less active clays such as kaolinite. Table 1 shows evidence of how both natural sodium and calcium bentonites have geotechnical properties significantly different to other natural clays.

Smectite (usually montmorillonite) is the dominant clay mineral in bentonite. The chemical formula for the montmorillonite mineral is $Mg.Ca_2O.Al_2O_3.5SiO_2, nH_2O$; where n is considered to be equal to about 8. There is usually isomorphous substitution of magnesium and iron for aluminium in the octahedral sheets. As a direct consequence, a large amount of water is attracted into the space between the layers. The special thixotropy property of bentonite makes it a valuable material for a wide range of uses and applications. Therefore bentonite is also sometimes referred to as “the clay of thousand uses”. It is often used for a wide variety of engineering purposes; as drilling mud in rotary piling, in the construction of

diaphragm walls etc..

Table 1- Comparison of some of the Geotechnical Properties of Sodium / Calcium Bentonites

	Natural London Clay	Natural Calcium Bentonite	Natural Sodium Bentonite
Specific gravity	2.7	2.6-2.8	2.7-2.9
Liquid Limit (%)	70-75	100-150	500-700
Plastic limit (%)	10-20	70-100	450-630
Plasticity Index (%)	10-40	30-50	50-100
Activity	0.4-0.9	>1	>>1
Cation Exchange Capacity (meq/100g)	15-20	28-45	36-42
Surface area (m ² /g)		60-120	20-30
Free swell (ml/2g)	6-10	6-8	20-30
Hydraulic conductivity with water (m/s)	10 ⁻¹¹ to 10 ⁻⁹	6x10 ⁻¹¹	6x10 ⁻¹²
Hydraulic conductivity with 1.5M CaCl ₂ (m/s)		6x10 ⁻¹⁰	9x10 ⁻¹¹

The unique self-healing characteristic of bentonites tolerates minor discontinuities in the material. Furthermore for this reason, in applications such as landfill containment and sealing underground reservoirs against intrusive contaminants, clay mats are preferentially used where long term durability is vital.

The naturally occurring bentonites are more stable as calcium bentonites, as a consequence of the hierarchy in cation exchange. Therefore natural sodium

bentonites are comparably less readily available. Calcium bentonites have, by nature, a more coarsely aggregated internal structure providing a higher hydraulic conductivity and also have lesser swelling properties making them less suitable for providing a tight seal (self-healing effect) in cases of perforation. In order to utilise the better swelling properties of sodium bentonite, calcium bentonite for instance is sometimes activated with soda (sodium carbonate) and thus the primary calcium ions get replaced by sodium. On the other hand, any calcium ion in the leachate is likely to convert the sodium of the sodium bentonite into calcium. A reduction in swelling occurs in instances where high concentrations of ions such as calcium, magnesium, potassium, chloride and sulphate are present in real ground water.

2.2. Geosynthetic clay liners (GCLs):

GCLs are a composite consisting of a relative thin processed bentonite layer either bonded to a geomembrane or encapsulated between two sheets of geotextiles. Geomembranes are impervious polymeric sheet materials, whereas geotextiles are either in the form of woven or non-woven sheet material. Variety of GCL products is now available worldwide. The quality and quantity of bentonite clay used in the liner defines the performance efficiency of a GCL. It is therefore necessary that the type of bentonite in the GCL must be compatible with the leachate to be retained; lest it will cause chemically induced c axis contraction, double layer shrinkage and consequent clay cracking. On the other hand, the performance of bentonite in GCLs can be increased with the addition of linear polymer chains of the sodium polyacrylate and acrylonitrile type. Non uniform and disproportionate mixing can occur when the

polymer is mixed in dry with the air dry bentonite. Furthermore the initial hydration of an air dry GCL needs to be a critical process in the attaching of the water-soluble polymer onto the bentonite surface. Consequently the process of factory prehydration with a liquid polymer is necessarily desirable to ensure that the polymer is uniformly mixed with the clay. The very necessary initial hydration of GCLs with water during installation and prior to the permeation with leachate generally result in a lower hydraulic conductivity. Level of hydration achieved prior to contact with leachate is important. Unfortunately, there is very little documented research on this topic. Daniel et al (1993) indicated that in contact with soil at the wilting point, bentonite can be expected to have its water content increased to about 50%. They also demonstrated that the bentonite is efficient in its uptake of water from the underlying soil. However, effectively flooding of the dry granular GCL is important and can provide a challenge on site (Didea and Comeaga, 1993), where careful supervision is deemed necessary on site. Approximately 15 litres of water are required per square metre (150m³ per hectare) for satisfactory hydration. In the case of compacted clay liners (CCLs), the installation water contents are determined "in its swollen condition". The thixotropic properties of sodium bentonite are adversely affected by the presence of electrolytes (particularly trivalent ions). These may well be in the local ground water supply used to hydrate the GCL prior to placing the backfill or pouring of the concrete. This can seriously impair the design performance of the GCL.

3. Effect of salinity on the soil consistency:

Di Maio (1996) demonstrated that the mechanical behaviour of clays (particularly clays such as Ponzantonite) is strongly influenced by pore fluid composition. He further showed that the exposure to new pore fluids produced a transient stage during which the clays suffer noticeable volume changes. The residual shear strength was also observed to be influenced by the salt concentrations particularly at concentrations < 0.5 M. The angle of residual friction was enhanced in the presence of saline solutions. There was negligible variations for concentrations > 0.5 M. He further concluded that on re exposure to water, Na^+ changes were reversible : and on the contrary, where water replaced CaCl_2 or KCl solutions, residual shear strength showed only a slight decrease and there was no swelling visible even after months.

In this study, Wyoming Bentonite and four other bentonite products were mixed with varying concentrations of artificial sea water made using tropic marine, a sea salt supplied for the use in tropical fish tanks. Liquid limit tests for these clay mixes were determined using the falling cone penetrometer. The tests showed that the liquid limit observed was highest when the clays were mixed with deionised water and the liquid limit decreased with increasing sea water concentration in all the cases.

The liquid limit observations for the clay mix, Liner 1 and Liner 2 were similar and showed a 20 % lesser effect than the Wyoming Bentonite and Liner 3. The liner 3 contained air dried bentonite mixed with polymer in a dry state. It is therefore not surprising that the LL values observed for the Wyoming bentonite and the liner 3 were

similar and that increasing salinity had little effect on change in the soil consistency. This demonstrated the need for proper factory processing with a liquid polymer being mixed intimately with bentonite clay prehydrated to a value in excess of the plastic limit.

4. Cation exchange capacity (CEC):

Cation exchange capacity is a fundamental electrochemical soil property and is particularly significant to the behaviour of clay soil (Alther, 1983; Wilding and Rultedge, 1966; Egloffstein, 1995). Cations due to their positive charge are attracted to negatively charged surfaces in the soil. The greater the ionic concentration in the solution, the more likely it is to become adsorbed. The greater the charge on the cation, the more likely is the ions to be adsorbed. Hydrogen due to its small size is adsorbed much more strongly than would occur if adsorption was strictly based on charge alone.

4.1. Determination of CEC.:

When a solution of methylene blue is added a little at a time to a sample of clay until the cation exchange capacity of the clay is reached, the amount of dye adsorbed is equal to the amount added (Bensted, 1985). Any additions beyond this point are not adsorbed. This amount of methylene blue adsorbed by or exchanged on to clay from an aqueous clay solution is usually determined by titration (Nevins and Weintritt, 1967) when the end point of titration is normally defined with the halo method. Small quantities of methylene blue solution are gradually added to a stirred clay suspension, and a drop of this suspension is put with a glass rod on filter paper

(Whatman filter paper No.1). The initial colourless waterfront will spread in a circle on the filter paper with the blue-coloured clay remaining in the centre. At the end point a light blue halo appears as a sky blue coloration radiating from the normally darkly-dyed solids in the centre.

During this research tests were carried out on Wyoming Bentonite as well as 4 different GCLs, labelled Liner A, B, C and D. The CEC observations (Table 2) on all the samples apart from the liner C fill show a decrease in CEC when the clay fill had been placed in solutions of increasing cationic concentrations suggesting that a process of cation exchange took place reducing the CEC in the modified clay. The levels of Na⁺, K⁺, and NH₄⁺ in MSW leachate are sufficiently high that they can effectively exchange some of Ca⁺⁺ and Mg⁺⁺ present on natural clays during advection and diffusion. CEC must be adopted as a good performance indicator of GCLs and that a high CEC is desirable (Eggloffstein, 1995).

The interpretation of this behaviour can be drawn from information available in various literature sources on the chemistry of clay

Table 2 – Swell index and cation exchange capacity observation for the clay in the liners

Property		Clay infills from liner				Untreated Wyoming Bentonite
		A	B	C	D	
Swell index of clay in: (mL/2g of clay)	Deionised water	30	25	24	23	30
	Hard water	21.5	27	22.5	43	28.5
	Soft water	24	29	27	30	25
	Sea water	5.5	6	7	7	6.5

CEC of clay in: (meq/100g clay)	Na ⁺ 10,000ppm	7	6	8	21.5	10.5
	Na ⁺ 100,000ppm	4	3.5	4.5	5.5	4
	Ca ⁺⁺ 10,000ppm	5.5	4.5	7	6.5	8.5
	Deionised water	56	66	65	70	57
	Sea water	36	38	45	49	41
	Na ⁺ 2,500ppm	56	60	64	68	56
	Na ⁺ 5,000ppm	53	59	62	58	56
	Na ⁺ 10,000ppm	43	47	51	57	46
Na ⁺ 100,000ppm	36	36	44	44	40	
Ca ⁺⁺ 10,000ppm	38	40	42	64	42	

minerals. In general, initial saturation of sodium montmorillonite with a multivalent-rich solution of calcium chloride, causes the divalent cations (Ca²⁺) to immediately occupy most of the cationic sites originally taken by the sodium. When permeated with a leachate containing multivalent cations, the spacing between the platelets gradually decreases, but the dispersed arrangement of the clay fabric is retained. However, as the amount of negativity increases on the soil surface, the sum of exchangeable cations also increases to a saturation point and then decreases as the negativity decreases. Cation exchange capacity is the sum of exchangeable cations a soil can absorb, or in simpler terms, the amount of negative charge on soil. Figures 2 and 3 show the changes in CEC observed with the test clays in increasing salinity.

5. Effect on volume change:

The influence of salinity on free swell is illustrated in figure 4. Further the swell index observations summarized in table 2 show that with deionised water clay infill in liner A gave similar value of 30 mL/2g as that of the Wyoming bentonite. However the infills from liners B, C and D gave somewhat similar but a lower swell index. This may be a consequence of any polymers that may be added during the factory processing of the clay.

Figures 5 and 6 illustrate the free swell observations for a liner infill when placed in sea water and deionised water. Di Maio also observed that the bentonite consolidated to 640 kPa showed a decrease (sudden collapse) in volume when exposed to NaCl, KCl or CaCl₂. This phenomenon is the cause for the cracking in the clays even when submerged under a saline environment. Free swell of the bentonite increases with decreasing salinity. The values of free swell in 100 % sea water is even up to 4 times lesser than in deionised water.

6. Conclusions:

The following is a summary of the findings;

- The colloidal nature of the bentonite makes it expansive and susceptible to the double layer effects of pore electrolyte concentration.
- Bentonite swells more in deionized water and swelling pressure is larger in deionized water than in salt water.
 - It is necessarily significant to appreciate the reaction of the GCL with the chemical make up of the local groundwater or the leachate.
- The dense prehydrated GCL (Liner 3) showed fewer propensities to polyvalent metal ions.

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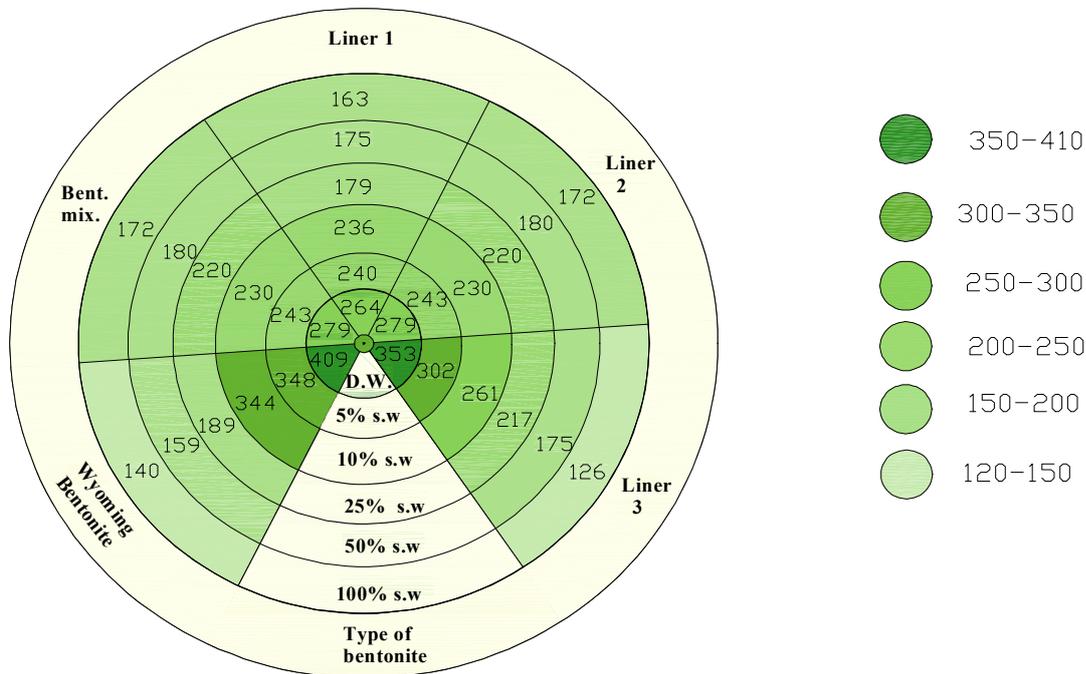


Figure 1 - Presentation of the observed liquid limit values (LL) for the clay samples mixed with different concentrations of sea water.

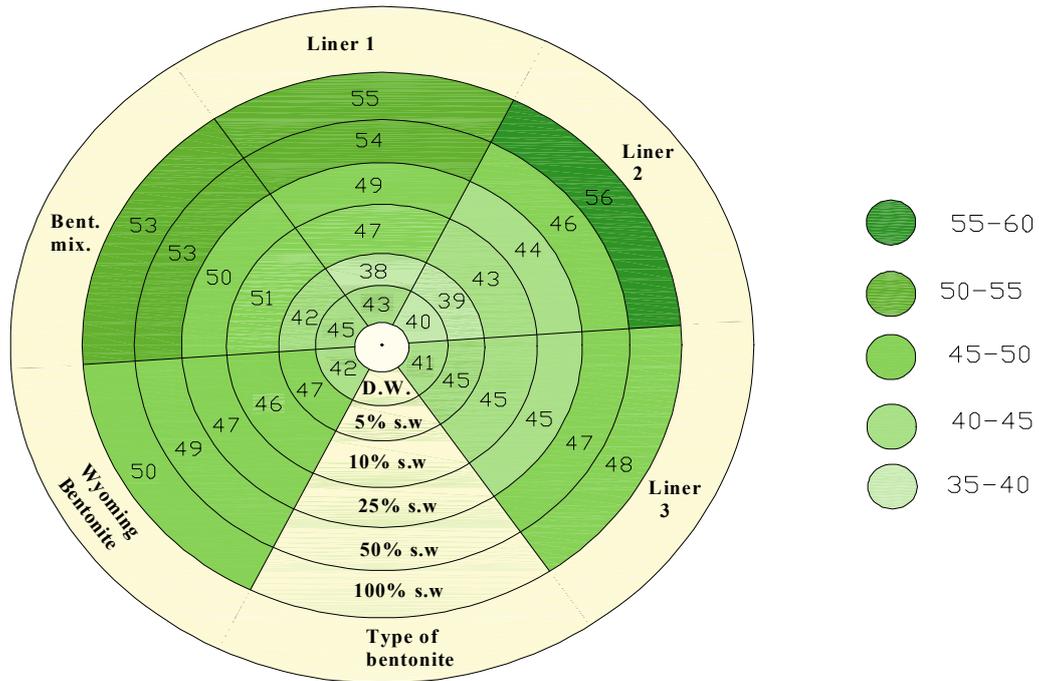


Figure 2 – Presentation of the Cation Exchange Capacity results

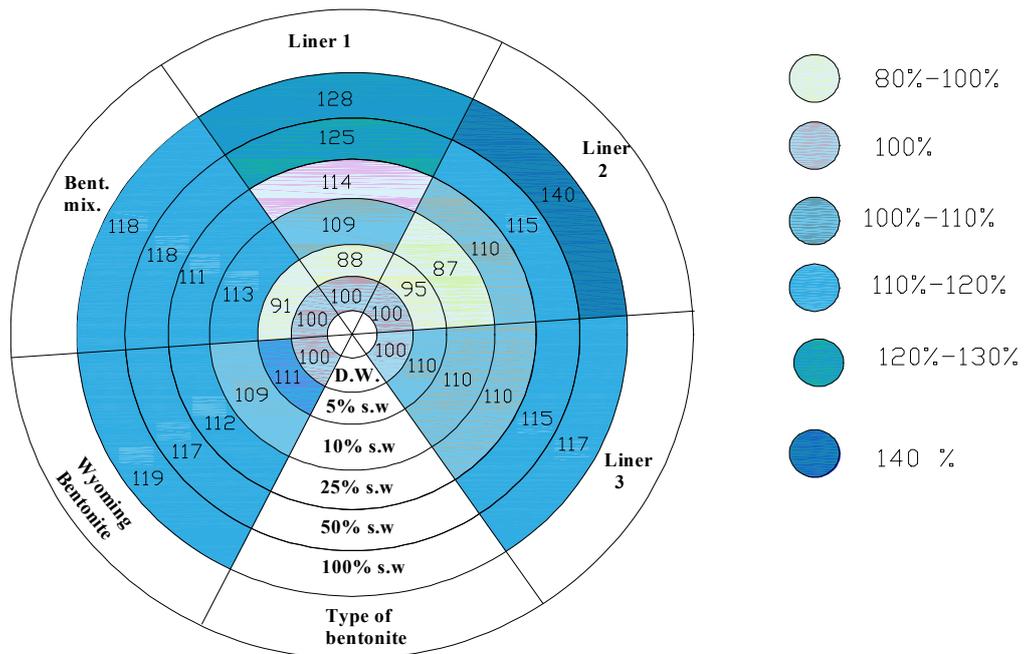


Figure 3 – CEC results presented as a percentage of the CEC for sample in distilled water



Figure 4 – Free swell of clay liner infill in sea water (left) and deionised water (right)

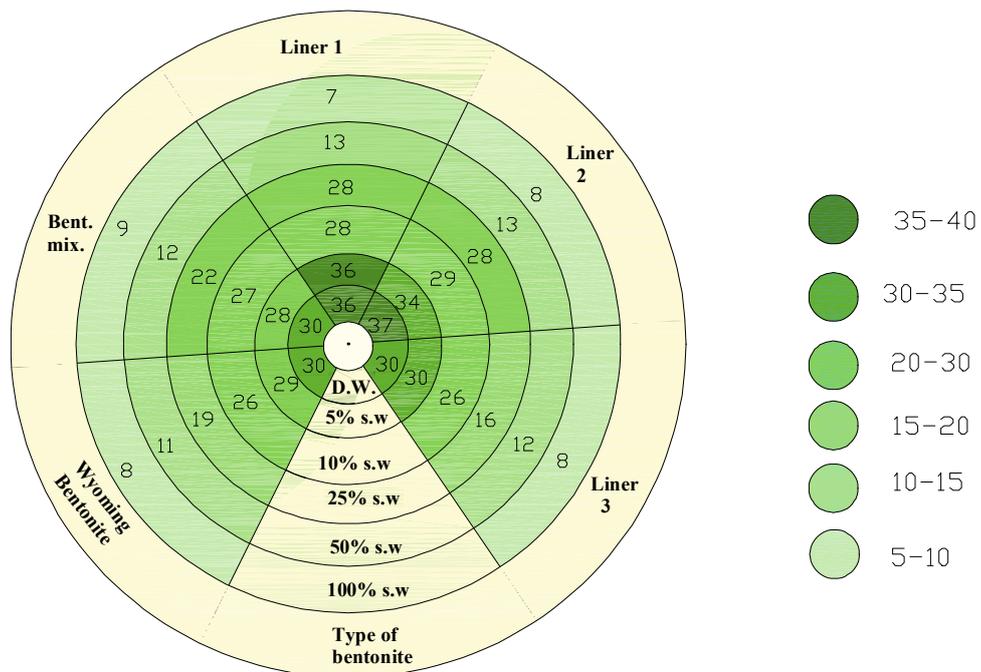


Figure 5 – Presentation of the observed Free swell results.

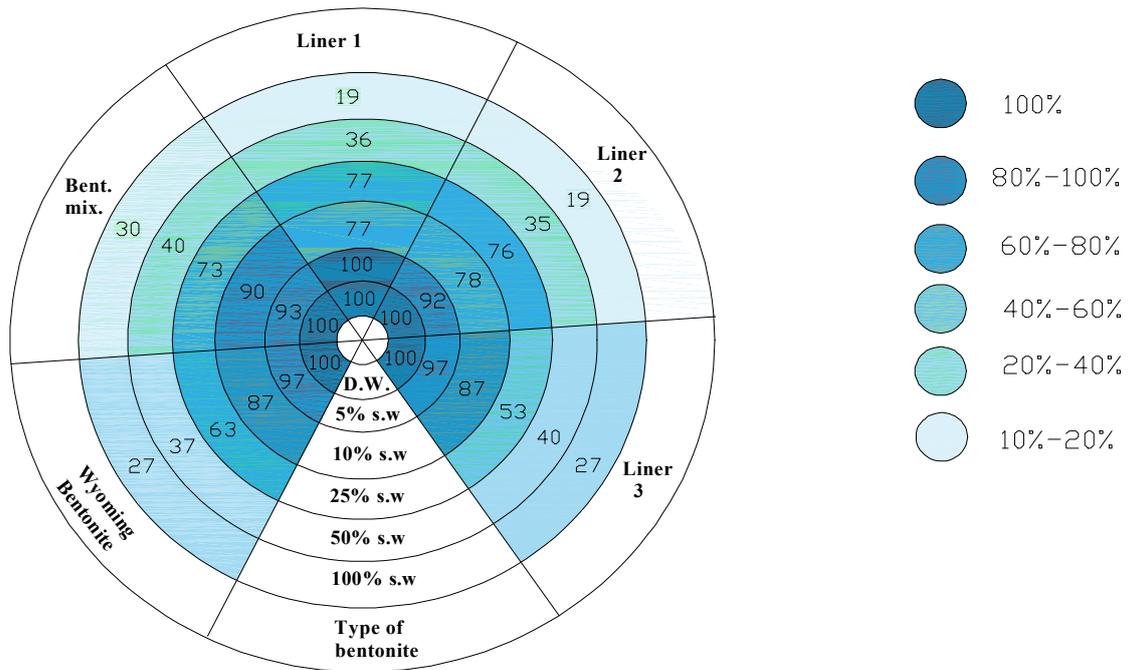


Figure 6 – Presentation of Free Swell changes as a percentage of the free swell of the sample in distilled water