Indian Bentonites and Their Use in Diaphragm Walling and Piling

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Introduction

India has rich deposits of bentonites. About 75 million ton of natural reserves have been estimated in Rajasthan, Gujarat, Tamil Nadu, Bihar, Jammu and Kashmir. Their quality however, varies. Some of them are good for bleaching purposes only and do not show high swelling potential which is desirable in stabilising bore holes and trenches. Appendix I lists a few leading suppliers of Indian bentonities. Some firms supply natural bentonite after drying and pulverising. Others claim to produce processed bentonite suited to the specifications laid down by the user. Indian bentonites have found their market in Srilanka, Sudan, Thailand and Italy.

Mineralogy of Bentonites

Bentonite is formed from the decomposition of volcanic ash and is largely composed of the clay minerals montmorillonite. The colour ranges from white to light green and light blue when fresh. On exposure it changes to light cream, yellow and in some cases to brown or red. The crystal characteristics of a bentonite has been extensively investigated. The central octahedrally coordinated gibbsite layer is bonded through oxygen links to the two outer tetrahedrally coordinated silicate layers. Replacement of magnesium for aluminium in the octahedral layer or aluminium for silicon in the tetrahedral layer causes a net deficit of electric charge within the crystal, which is countered by the presence of exchangeable cations located on the clay surface. These exchangeable cations are mobile and can be made to undergo substitution. The surface of a bentonite crystal is negatively charged, and the edge of the crystal has a series of broken bonds and may carry a positive, neutral or negative charge depending upon the environment. Most bentonities have sodium and calcium in the exchangeable position. Addition of water to dry bentonite causes inter-lamellar swelling. The water is absorbed in the space between individual crystals forcing them apart. The calcium exchanged bentonites swell to a limited extent but sodium exchanged bentonites show considerably large swelling. The swelling potential of a bentonite is due to the like electrical charges on the crystal surface, creating a repulsion between surfaces, Figure 1. Swelling takes place normal to the longer dimensions of the crystal. Bentonite suspensions

(a) DRY BENTONITE PARTICLES

(b) PARTLY HYDRATED BENTONITE PARTICLES WITH HYDRATION WATER HELD AROUND PARTICLES

(c) FORMATION OF GEL STRUCTURE BY ATTRACTION OF THE POSITIVE END CHARGES AND NEGATIVE SURFACE CHARGES

(d) BREAKDOWN OF GEL STRUCTURE UNDER SHEAR. GEL STRUCTURE REFORMS WHEN SHEARING FORCE REMOVED

(e) FLOCCULATED OR AGGREGATED STRUCTURE CAUSED BY ELECROLYTES (NaCl) REDUCING REPULSION BETWEEN FLALKES

(f) DISPERSED STRUCTURE CAUSED BY ELECTROLYTES (NaOH) INCREASING REPULSION BETWEEN FLAKES DUE TO REPLACEMENT OF POSITIVE BY NEGATIVE END CHARGES
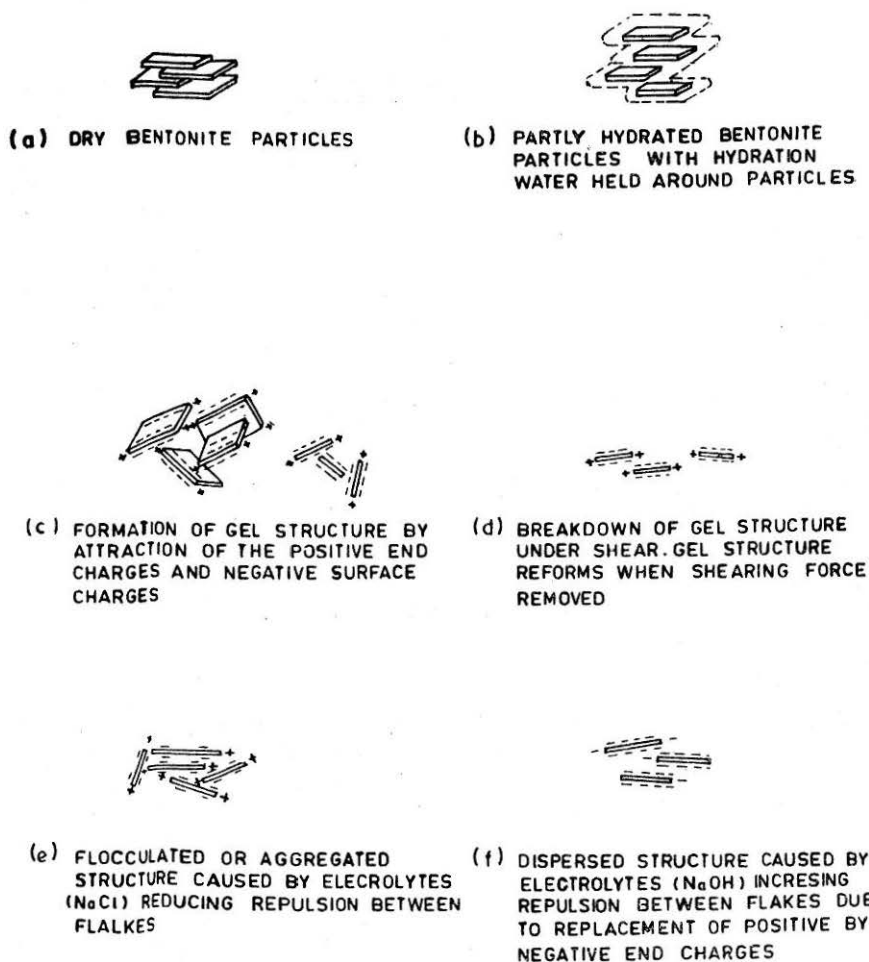
FIGURE 1 Hydration of bentonite powder, flocculation and dispersion of bentonite suspensions

in water containing less than one per cent solids are generally free flowing and may be represented by a newtonian model. But suspensions containing 1-15 per cent solids show anomalous properties represented by a non-newtonian model. The flow of such suspensions, if assumed to be a Bingham body is represented by two parameters viz., Bingham yield stress (τ_0) and plastic viscosity η_{PL}.

At rest, bentonite suspensions undergo thixotropic gelation. If stirred vigorously, the suspension will flow like a liquid. This sol-gel transformation is reversible, and may be repeated indefinitely. Gel strength of a bentonite increases with rest. This has been explained by the presence of negative and positive electric charges on the surface and edges of the bentonite crystal. Leonard and Dempsey (1963) has shown experimentally that for bentonite suspension, Bingham yield value (τ_0) increases linearly with total base exchange capacity, if exchangeable sodium is kept

constant.   They have also shown that τ_0 increases linearly with exchangeable sodium if total base exchange capacity is kept constant.

Physico-Chemical Properties of Indian Bentonites

Seven bentonite samples were analysed for their particle size, Atterberg limits, differential free swell PH value, base exchange capacity, differential thermal analysis, and one sample for X-ray diffraction.   Physical and chemical properties are presented in Table 1 and 2·   They reveal variation in clay content from 62 to 89 per cent; silt content from 7 to 19 per cent; Liquid limit (w_L) from 260 to 412 per cent; Plastic limit (w_p) from 32 to 63 per cent; Plasticity Index from 207 to 363 per cent and Differential free swell (DFS) from 424 to 1100 per cent.

TABLE 1

Sample	Mechanical analysis			Atterberg's limits			DFS	Activity
	Sand	Silt	Clay	W_L	W_P	I_P		A
B_1	3.8	7.1	89.1	412	49	363	1100	4.07
B_2	3.1	14.9	82.0	352	37	315	713	3.84
B_3	4.3	11.4	84.3	330	63	267	567	2.93
B_4	4.4	7.5	88.0	318	51	267	547	3.04
B_5	5.9	12.5	81.6	288	48	240	450	2·94
B_6	3.1	18.9	78.0	268	32	236	433	3.02
B_7	20.2	17.5	63.3	260	53	207	424	3.26

TABLE 2

| Sample	PH value	Total base exchange capacity meq/100 gm	Exchangeable sodiun Na^+ meq/100 gm
B_1	9.1	76.64	55.4
B_2	9.8	64.8	50.8
B_3	8.95	63.5	55.0
B_4	9.0	61.69	57.1
B_5	8.9	43.6	36·0
B_6	9.1	46.4	40.3
B_7	9.3	31.43	—

Differential free swell (*DFS*) per cent $\dfrac{V_2 - V_1}{V_1} \times 100$ per cent

where $V_1 =$ volume of 10 gm of oven dried bentonite powder poured gently in a graduated cylinder containing kerosene.
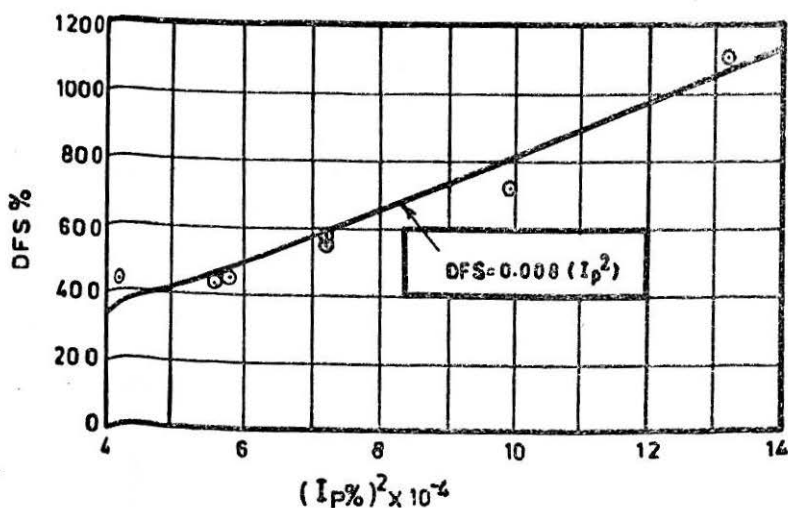
$V_2 =$ volume of 10 gm of oven dried bentonite powder poured gently and slowly in a graduated cylinder containing water.

Both the volumes are read after 24 hours of pouring in the graduated cylinders.

From the test results presented in Figure 2 and 2A the following correlations can be established with errors not exceeding $\pm$ 10 per cent.
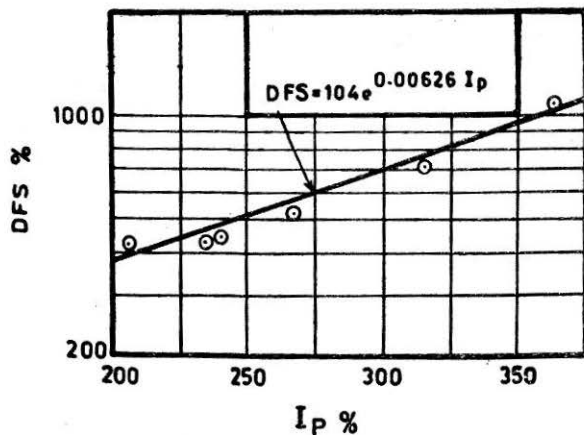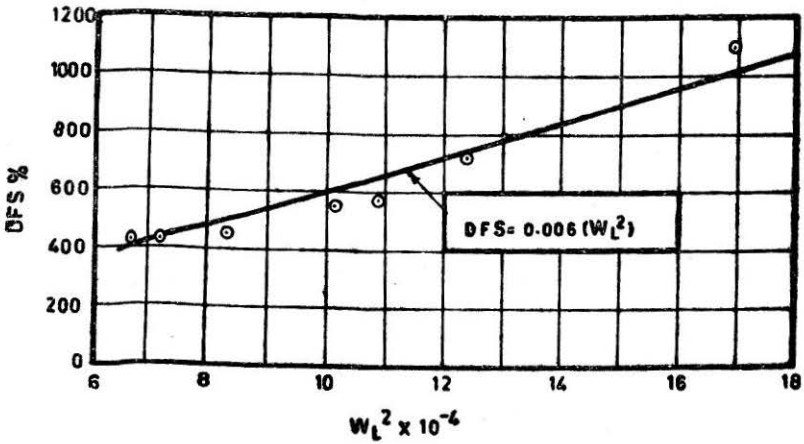

(a)

(b)

FIGURE 2 (a) Differential free swell *vs* plasticity index
FIGURE 2 (b) Differential free swell *vs* square of plasticity index
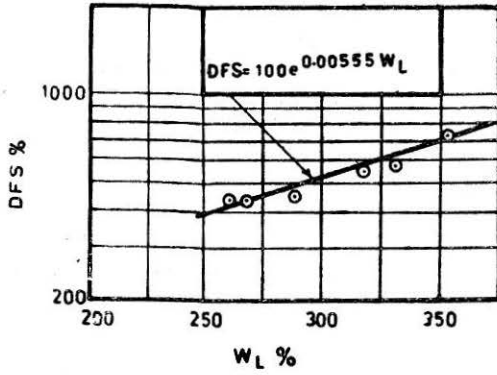
(a)

(b)

FIGURE 2A (*a*) Differential free swell *vs* liquid limit
FIGURE 2A (*b*) Differential free swell *vs* square of liquid limit

$$DFS = 104 \, e^{0.00626 I_p} \qquad \qquad ...(1)$$

$$DFS = 100 \, e^{0.00555 WL} \qquad \qquad ...(2)$$

Or more simply, these can be written as follows:

$$DFS = 0.006 \, w_L^2 \qquad \qquad ...(3)$$

$$DFS = 0.008 \, I_P^2 \qquad \qquad ...(4)$$

Ph Value

The *PH* value of the samples varied from 8.9 to 9.8 as against the specified desirable range 9 to 11.5 indicating need for 'additives' to ensure better dispersion. Small percentages of additives such as sodium hydroxide or sodium carbonate may be used to improve *PH* value.

Total Base Exchange Capacity (BEC)

Total *BEC* of the samples ranged between 31 to 76 meq per 100 g. Total BEC of good bentonites generally vary between 80 to 100 meq per 100g. The lower values found in Indian Bentonites are attributable to relatively smaller percentage of montmorillonite and greater proportions of non clay minerals like silicates. Separation of clay mineral from non clay mineral call for processing of bentonites, which. if resorted to will improve the *BEC*. Exchangeable sodium of the bentonite samples was found to vary from 36 to 57 meq per 100g of clay.

Differential Thermal Analysis (DTA)

Theremograms shown in Figure 3 indicate the presence of endothermic
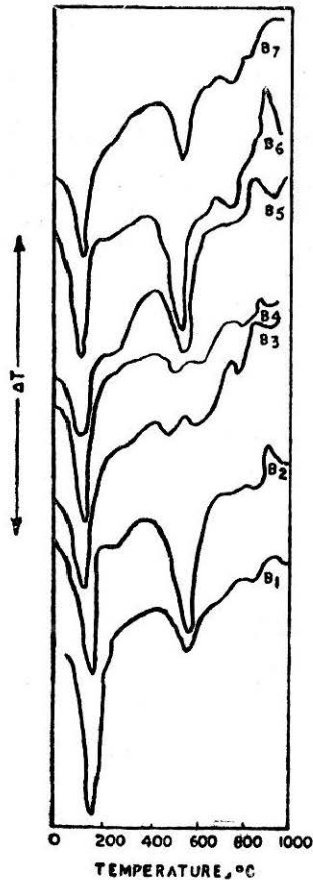

FIGURE 3 Thermograms of bentonite samples

peak at 140-160°C followed by a larger peak at 550-580°C. The first peak indicates the loss of hydroscopic moisture and the second represents the loss of hydroxyl water of minerals.

In samples B 6 and B 7, the peak is widened upto 700°C indicating the presence of montmorillonite and kaolinite. The exothermic effect due to break down of crystal structure appears in the range of 900-950°C These thermograms compare well with those reported by Mackenzie (1957) and Grim (1962) for montmorillonite samples, the only difference being that dehydroxylation temperature for all the samples is lower than generally reported. This appears to be due to the presence of iron, besides Kaolinite. Samples B1, B3, B6 and B7 show presence of fairly high proportion of montmorillonite while in samples B2, B4 and B5 appreciable quantities of Kaolinite and quartz are indicated in addition of some montmorillonite.

X-Ray Analysis

X-ray analysis of sample B2 confirms the presence of montmorillonite along with some kaolinite and quartz.

Bentonite Suspensions

In order to establish relationships between concentration percentage, density of suspension, Marsh funnel viscosity, plastic viscosity and Bingham yield value, homogeneous suspensions of bentonite samples were prepared in the laboratory at room temperature of $20° \pm 2°C$. The tests were performed immediately after stirring to avoid the effects of thixotrophy. Figure 4 depicts the relationship between density (γ_s) of fresh slurry and concentration percentage (C). It can be written

$$\gamma_s = 1.0 + 0.006 \ C \qquad \qquad \text{... (5)}$$

γ_s = density of fresh slurry (g/ml)

C = concentration of bentonite (per cent)

Viscosity (η) of bentonite slurries were determined at different densties using Marsh funnel (Boyes 1975). The results are presented in Figure 5. Density of bentonite suspensions are found to decrease with increasing *DFS*, for the same viscosity of suspension, Figure 6. The following relationship has been found to fit the test data:

$$\gamma_s = 1.06 + \eta \times 10^{-5} \ (80 - 0.0125 \ DFS) - 4.5 \times 10^{-5} \ DFS \qquad \text{... (6)}$$

The equation 6 indicates that the Marsh funnel viscosity (η) of a bentonite of given quality (*DFS*) can be increased by increasing the density of the slurry (γ_s). This equation wll prove useful to field engineers in computing the density of slurry (γ_s) required for the bentonite available at the site to achieve the specified value of Marsh funnel viscosity.

Rheological Properties

Bingham Yield Value (τ_o)

Flow characteristics of freshly prepared suspensions of B2,B6 were determined for 2.5 to 10 per cent concentrations at 20°C+2°C using
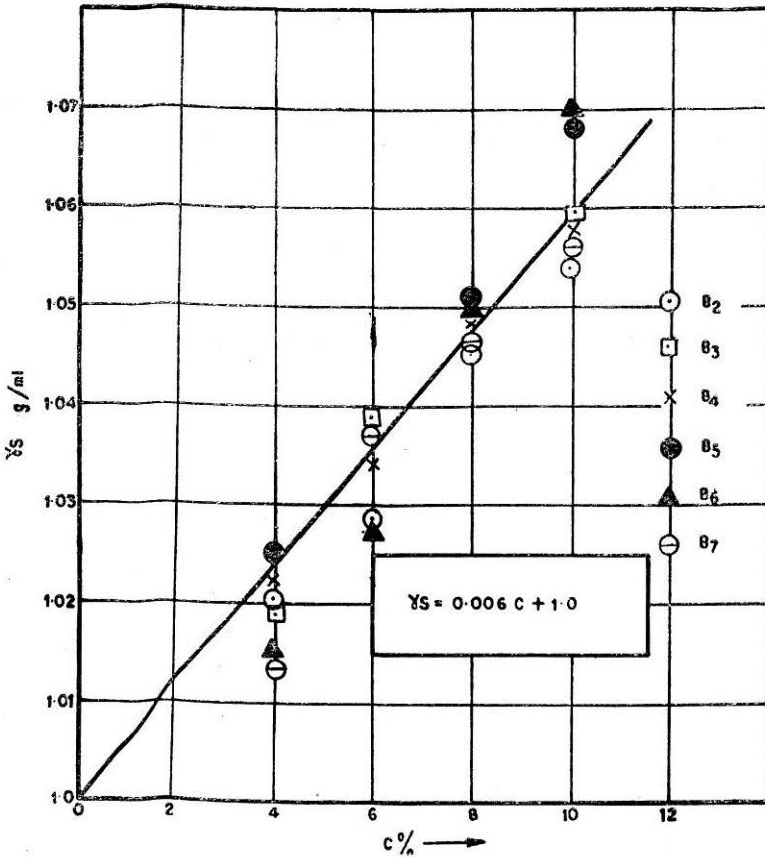
FIGURE 4 Density of slurry *vs* concentration

Brook-field rotational viscometer. The results are shown in Figure 7. It can be seen that τ_o for B2 varies from 1 to 31 dynes/cm² as the concentration varies from 2 to 7 per cent. For B6 suspension, values of τ_o increased from 1 to 23 dynes/cm² as concentration varied from 5 to 10 per cent. The value of τ_o is therefore seen to increase with the quality of bentonite and concentration.

Plastic Viscosity (η_{PL})

Plastic viscosity values were also measured for samples B2 and B6 (Figure 8). The values for samples B2 are in the range of 15 to 50 c.p. for concentrations varying from 2.5 to 7.5 per cent. For sample B6, η_{PL} varies from 10 to 27.5 c.p. for concentration ranging from 2.5 to 7.5 per cent. The data indicate increase of η_{PL} with the quality of bentonite and concentration.

Ten Minute Gel Strength

10 Min-Gel strength values were measured for samples B1, B3, B5 and B6. The results are shown in Figure 9. With the increase in density
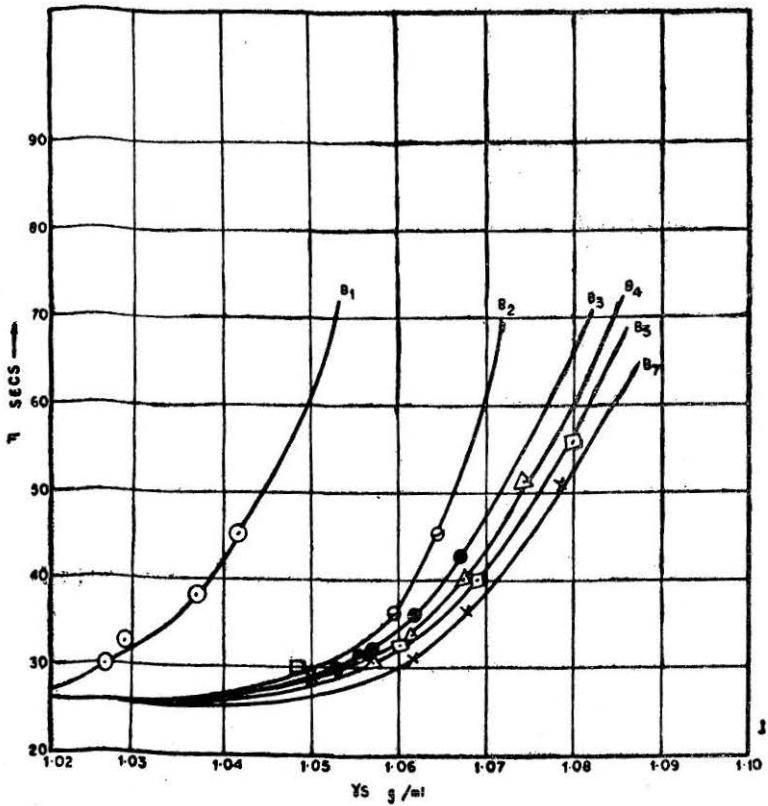
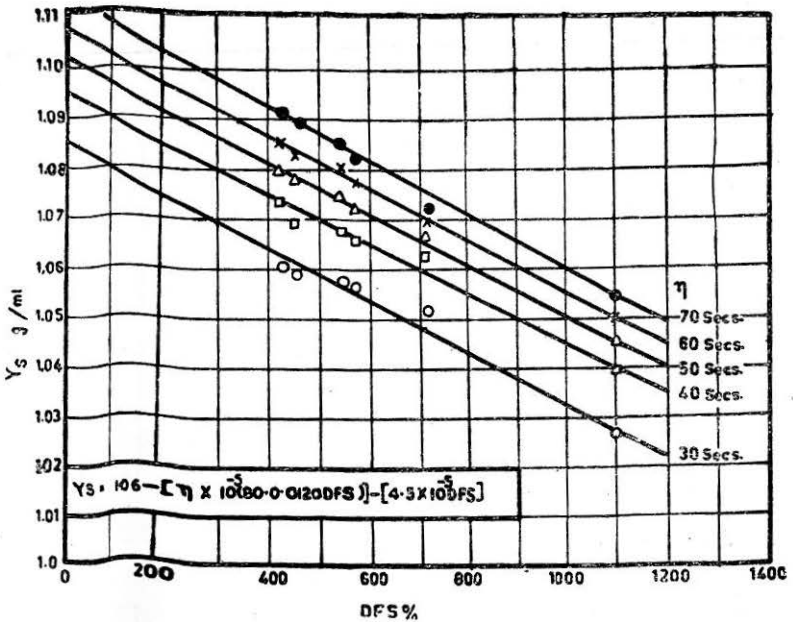FIGURE 5 Mooish funnel viscosity *vs* density of suspensions

FIGURE 6 Density *vs* differential free swell for different Marsh funnel viscosities
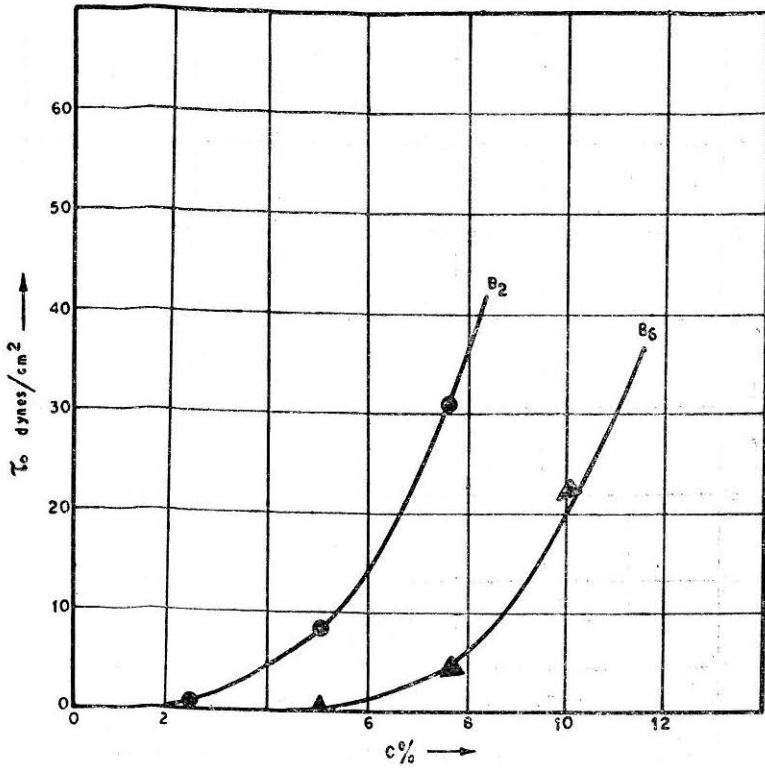
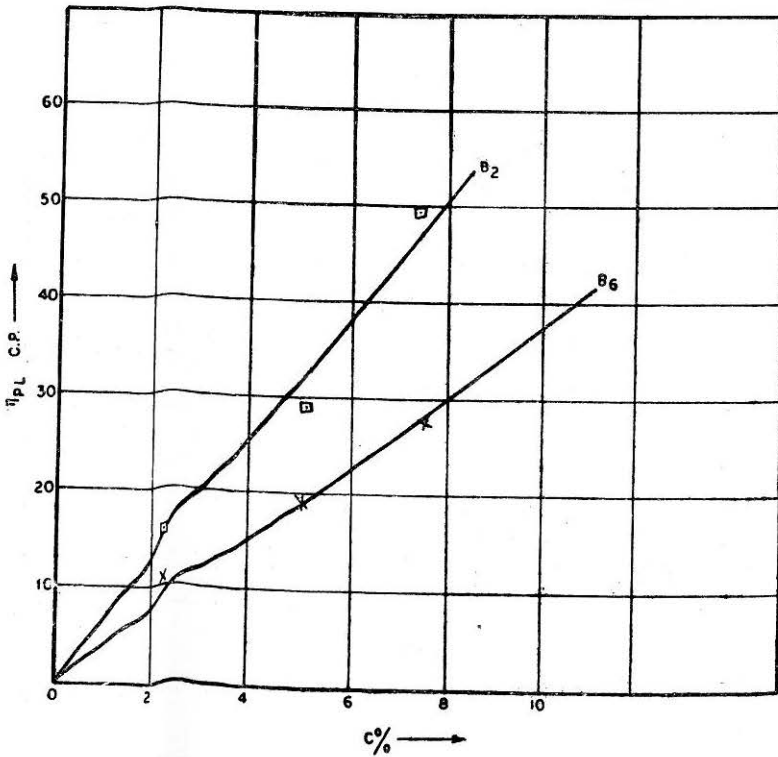FIGURE 7   Bingham yield stress *vs* concentration of slurries

FIGURE 8   Plastic viscosity *vs* concentration of slurries

of suspension, 10 min. Gel strength was found to increase. The gel strength values are higher for superior quality bentonites. For sample B1, the value of strength is greater than 60 dyne/cm^2 even at a density of 1.037 gm/ml. Preferable values of 10 min. Gel strength for bentonites in the construction work range between 50-200 dynes/$cm.^2$ For sample B6, which is of poor quality the value of 10 min Gel strength is only 6 dynes/cm^2 at the density of 1.037 gm/ml. The values of density required for 50 dynes/cm^2 gel strength for B1, B3, B5 and B6 samples respectively are 1.035, 1·0425, 1.05 and 1.06 gm/ml.

Effect of NaOH and NaCl

Effect of NaOH was studied on the values of Marsh funnel viscosity η. Bentonite sample B2 was mixed with 0.25, 0.50 and 1.0 per cent of NaOH weight of bentonite powder. Slurries of different densities were prepared and Marsh funnel viscosity η values were measured. The results are shown in Figure 10. It is revealed that NaOH addition improves the value of Marsh funnel viscosity. One per cent NaOH could give a η value of 50 sec. at a density of 1.036 gm/ml, which in original sample could have been attained at a density of 1.067 gm/ml. This indicates the possibility of saving in bentonite powder by treating it with NaOH.

Bentonite sample B1 was mixed with 1 to 4 per cent NaCl by weight of bentonite powder. This was then mixed with water to form bentonite
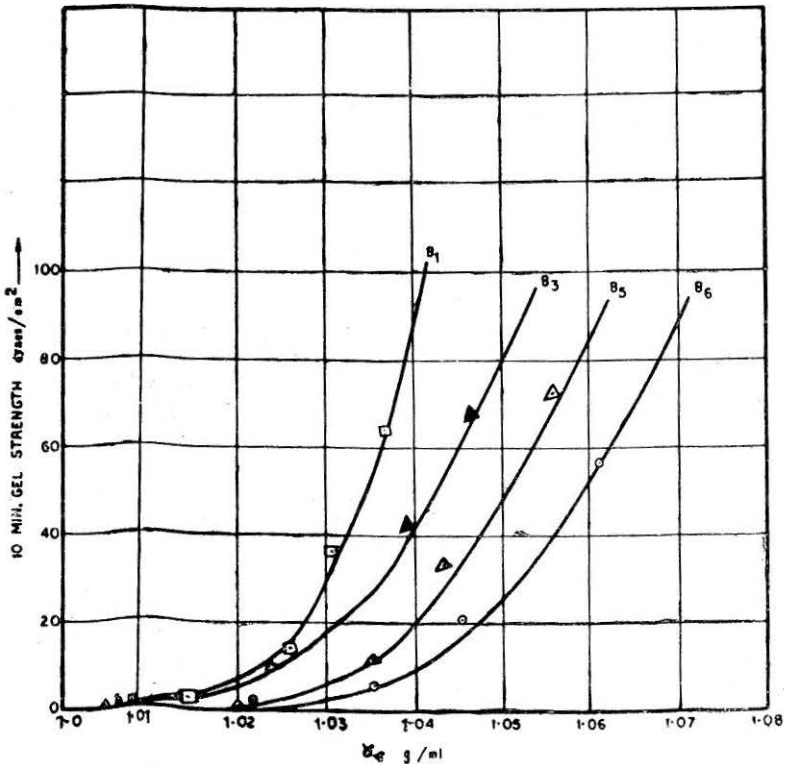

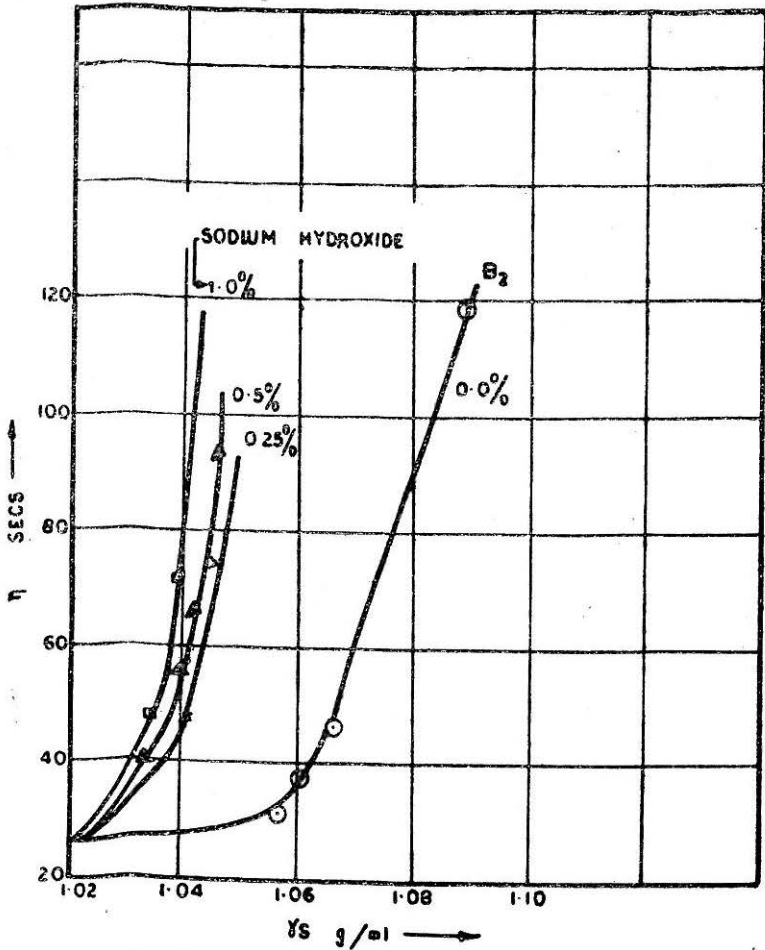FIGURE 9   10 minutes gel strength *vs* density

FIGURE 10   Effect of sodium hydroxide on Marsh funnel viscosity

suspensions of different densities. The suspensions were tested for Marsh funnel viscosity values. The results are shown in Figure 11. It can be seen that presence of only 1.0 per cent NaCl increases the viscosity. Further increase of NaCl reduces the value of viscosity. Higher the value of NaCl, the higher is the reduction in viscosity. At a density of 1.032 gm/ml, the value of viscosity for 1, 2, 3 and 4 per cent NaCl were respectively 42 sec., 36 sec, 31 sec. and 28 sec.

Saline water, or NaCl when present as an electrolyte in the slurry acts as a flocculant as shown in Figure 1 and affects adversely on the viscosity of slurry. On the contrary NaOH acts as a dispersent Figure 1. It improves the pH value and viscosity of the slurry. Therefore, it can be used as an additive to improve the quality of otherwise poor bentonites.

Guidelines for Field Engineers in the Selection of Bentonites

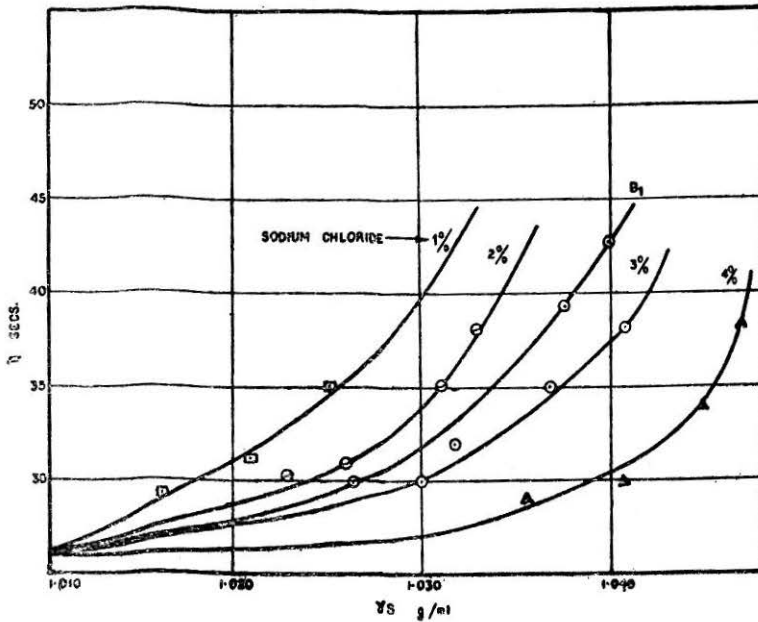The properties of bentonite powder which can be easily tested in a

FIGURE 11   Effect of sodium chloride on Marsh funnel viscosity

field laboratory are clay, silt and sand contents, Atterberg's limits and differential free swell. Chemical tests like base exchange capacity, exchangeable sodium percentage or DTA etc. are generally difficult and time consuming and can not be done in a field laboratory. For a medium quality Indian bentonite, probable values of different properties of powder and slurry are given in Table 6. To use a superior sample is more economical and safe. The slurry used should be stable and water should not separate out from the free standing slurry.

Guidelines for Preparation of Bentonite Slurry

After selecting a suitable bentonite powder, the next step is the preparation of bentonite slurry. Water used for this purpose should be free of impurities. Salt water should be generally avoided and ordinary tap water favoured. Predetermined quantity of bentonite powder should be added to a known volume of water and mixed properly to form a fully hydrated, homogeneous and lump free slurry. This may be done in shortest possible time with the help of suitable mixer. Better the quality of bentonite, greater is the dispersive effort required to produce a slurry of optimum rheological properties. Boyes (1975) has described a few slurry mixing plants and one is shown in Figure 12. The design of filter nozzle was made by Prepakt Ltd. (U.K.). Using this plant, base exchanged bentonites could be made to form lump free suspension within 5-10 minutes. Improved mixing chuld be obtained by using special high shear blending machines such as Silverson mixer. This has been successfully used to form carboxy-methyl-cellulose-water solution for diaphragm walling work. Premier colloid mill has also been found useful in diaphragm walling work.
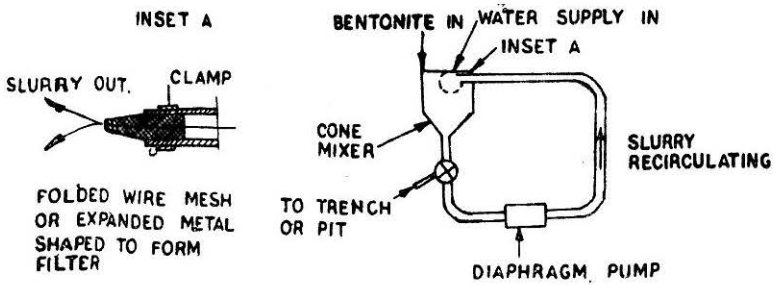
FIGURE 12   A typical slurry mixing plant

The colcrete mixer has proved very successful in mixing bentonite slurries (Figure 13). Bentonite suspensions using high BEC bentonites, have been formed in only 2 minutes. This mixer has also successfully dispersed polymer treated sodium bentonite.
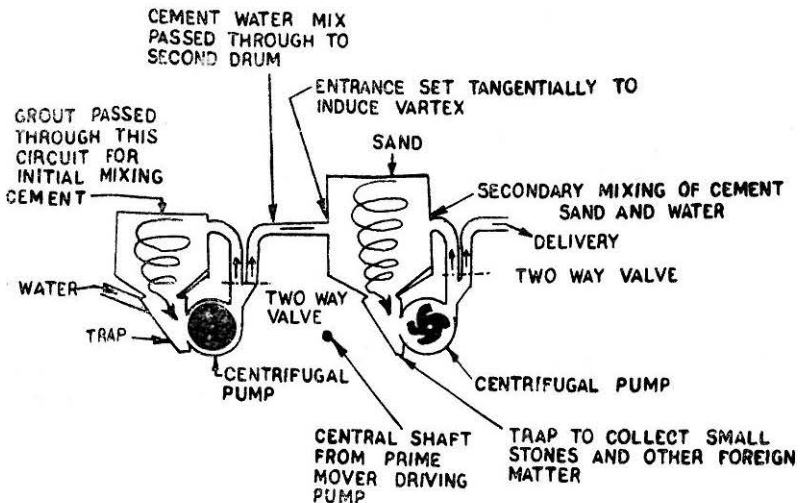
FIGURE 13   Colcrete double drum colloid grout mixer

Requirements of Bentonite Slurry

The functions of a bentonite slurry when used in piling or diaphragm walling are :

— to exert fluid pressure on the walls of borehole or trench and prevent it from collapsing.

— to form a filter cake on the walls without permeating into the subsoil.

— to suspend detritus to avoid sludgy layers building up at the base of the excavation or borehole.

— should get displaced by tremie concrete leaving no trace on reinforcement or within the poured concrete.

— recycling should be possible after screening or hydrocycloning to remove detritus.

— should be easily pumpable.

Sliwinski and Fleming (1975) have shown that use of poor quality suspensions in the construction of diaphragm walls may cause trouble. Excessive overbreaks and cavities may occur below guide wall. This may be due to shallow guide walls, high water table or insufficient head of bentonite coupled to a low viscosity suspension having low gel strength. The bentonite filter cake may build up quickly and become thick and porous. According to Hutchinson et. al. (1975), a slurry which forms a good filter cake on the wall of an excavation (to enable the hydrostatic pressure of the mud to be exerted for stabilization of the face) may be too resistant to flow, hindering clean displacement while tremie concreting. On the other hand, a slurry which is easily displaced may not build a suitable filter cake. A dense slurry which is suitable for exerting a large hydrostatic pressure for stabilization may become trapped in the bottom of the trench or borehole. For freshly prepared and hydrated bentonite slurry, there is a fairly well defined concentration limit below which the rate of filter cake build up is slow and an upper limit above which the slurry is difficult to handle.

Excessive loss of bentonite may occur in pervious strata causing filter cake formation to be poor or non-existent. Loss of bentonite can also be due to low viscosity and low gel strength. Hutchinson et. al. (1975) have suggested that conventional fluid loss test is irrelevant. A new test which substitutes actual site material for filter paper should be used to simulate the field conditions. Unless the laboratory and the field conditions are identical, the cake forming ability and fluid loss of a slurry do not give meaningful results.

Veder (1975) reports a simple apparatus for studying the fluid loss at low pressures by using site material instead of standard filter paper under high pressure. Veder's device to study the displacement of bentonite cake while pouring the concrete is also noteworthy.

Tremie concrete may not fully displace bentonite, if the density, viscosity, and gel strength of bentonite are too high. The suspension must be displaced easily from the bottom of the trench, from around inserts, boxes, reinforcement and panel joints and the walls of a trench, otherwise, low skin friction, low bearing at the base, reduced bond strength of reinforcement with concrete, cavities around inserts and boxes, leaky joints and other allied problems may arise. These have been discussed by Anon (1967). Therefore, density of the suspension near the base of the trench should be less than 1.25 gm/ml. In order to ensure quality finish, good quality control on the properties of bentonite should be exercised. This will also reduce trouble of failures of trenches as also uneconomical use of bentonite suspensions.

Contamination by detritus, ground water or cement can drastically alter the properties of bentonite slurry. Limits within which the slurry can be used from practical considerations must therefore be specified. These limits must be wide enough to suit the requirements of stability, often determined from analytical considerations.

Specifications of Bentonite Slurry

The Federation of Piling Specialists (FPS) specification (Table 3) consider only four properties of bentonite clay to be adequate for practical purpose. These properties are density, Marsh funnel viscosity, pH value and 10 Min. Gel strength. But Hutchinson (loc cit) has also considered the importance of sand content and plastic viscosity. He considered Marsh funnel viscosity as a qualitative test only. His recommendations are comparatively elaborate but do not take into account the test concerning fluid loss and filter cake thickness although he has made a mention of these and other tests in the summary of tests to determine properties of bentonite slurry (Table 4). Hodgson (1975) during construction of diaphragm wall at Victoria street London, tested the bentonite slurry more rigorously for control and reuse. He included the tests for measurement of apparent viscosity, Bingham yield value, and fluid loss (Table 3). He concluded that the time and cost involved in site testing of bentonite for quality control was small. Littlejohn, (Table 5) has only quoted the density range of bentoitne slurries used successfully in different types of strata in actual field works.

TABLE 3. Specifications of Bentonite Slurry used in Diaphragm Wall Construction

Property	FPS specifications	Hutchinson et. al. (1975)	Hodgson (1975)
Marsh funnel viscosity (sec)	30—90	—	32—35
Plastic viscosity (cp)	—	20	12—30
Bingham yield value (dyne/cm²)	—	—	24—144
Density (gm/ml)	< 1.10	1.034—1.25	1.02—1.09
10 Min Gel strength (dyne/cm²)	14—100	50—200	48—192
Sand content (percentage)	—	1.0—25.0	<5
pH value	9.5—12	<11.7	10—12
Fluid loss (cm³)	—	—	11—15
Concentration (percentage)	—	>4.5	—

Reuse of Bentonite Slurry

The bentonite slurry used in the construction of one pile or diaphragm wall panel, may be reused in other piles or panels provided it is not contaminated and passes the prescribed specifications. If after testing, the slurry is found unfit, it is either rejected or treated for reuse. The treatment may be mechanical or chemical or both. Vibrating screens and hydrocylones are the mechanical devices which make the slurry free of silt and sand contamination. For small quantities of large size particles of

present in the slurry pits and holding tanks may be dug at the site to separate out the coarser particles, The depth of the pits should be about 1.5m and sides should suitably slope, say 1 in $2\frac{1}{2}$. Some of the useful chemical additives used for treatment are listed below :

TABLE 4 Summary of Tests to Determine Properties of
Bentonite Slurry (following Hutchinson 1975)

Property	Definition	Current test method
Concentration	Kg of bentonite dry powder added in 100 kg of water	—
Density	Mass of unit volume of slurry	Mud balance
Marsh cone viscosity	Time in seconds for a fixed volume of slurry to drain from a standard cone	Standard Marsh cone as used by drilling companies
10 min/gel strength	Shear strength attained by the slurry after quiescent period of 10 min. (Slurry violently sheared before starting)	Fann viscometer, falling tube shearometer
pH	Logarithm of the reciprocal of the hydrogen ion concentration	pH meter, pH paper strips
Sand content	Percentage of sand in suspension greater than 200 mesh	200 Mesh screen.
Fluid loss	Volume of fluid lost in set time from fixed volume of slurry when filtered at set pressure through standard filter medium	Standard fluid loss apparatus, 600cc of slurry filtered at 100 lbs/in^2, for 30 min. through filter paper.
Filter cake thickness	Thickness of filter cake built up under standard filtering condition	Measure filter cake built up in fluid loss test.
Bingham yield stress, plastic viscosity and apparent viscosity	For a bentonite slurry (behaving as a Bingham body) under shearing conditions	Faan viscometer

$$\tau = \tau_o + \eta_{PL}\varepsilon$$
where τ = shear stress
τ_o = Bingham yield stress
η_{PL} = plastic viscosity
ε = shear rate
apparent viscosity
$$\eta_{AP} = \frac{\tau}{\varepsilon}$$

Boyes 1975 has described the equipments and test method in greater details

1. Sodium carboxy-methyl-cellulose (SCMC) is used at 0.1 per cent concentration of slurry and 10 per cent water dilution is carried out. This counteracts 20 per cent or more silt intermixed into the slurry. Sodium fuminate may also be added along with SCMC.

2. For sea water contamination, ferrochrome-lignosulphonate is used as an additive. Because its *pH* value is 3.5, it should be used with sodium hydroxide, caustic soda or chrome lignite. This is also effective for reducing calcium concentration due to cement contamination.

3. Sodium Phosphate is used to counter cement contamination by removing calcium and dispersing clay.

4. Sodium bicarbonate and sodium carborate are used to precipitate calcium and magnesium hardness.

5. Presheared asbestos in granule from is used for viscosity building and filter loss control.

6. Starch, on absorbing water becomes spongy and helps in plugging the openings in the filter cake.

7. Tannins and Lignins are used for calcium contamination and as dispersants.

Sampling and Checking the Quality of Bentonite Slurry

During the excavation of a bore hole or trench in the ground, bentonite slurry is pumped in but before doing so, the properties of the slurry given in Table 3 are tested and control of the properties is exercised by sampling and testing the slurry from time to time.

TABLE 5 Specifications of Bentonite Slurry used in Diaphragm
Wall Construction (after Little John 1971)

Strata	Density of Slurry used g/ml
Cobbles in hard clay	1.05—1.10
Sand and Gravel	1.10—1.24
Sand—Silt	1.15
Shale, gravel sand and stone	1.15—1.20

The slurry supplied to the borehole or trench gets contaminated with cuttings and detritus materials and its properties get modified. This may result in instability of the bore hole or trench, reduced bond of reinforcement and poor strength of concrete itself. It may also result in inadequate displacement of sludgy layers near the bottom of the trench which brings down the bearing capacity of pile or diaphragm wall foundation and may cause leakages near the inserts, boxes, joints *etc*. The problem of excessive over breaks and cavities near the bottom of guide walls may also arise. Therefore, sampling of bentonite slurry near the bottom (about 0.2 m from the base of bore hole or trench) may be done using suitable sampler Figure 14).
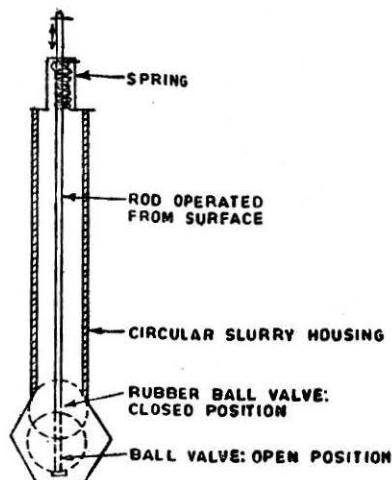
FIGURE 14 A typical slurry sampler tube

If the properties of slurry tested are found to be out of the specified range, the slurry should be replaced and concreting commenced only after fresh slurry of desired properties has fully replaced the contaminated slurry. This may be checked by testing the slurry flowing out of the pump. Bentonite sampling, testing and field control therefore, plays a vital role in producing quality work. It also helps in economical use of bentonite. When the slurry is too contaminated to be fit for reuse, it is cleaned by mechanical or chemical treatments. If the cost of treatment is too high, it is sent for disposal.

TABLE 6

Properties of an average Indian Bentonite Sample

Sl. No.	Property	Probable value
	Powder	
1.	Clay content	About 82 per cent
2.	Silt and sand content	About 18 per cent
3.	Liquid limit (WL)	About 350 per cent
4.	Plastic limit (WP)	About 35 per cent
5.	Plasticity Index (PI)	About 315 per cent
6.	Differential free swell (DFS)	About 710 per cent
	Slurry	
7.	Density (γ_s)	About 1.03 to 1.06 gm/ml
8.	Concentration (C)	5 to 10 per cent
9.	Marsh funnel viscosity (η)	27-37 secs
10.	PH value viscosity (η)	8.5-9.0
11.	Bingham yield stress (τ_0)	10-50 dynes/cm²
12.	Plastic viscosity (η_{PL})	30-60 c.p.
13.	10 min gel strength	20-100 dynes/cm²

Concluding Remarks

1. Quality of Indian bentonites, as revealed by the study of their physical, physico-chemical, chemical and rheological properties, vary considerably and ranks below those of the Wyoming bentonite of USA or other base exchanged bentonites reported in the literature. Nevertheless these are suitable for diaphragm walling ahd bored piling in as much as most of them qualify the minimum stipulated standards for such use.

2. Differential free swell constitutes one of the most simple and important test for determining the suitability of bentonites. The differential free swell (DFS) is related to Liquid limit (W_L) and Plasticlty index (I_p), with errors not exceeding $\pm$ 10 per cent, in the following manners:

$$DFS = 104\ e^{0.00626I_p}$$

$$DFS = 100\ e^{0.00555W_L}$$

Also, if the DFS and Marsh Funnel viscosity η specified for a particular purpose are known, the minimum density of slurry (γ_s) required can be calculated using the relationship.

$$\gamma_s = 1.06 + \eta \times 10^{-5}\ (80 - 0.0125\ DFS) - 4.5 \times 10^{-5}\ DFS$$

Once required density of slurry is known, the quantity (C) of the powder to be added can be calculated using the following relationship:

$$\gamma_s = 1.0 + 0.006\ C$$

3. Quality of a bentonite and its quantity required for preparing drilling mud of particular specifications are intimately related. Consumption of bentonite can be reduced considerably, if quality is improved by suitably processing the powder and field checks are exercised in using no more than specified quantity. Also, during construction of diaphragm walls or bored piles, sampling, testing and quality control of bentonite slurry to be pumped or already present in the trench or borehole deserve due attention. The guidelines to field engineers on sampling, use and reuse of bentonite slurry have been provided in the paper.

Acknowledgements

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Appendix-I

Manufacturers of bentonite powder

1. M/s Industrial Minerals and Chemical Co. P Ltd., 125, Narayan Dhuru Street, Nagdevi, Bombay-400003.

2. M/s Bharat Pulverizing Mills P. Ltd., Hexamer House, 28-A, Sayani Road, Bombay-28.

3. M/s Ambica Minechem Industries, 21, Industrial Plot, Madhia Road, Bhavnagar, Gujarat.

4. M/s Balco, 4859, Harbans Singh Street, 24, Darya Ganj, Delhi-110006.

Notations

A = activity of bentonite

C = concentration of bentonite slurry per cent

γ_s = density of bentonite slurry, gm/ml

DFS = differential free swell, per cent

W_L = liquid limit, per cent

W_P = plastic limit, per cent

I_P = plasticity index, per cent

η = Marsh funnel viscosity, secs.

η_{AP} = apparent viscosity, centi poise

η_{PL} = plastic viscosity, centi poise

τ = shear strss, dynes/cm^2

τ_0 = Bingham yield stress, dynes/cm^2

ε = shear rate, sec^{-1}.

BEC = base exchange capacity, meq per 100 g.