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Testing of Bentonite Suspensions

von

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Vorwort des Herausgebers

Der Beitrag geht auf ein Forschungsvorhaben des Instituts mit dem Thema "Filtratwasserabgabe als Gütekriterium der Stützflüssigkeit bei der Herstellung von Schlitzwänden" zurück. Diese Forschung wurde bereits 1977 im Auftrag des Instituts für Bautechnik, Berlin (Gesch. Z. IV/1-5-167/77) begonnen und im August 1980 mit Schlußbericht abgeschlossen.

Die Notwendigkeit des untersuchten Problems stellte sich damals im Rahmen der DIN-Normarbeit zu Schlitzwandkonstruktionen. Mit dieser Forschungsarbeit gelang es, das Synärese-Phänomen von Stützflüssigkeiten mit Hilfe von Zentrifugalversuchen zu beobachten und zu beschreiben und aus den Ergebnissen Rückschlüsse auf die Filtratwasserabgabe bzw. auf die Stabilität dieser Suspensionen zu ziehen. Obwohl diese Versuchstechnik nicht in die Norm einging, behalten die Ergebnisse der Forschungsarbeit ihren wissenschaftlichen und auch praktischen Wert, so daß sie nachträglich in erweiterter Auswertung ihre Veröffentlichung in diesem Heft der Schriftenreihe finden.

Die Publikation stammt aus der Feder von Herrn Dr.-Ing. K. S. Maini und erfolgt in seiner Muttersprache, um die Originalität zu bewahren. Die vorangestellte deutsche Zusammenfassung informiert über Zweck und Inhalt der Untersuchungen sowie über die wesentlichen Ergebnisse.

München, im September 1987 R. Floss

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A b s t r a k t

Zweck und Inhalt der Untersuchung

Zur Zeit gibt es keine Untersuchungsmethode zur Bestimmung der Stabilität einer Suspension, deren Ergebnis in einer auch für Entscheidungen an der Baustelle akzeptablen Zeit zu erhalten wäre. Um diese Lücke zu schließen, wurde versucht, die Stabilität im verstärkten Schwerefeld einer Zentrifuge zu untersuchen und die Ergebnisse mit üblichen Sedimentationsversuchen und Filterpressversuchen zu vergleichen.

An zwei Baustellen sind Suspensionsproben entnommen worden, um mit Hilfe verschiedener Laborversuche die Eigenschaften der an den Baustellen angemischten und bereits gebrauchten Suspensionen erfassen zu können. Insgesamt sind auf den beiden Baustellen drei Bentonitarten (Tixoton, Ultragel und BI) verwendet und untersucht worden. Auch die Auswirkung der Art des Mischens auf die Stabilität von Suspensionen wurde untersucht, und zwar durch vergleichende Versuche an Bentonitsuspensionen, die in den Betriebseinrichtungen der Baustellen beziehungsweise im Labor aufbereitet worden sind. Außerdem wurden zusätzlich zu den üblichen Routine pH-Tests Messungen der elektrischen Leitfähigkeit vorgenommen.

Das spezifische Gewicht der Schlitzwandsuspension wurde an Proben aus unterschiedlichen Entnahmetiefen ermittelt. Nomogramme und Tabellen, mit denen der Sandgehalt einer Suspension an der Baustelle ermittelt werden kann, sind beigefügt.

Für den Bau von Schlitzwänden werden auch Zusatzmittel in den Bentonitsuspensionen verwendet, um die Viskosität zu erhöhen und die Flüssigkeitsabscheidung zu vermindern. Die Wirkung eines solchen Zusatzmittels "Antisol" wurde untersucht. Die Untersuchungen wurden auch auf ein anderes Zusatzmittel "Tricosal", das üblicherweise nicht im

Schlitzwandverfahren, sondern in der Beton- und Injektionstechnik verwendet wird, erweitert. Durch Zusatz dieser Mittel verändert sich die Thixotropie von Suspensionen. Untersuchungen im Rotationsviskosimeter mit steigendem und fallendem Schergeschwindigkeitsgefälle dienten der Aufklärung dieses Phänomens.

Ergebnisse und Schlußfolgerungen

Aufgrund der Untersuchungen sind folgende Ergebnisse von Interesse:

1. Ein neues Untersuchungsverfahren in Form von Zentrifugalversuchen wird vorgestellt. Die Ergebnisse zeigen, daß Sedimentations- und Synäresevorgang beschleunigt werden können und daß eine Drehgeschwindigkeit der Zentrifuge von 500 U/min für eine Dauer von 10 Minuten ähnliche Ergebnisse zeigt, wie ein Sedimentationsversuch von der Dauer eines Tages. Der Versuch ist einfach durchzuführen und nach einer Versuchsdauer von 10 Minuten läßt sich über die Stabilität einer Suspension aussagen.
2. Für reine Bentonitsuspensionen kann als Kriterium zwischen stabilen und unstabilen Suspensionen eine Filtratwasserabgabe im Filterpreßversuch von $f_{7,5} = 20\ cm^3$ angegeben werden.
3. Die Ergebnisse der Zentrifugal- und Filterpreßversuche zeigen, daß in der Supraton-Anlage die Aufbereitung , die bei einer Tourenzahl von 2950 U/min mit einem Durchsatz von 20 m^3/h erzielt wird, für Thixoton und BI ausreichend ist. Im Fall von Ultragel ist sie nicht ausreichend und eine zusätzliche Energie erforderlich, um volle Dispergierung und Ausquellung zu erreichen. Filtratwasserabgabe und Wasserabscheidung der in der Supraton-Anlage aufbereiteten Bentonite Tixoton und BI vergrößerten sich daher bereits nach einmaliger Verwendung, während die gleichen Größen sich bei Ultragel zunächst verbesserten und erst bei mehrmaliger Verwendung anstiegen.
4. Die Messungen von Suspensionsdichten zeigen erwartungsgemäß, daß diese mit der Tiefe zunehmen. Mit steigendem Sandgehalt in der stützenden Flüssigkeit erhöht sich die Dichte. Um diesen Sandge-

halt zu ermitteln, wurden Nomogramme und Tabellen für 3, 4 und 5 %ige Bentonitsuspensionen aufgestellt. Diese Nomogramme und Tabellen erübrigen die Ermittlung des Sandgehalts durch Siebung an der Baustelle. Die Kontrolle des Sandgehalts der Suspension ist bei Schlitzwandarbeiten im besonderen vor dem Betoniervorgang und vor der Wiederwendung gebrauchter Suspension erforderlich.

5. Ein Vergleich zwischen pH-Messungen und Messungen der elektrischen Leitfähigkeit zeigt, daß leztere Unterschiede in Dichte und durch Verunreinigungen genauer anzeigt. Zum Beispiel lieferten 3 bzw. 4 %ige Bentonitsuspensionen pH-Werte von 9,2 bzw 9,3. Die entsprechenden elektrischen Leitfähigkeiten ergaben sich dagegen zu mS = 108 bzw. 128.
6. Mit der Anwendung des Zusatzmittels "Antisol" (normalerweise im Schlitzwandverfahren verwendet) nehmen sowohl der Marsh-Trichter-Wert als auch die Bingham-Fließgrenze zu. Die Filtratwasserabgabe und die Filterkuchendicke (gemessen in der Filterpresse) nehmen ab.
7. Mit der Anwendung des Zusatzmittels "Tricosal" (im allgemeinen in der Beton- und Injektionstechnik verwendet) nehmen sowohl der Marsh-Trichter-Wert als auch die Bingham-Fließgrenze ab. Die Filtratwasserabgabe und die Filterkuchendicke erhöhen sich.
8. Beide Mittel verändern auch die Thixotropie von Bentonitsuspensionen. Die Wirkung der Zusatzmittel auf die Thixotropie wurde mit Hilfe der "Thixotropie-Schleife" veranschaulicht. Die Zugabe von Antisol erhöht die Thixotropie (größere Flächen der Thixotropie-Schleifen). Die Zugabe von "Tricosal" läßt andererseits die Thixotropie abnehmen. Diese Abnahme geht im Falle der 3 %igen BI- und Tixoton- Suspensionen so weit, daß die thixotrope Eigenschaft wegfällt.

1 Introduction

The purpose of this report is to give the main features of a research programme carried out at the Institute of Soil Mechanics and Foundation Engineering of the Technical University of Munich in joint cooperation with the local contractors Held & Francke.

In modern times the use of bentonite slurry is responsible for the spectacular growth of cast-in-place diaphragm walls. The maintenance of the correct slurry properties require that efficient laboratory testing be performed. On the basis of progress made so far it can be said that slurry testing has reached the point where it has developed from an art to a science. In order to provide a check on the properties of the slurry two construction sites (both in Munich) were selected for this project. At the construction site of Bayerische Landesbank two types of bentonite were used, Tixoton (Süd-Chemie) in the beginning phase and Ultragel (International GmbH Duisburg) in the later stage. For the second construction site at Karlsplatz, Tixoton and BI (Erbslöh) were used. All bentonites used here were of the converted type. For the preparation of bentonite slurry Supraton mixers (2950 rpm) were used at both of the construction sites. Samples of bentonite suspensions were taken during different stages and from various depths. They were then tested in the soil-mechanics laboratory of the Technical University Munich.

1.1 Features of the research programme

A bentonite suspension is stable when its constituents do not segregate. This property is generally determined in the laboratory where the suspension is observed in a graduated glass cylinder over a period of 7 days or (though incorrectly) by observing the fluid loss in a filter press. The purpose of the research programme was to see if the stability of the suspension could be tested quickly and effectively in a centrifugal apparatus. In addition, other test were planned to be performed to determine the rheological yield value τ_0, marsh cone viscosity, suspension density ρ_F, and pH-values. A by-product of practical importance later crystalized in the form that sand contents of the slurry could be determined without the sand content test. A part of the follow-up research ist also included, in which the effect of two different additives was studied with particular attention to thixotropy.

1.2 General remarks on slurries and properties of bentonites

For the construction of good quality diaphragm walls bentonite slurries must fulfill the following requirements:

a) Exert stabilising pressure on permeable walls of the trench
b) hold the detritus in suspensions and not allow it to settle down at the excavation base
c) the slurry itself be stable
d) the slurry should allow itself to be displaced by the advancing concrete
e) should allow easy pumping.

It can be seen at a glance that thick as well as very fluid slurries are required simultaneously in order to meet all the requirements listed above. The purpose of testing therefore is to set up the guide lines within which the properties of a given slurry should lie.

In connection with bentonite suspensions the terms suspension, dispersion and hydration are well known. While the suspension and dispersion are time-independent the process of hydration is time-dependent. During hydration more and more water enters the bentonite crystal layers and forces the layers to move apart from each other thus increasing the volume manifold. In comparison to the natural clay the industrial treated bentonites can therefore hold more water in its structural lattice. This phenomenon of increase in volume from dry state to wet state is shown in Fig 1. In addition the industrial activation of the clay forces an increase in the values of liquid limit. It is expected that bentonites with a higher value of liquid limit will also require a longer period of hydration than the ones with lower values.

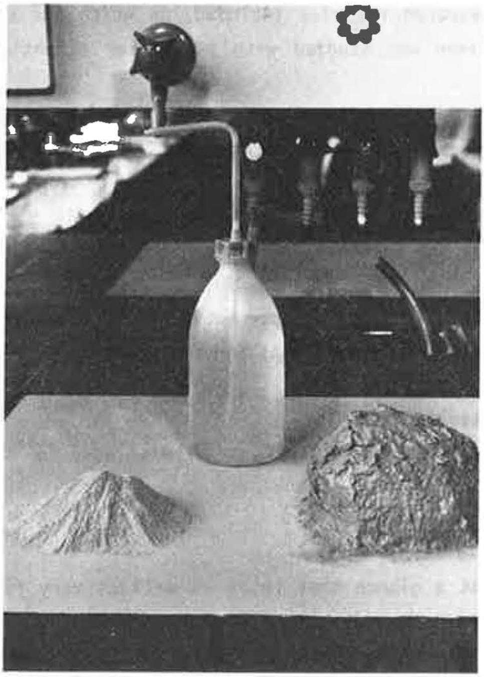


Fig. 1 Shows volume increase of bentonite (here Tixoton) from dry to wet state

In order to check the effect of activation on the liquid limit values a sample from Moosburg (place from where Süd-Chemie gets its material before converting it to Tixoton) was tested in the laboratory. The liquid limit before activation was $w_L = 95$ % and after activation it rocketed to a value of $w_L = 477$ %. The liquid limit values were determined for the other bentonite types as well in order to draw a comparison. The values were:

1. Ultragel (Duisburg w_L = 578 %
1. Tixoton (Süd-Chemie) w_L = 477 %
3. BI (Erbslöh) w_L = 355 %
4. S-Super (Erbslöh) w_L = 514 %.

2 Centrifugal test

In the explanatory notes to the German Standards DIN 4127 (sections 3.5 and 3.6) it is mentioned that knowledge of sedimentation and consolidation processes are important for execution of good quality diaphragm walls and that the filtration test does not fullfil these requirements. The filtration test has however been included in DIN 4127 for want of a better method. Centrifugal test was therefore adopted to fill up this gap.

In the case of sedimentation test the volume of water V_w (cm^3) that collects on the top of the graduated cylinder is measured after 3 hours, 1, 3 and 7 days. The ratio of V_w to original suspension volume V_o is given as $s = V_w/V_o$ %. For practical application a period of 7 days is too long a time for the execution of a routine sedimentation test and its use is generally avoided.

The sedimentation is caused by the gravitational force. In a centrifugal apparatus the acting force can be increased manifold and is dependent on the rotational revolutions per minute. The relationship between the gravitational increase b, and revolutions per minute U can be expressed as follows:

$$b = N \cdot g = \left(\frac{2\pi . U}{60}\right)^2 . 1 \quad (m/s^2)$$

where N = factor expressing gravitational increase
U = revolutions per minute
l = distance from axis of rotation (m).

It can be readily seen that for U = 500 and l = 5 cm the increased force due to centrifugal force is 14 times the gravitational force. The process of sedimentation and consolidation is therefore accelerated.

2.1 Centrifugal testing procedure

For performing this test a centrifuge with 4 symmetrically placed cylinders with a capacity of 100 cm^3 (bentonite suspension) each was available (see Fig. 2). When the test is run, a certain amount of water gets separated and collects at the top of each cylinder. As in the case of sedimentation test the ratio of separated water volume to original volume V_0 will be expressed as a percentage and denoted here with Z.

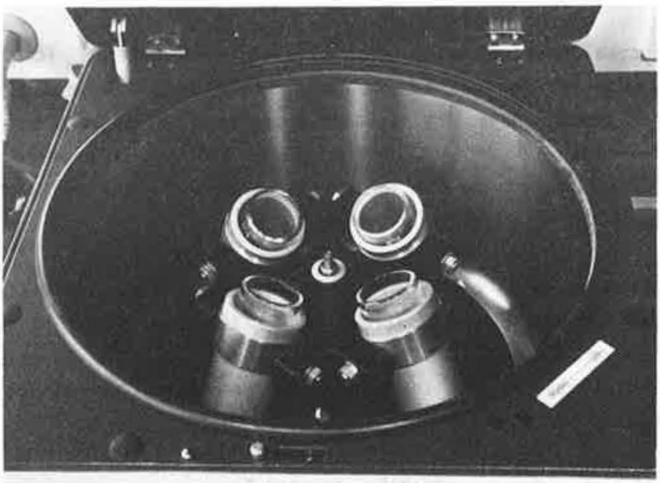


Fig. 2 Centrifuge with four symmetrically placed cylinders

The tests were carried out with four different speeds of 500, 750, 1000 and 1250 rpm for three different test durations of 10, 20 and 30 minutes.

The centrifugal tests were performed on 3 different bentonite types, i.e. Tixoton, Ultragel and BI. The results are given in Table 1 to 4 (Appendix A). In the presentation of results distinction is made between four different phases which a bentonite suspension goes through.

Phase 1
"Silo" means the sample is taken after mixing and before the suspension is pumped to the trench.

Phase 2
"Trench" means the suspension finds itself in the trench and has taken up detritus during excavation.

Phase 3
"Pre-cyclone" means the suspension has taken up so much detritus that it should either be disposed of or passed through a cyclone.

Phase 4
"Post-cyclone" means the bentonite slurry that comes out after treatment from a cyclone.

2.2 Centrifugal test results

Limiting values of Z in % ($Z = \frac{\text{separated-water volume}}{\text{original suspension volume}}$)

Type of Bentonite	Silo		Trench
Tixoton (Bayer. Landesbank)	<1, <1, 11.89, <1	%	up to 20 %
Ultragel (Bayer. Landesbank)	34.8, 42.79	%	up to 26 %
Tixoton (Karlsplatz)	3.41, 8.67	%	up to 24 %
BI (Karlsplatz)	<1, <1, <1, <1, <1	%	up to 23 %

Table 5 Test values of Z for silo and trench phases of bentonite suspensions

Considering centrifugal tests in isolation it seems that mixing at site with "Supraton" in case of Ultragel is not efficient and that this type of bentonite requires additional external shearing in order to unfold its optimum effectiveness. This is indicated by the fact that Z-values for silo slurry of 34.8 and 42.79 % decreased to 26 % for trench values. The explanation lies in the fact that in case of a not-well-mixed slurry additional mixing is provided by the churning effect caused by the grab when excavation work is done in the trench.

In case of Tixoton and BI the mixing done by Supraton at site seems to be satisfactory. It is interesting to note that the value of Z (%) levels off to an almost uniform value for all types of bentonites as the excavation work in the trench progresses.

3 Filter-press test

Water-loss or filtration of the slurry is determined in a filter-press. In Germany the test is carried out according to instructions contained in DIN 4127 which itself is based on the original test RP-13B of the American Petroleum Institute.

A pressure of 0.7 MN/m^2 is brought on the upper face of suspension in the container (see Fig. 3) and the water-loss 'f' (cm^3) is collected in a graduated cylinder. In the original test the duration of the test was 30 minutes but this has been reduced to 7.5 minutes because of the following simple mathematical relationship:

$$Q_2 = Q_1 \sqrt{T_2/T_1}$$

where Q_1 = filtrate (cm^3), a known value measured at time T_1

Q_2 = is the unknown filtrate value to be calculated from a given time T_2

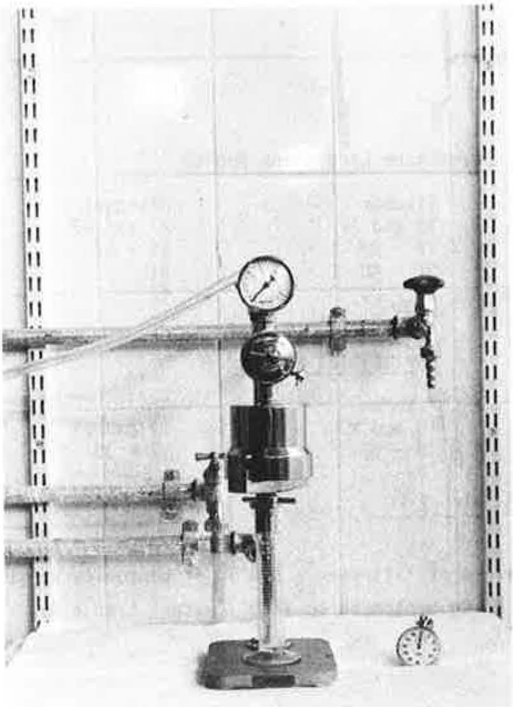


Fig. 3 Filter-press apparatus

From the above equation it can be seen that the 30 minutes fluid loss is twice the value obtained at 7.5 minutes. The values reported herein are filtrate values in cm^3 for a test duration of 7.5 minutes.

From the results of tests given in Appendix B the following filtrate limiting values can be shown to exist (Tables 6 and 7).

3.1 Filter-press results

Bayerische Landesbank Munich

Slurry-phase	Tixoton	Ultragel
Phase 1 Silo	16 and 17	27 and 47
Phase 2 Trench	12 - 39	15 - 57
Phase 3 Pre cyclone	37 - 40	51
Phase 4 Post cyclone	31 - 33	47

Karlsplatz, Munich

Slurry Phase	Tixoton	BI
Phase 1 Silo	18 and 23	17 and 21
Phase 2 Trench	10 - 36	17 - 39
Phase 3 Pre cyclone	-	-
Phase 4 Post cyclone	-	-

Table 6 Limiting values of $filtrate_{7.5}$ (cm^3) for bentonite suspension containing 40 kg bentonite to 1000 l water, i.e. 4 %)

Test site	Tixoton	Ultragel	BI	Remarks
Laboratory	17 - 20	13 - 22	15 - 16	An upper limit of f = 20 cm^3 can be stipulated as a criterion for stable suspension for all three bentonites
Silo (at site)	16 - 23	27 and 47	17 and 21	Except for Ultragel the same limit of f = 20 cm^3 can be set a criteria for stable suspension for at-site mixing

Table 7 Values of $filtrate_{7.5}$ (cm^3) for bentonite suspension (of 4 %) mixed in the laboratory with a high-shear mixer

Comparing the laboratory values of filtrate 'f' with the silo values one sees that values of $f = 27$ and $47\ cm^3$ in case of Ultragel mixed at site are much higher than the values of $13 - 22\ cm^3$ for laboratory values. As in the case of centrifugal tests the comparison points in the direction of inadequate mixing at site in the case of Ultragel. In case of Tixoton and BI a criterion can be recommended in that the value of f (cm^3) should not exceed $20\ cm^3$ in order to remain in a stable domain.

According to the German standard DIN 4127 neat bentonite suspensions having $f < 15\ cm^3$ lie in a stable range. It is implied that $f > 15\ cm^3$ are unstable.

Looking at the results one sees that laboratory values in case of Tixoton lie between $17 - 23\ cm^3$, for Ultragel between $13 - 23\ cm^3$ and for BI between $15 - 16\ cm^3$. Therefore according to the results presented here a limiting value of $f = 20\ cm^3$ instead of $15\ cm^3$ seems to be more logical.

4 Sedimentation test

This test was carried out simultaneously with two different diameters of the graduated cylinder (5.92 cm and 12.85 cm diameter). The height of suspensions in both cases was 20 cm (see Fig. 4). After the given suspension sample was poured into the cylinder, readings were taken of the separated water after 3 hours, 1 day, 3 days and 7 days and are represented by "s" as percentage of the original volume of suspension. The results of two tests are given below. For clarity the results of centrifugal tests are also added.

The comparison consists of centrifugal tests of 500 rpm and a duration of 10 minutes with the sedimentation test values after a duration of one day and taking the average of the two values (for 5.92 cm and 12.85 cm diameter graduated cylinders).

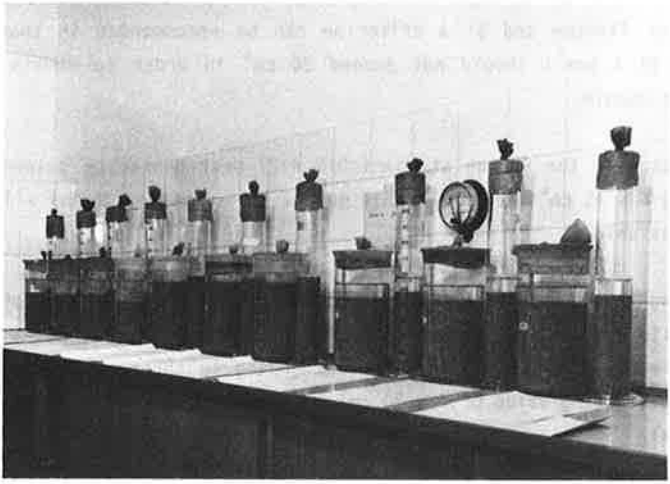


Fig. 4 Sedimentation test with two different diameters of graduated cylinders

4.1 Comparison of sedimentation tests with centrifugal tests

The results of sedimentation tests are presented below in the form of a comparison between sedimentation and centrifugal tests (Table 8).

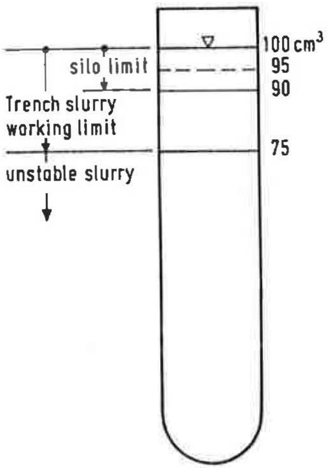
For comparison purposes centrifugal test of 500 rpm with a duration of 10 minmutes versus sedimentation test with a duration of one day was adopted.

It can be seen that centrifugal test of 500/10' compares very well with the results of sedimentation test of 1 day duration in the case of Tixoton.

	Tixoton			Ultragel			BI	
Sample No.	Centr. Test 500/10' Z (%)	Sedimen-tation after 1 day s (%)	Sample No.	Centr. Test 500/10' Z (%)	Sedimen-tation after 1 day s (%)	Sample No.	Centr. Test 500/10' Z (5)	Sedimen-tation after 1 day s (%)
2	<1.00	<1.00	40	22.57	16.15	73	<1.00	<1.00
4	16.67	18.00	41	17.16	12.05	74	<1.00	<1.00
7	8.32	12.05	42	34.80	22.95	75	<1.00	<1.00
9	16.12	14.40	43	18.36	11.85	79	15.25	13.50
10	11.89	10.60	47	16.64	9.05	81	<1.00	<1.00
11	19.63	21.80	49	42.79	29.85	82	17.12	2.20
13	20.15	22.05	50	26.06	28.95	84	20.13	19.50
14	18.71	16.15						
21	7.05	7.15				86	18.34	1.90
23	11.25	7.45					(3.5 % suspension)	
27	<1.00	<1.00						
28	17.83	16.45						

results of tests 53 to 71
not included here because the
tendency is the same as
indicated above

Tab 8 Comparison of centrifugal and sedimentation tests for 4 % bentonite suspensions



▽ Level of suspension before centrifugal test

Level of separated water does not lie below 95 cm^3 mark

Level of separated water does not lie below 90 cm^3 mark

Level of separated water does not lie below 75 cm^3 mark

Below the 75 cm^3 mark the slurry is unstable

Fig. 5 Suggested graduations on sample cylinder in a centrifugal test

The adoption of centrifugal test is recommended for the following reasons:

1. Compared to other standard tests such als filter-press the centrifugal test represents true sedimentation process in the trench.

2. The test can be run either in the laboratory or at site and the results can be gotten after ten minutes to indicate whether the slurry is stable or unstable. This saving in time is very important and decisions or changes can be made quickly.

In case of Ultragel the centrifugal values are generally higher than those of sedimentation values s, again pointing to the fact that since the at-site mixing does not employ high shear the water absorption between layers cannot develop to a full extent.

In case of BI the results of Z and s compare very well except for sample 82. It must be pointed out that the percentage bentonite used at site differed for BI between 3 and 4 % according to need. It seems that in case of sample 82 3.5 instead of 4 % bentonite must have been used. To prove this point sample 86 has been included because here it was known that a 3.5 % suspension had been used. The results of the two samples 82 and 86 compare very well with each other.

4.2 Recommendations

It may be pointed out that centrifugal test results (500 rpm for a 10 minute duration) compare favourably with the sedimentation test results (1 day duration), indicating further that water-separation process remains the same except that in centrifugal test it is accellerated, i.e. water separated in a 10 minutes duration in a centrifugal test corresponds approximately to water separated in a sedimentation test over a period of one day. Taking into consideration the limiting values of Z (%) shown on page 9 a very practical and time-saving method is suggested.

In the centrifugal test the test tube containing 100 m^3 bentonite suspension can be graduated as follows (Fig. 5):

After the test has run for 10 minutes at 500 rpm the amount of water separated should not be below 90 cm^3 mark in case of neat bentonite suspensions and not below the 75 cm^3 mark in case of trench slurry. Below the 75 cm^3 mark the slurry is unstable.

5 Marsh funnel

5.1 Testing procedure

Routine slurry viscosity is generally measured with the Marsh funnel (Fig. 6). The test consists of letting the slurry flow out of the funnel. The time required in seconds is the funnel viscosity. It is pointed out here that the capacity of the funnel can either be a 946 cm^3 (1 quart) or 1000 cm^3.

This fact must be reported along with the results to avoid confusion. The results reported herein pertain to 1000 cm^3 capacity.

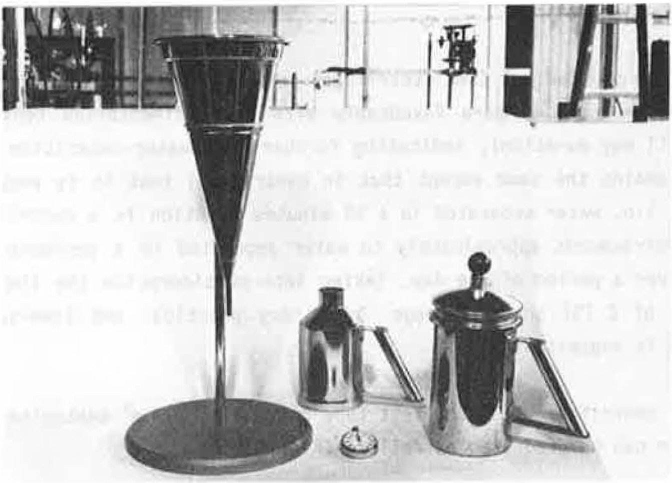


Fig. 6 Marsh funnel test

The Marsh funnel test in its simplicity is supposed to measure the viscosity. But actually the process is much more complex because of interaction between various factors such as density, viscosity and shear strength. Furthermore the slippage action between the surrounding wall of the funnel and the suspension is not a constant factor but undergoes a change due to reduction of pressure head when the suspension level is sinking. This should therefore be regarded as a very rough guide as far as viscosity is concerned.

5.2 Marsh funnel test results

For practical purposes the limiting values obtained from these tests for 4 % neat bentonite suspensions are givel below:

Tixoton suspension	t_{1000} = 33 - 36 sec
Ultragel suspension	t_{1000} = 38 - 42 sec
BI suspension	t_{1000} = 32 - 34 sec

From these results it can be said that Marsh values lie between 32 and 42 sec for a flow of 1000 m^3 suspension.

6 Specific gravity of trench slurry

During excavation detritus becomes mixed with the slurry. The contamination by detritus, ground water or cement causes a change in the relevant properties of slurry. When the condition of slurry is such that is has reached a low shear strength, then the slowly settling layers of sand and silt will build up a sludge at the excavation base. The tremied concrete is then unable to replace the slurry clearly from the excavation base. Moreover these sludge layers have higher viscosities, so that displacement past the reinforcing bars is impeeded. HUTCHISON (1974) has suggested that bentonite concentration of at least 4 % should be used. The underlying idea of prescribing a minimum of 4 % bentonite suspension is to achieve enough shear strength to hold the sand and silt particles in suspension: Because then about 60 % of detritus will be held in suspension. Below 4 % concentration a large portion of detritus settles down causing heavy sludge layers at the bottom of the excavation.

In order to provide a check on the sludge layers, the specific gravity of freshly mixed suspensions and that of samples taken from various depths of the trench wall were recorded. The values for freshly mixed suspensions lie between ρ_{sus} = 1.017 to 1.025 t/m³. For samples taken out of the trench, the density increased: ρ_F = 1.10 to 1.25 t/m³. As expected the values of ρ_F increased directly along the depth of the wall. The results are shown in Fig. 7.

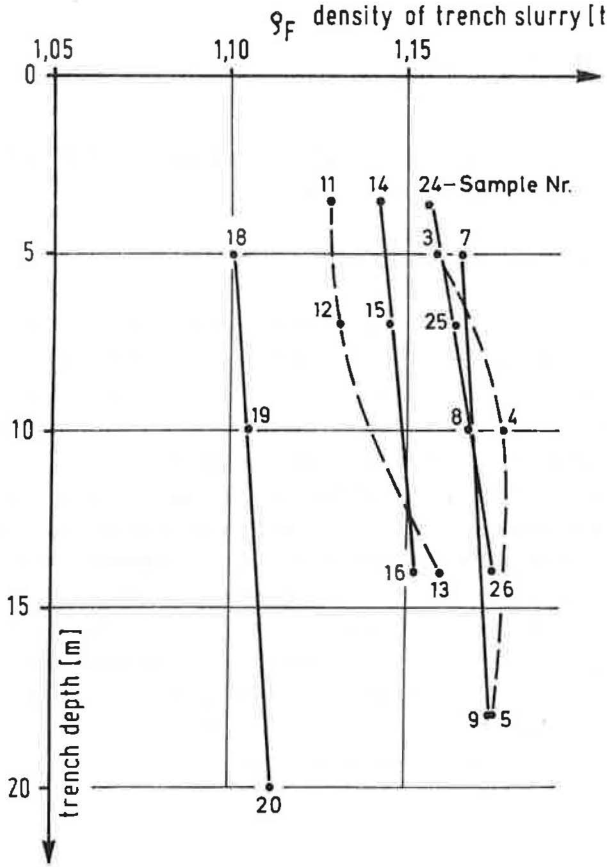


Fig. 7 shows the relationship between density of trench slurry and the sampling depth of the trench

When it is felt that with repetitious use of the slurry specific gravity has become high then the slurry must either be discarded or passed through a cyclone. In case of sample 28 the specific gravity ρ_F of 1.176 t/m³ was reduced to 1.129 t/m³ (sample 29), when passed through a cyclone at site. The values of filtrate water at the same time reduced from 37.2 to 30.8 cm³. Similar results were obtained for the set of samples 30 and 31. A comparison of grain size curves for pre and post cyclone treatment samples showed that primarily 15 % of grain sizes held in suspension were removed from the material passing through the cyclone (see Fig. 8 and Fig. 9).

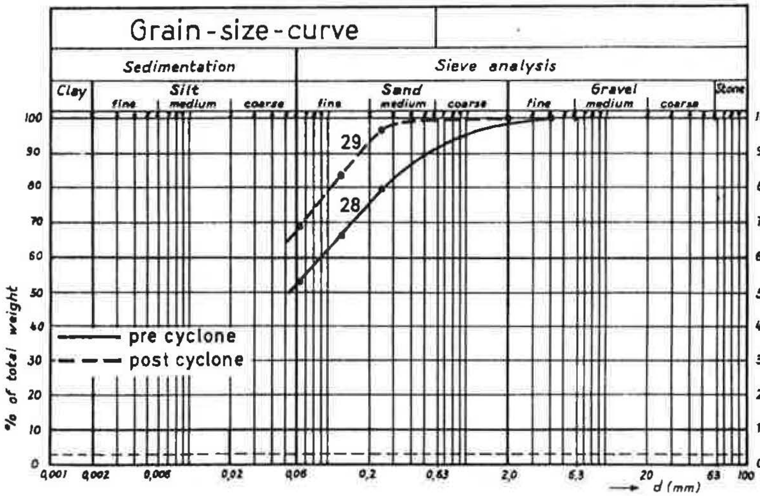


Fig. 8 Grain size curve of pre and post cyclone samples

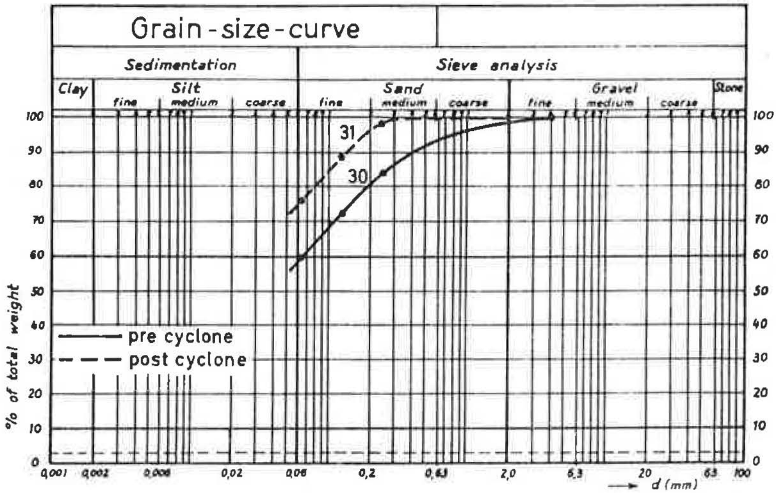


Fig. 9 Grain size curves of pre and post cyclone samples

7 pH-values

The pH-measurements were made with a portable pH-meter (Fig. 10) because of its greater reliability and accuracy over the paper strips. In Table 9 the results of pH- and filtrate water measurements are given.

A general tendency is shown to exist for all three types of bentonites. With increase in contamination the pH-value rises and the value of filtrate water also rises. The reason is that during contamination process more and more calcium ions replace the sodium ions in the structural lattice of the bentonite with the result that the sodium treated bentonite starts converting back to calcium bentonite. Compared to sodium bentonite the calcium bentonite has a smaller distance between the layered lattice structures, so that a portion of water molecules embedded in the sodium bentonite becomes free which in turn is responsible for an increase in the filtrate water.

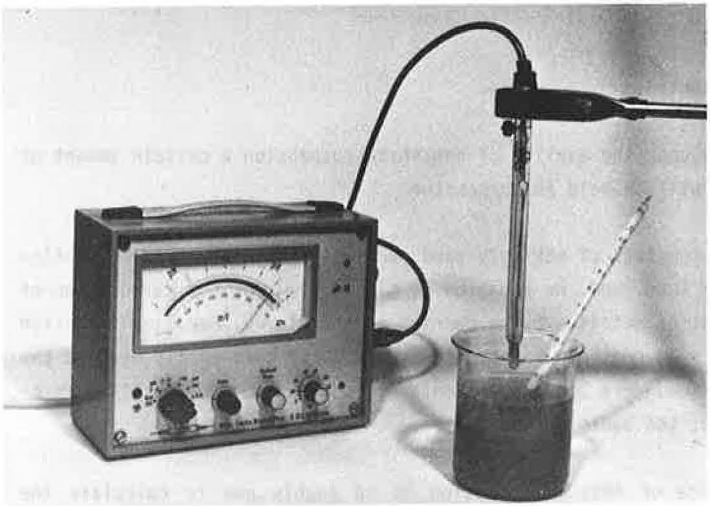


Fig. 10 pH measuring test

	limiting values	
	pH	f(cm^3)
Tixoton	9.6 to 12.3	10 to 39
Ultragel	9 to 12	15 to 76*
BI	9.8 to 12.5	17 to 39

* it is pointed out that the highest value of 76 recorded here will most likely be at the level of 39 (as in the case of Tixoton and BI)) if the suspension had been adequately mixed

Table 9 showing limiting values of pH and filtrate water for the three bentonite suspensions

8 Sand contents

Depending upon the quality of bentonite suspension a certain amount of detritus will be held in suspension.

Detritus consists of not only sand particles but also contains particles finer than sand. An equation is given below for the calculation of the amount of detritus being carried in the slurry. For simplification the term sand contents has been retained as is customarily used at the present time. Here by sand contents it is meant to include all particles except the bentonite particles.

The purpose of this presentation is to enable one to calculate the amount of detritus present in the trench slurry without performing any additional tests at site.

Based on the definition of specific gravity of a suspension

$$\rho_F = \frac{m_w + m_{Bent} + m_{sand}}{v_w + v_{Bent} + v_{sand}}$$

an equation can be derived for the calculation of sand contents in the following form:

$$m_{sand} = \frac{\rho_{sus}(\rho_{Bent} + \alpha.\rho_w) - (1+\alpha)\ \rho_w \cdot \rho_{Bent}}{(\rho_{Bent} + \alpha\rho_w) - \dfrac{(1+\alpha)\ \rho_w \cdot \rho_{Bent}}{\rho_{sand}}}$$

where ρ_w = = specific gravity of water

ρ_{Bent} = specific gravity of bentonite

ρ_{sand} = specific gravity of sand

$$\alpha = \frac{m_{Bent}}{m_w}$$

For quick use at site three separate nomographs are presented here - Fig. 11 to 13 -. The same information is also given in tabular form (see Table 10). For drawing those graphs the specific gravity of bentonite was taken as 2.75 t/m^3. It may be added here that the variation in values of ρ_{bent} between 2.65 and 2.75 t/m^3 has no practical significance. For direct reading of sand contents from the figures it is assumed that the specific gravity of slurry from the trench ist known, as well as the percentage of bentonite used in the preparation of the slurry. Values of 3 %, 4 % and 5 % (α = 0,03, 0,04 and 0,05 respectively) were adopted.

The density of sand from site would either be known or can be experimentally determined. The values generally lie in the range of 2.60 to 2.70 t/m^3. With this in view the values of ρ_{sand} = 2.60, 2.65 and 2.70 t/m^3 were selected for the preparation of the three nomographs.

Fig. 11 covers the case when ρ_{sand} = 2.70 t/m^3 and Fig. 12 covers the case when ρ_{sand} is 2.65 t/m^3 and Fig. 13 covers the case when ρ_{sand} is 2.60 t/m^3.

For illustration it is assumed that the specific gravity of the suspension (whose sand contents are to be calculated) from the trench is 1.20 t/m^3. The original bentonite percentage used was 4 %. The values of sand contents read from the figures are 0.288; 0.285 and 0.282 t/m^3 for three different values of ρ_{sand} of 2.60, 2.65 and 2.70 t/m^3 respectively In other words, depending upon the value of ρ_{sand}, detritus between 288 to 282 kg per 1000 l of suspension is being carried by the slurry.

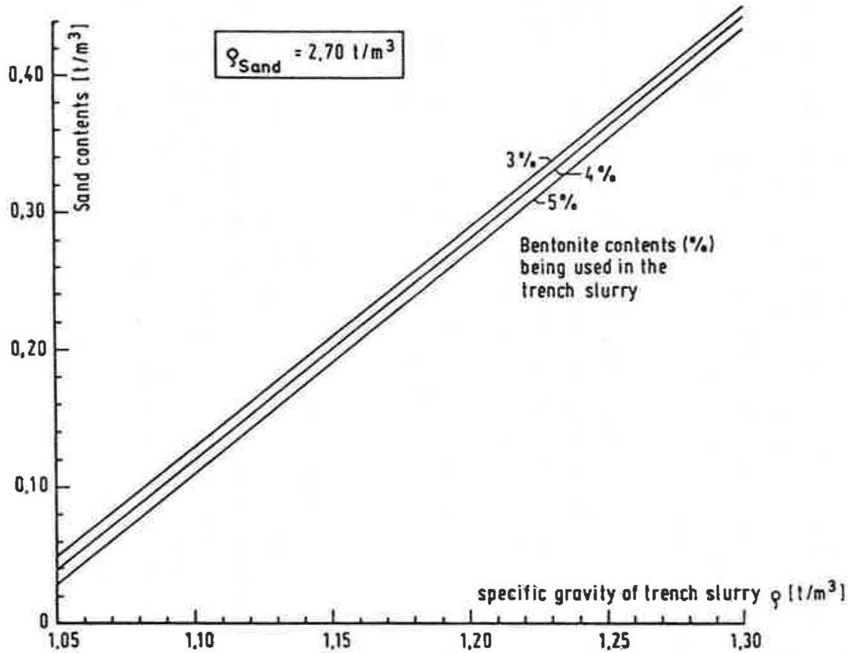


Fig. 11 Nomograph for calculating sand contents held in suspension in a trench slurry

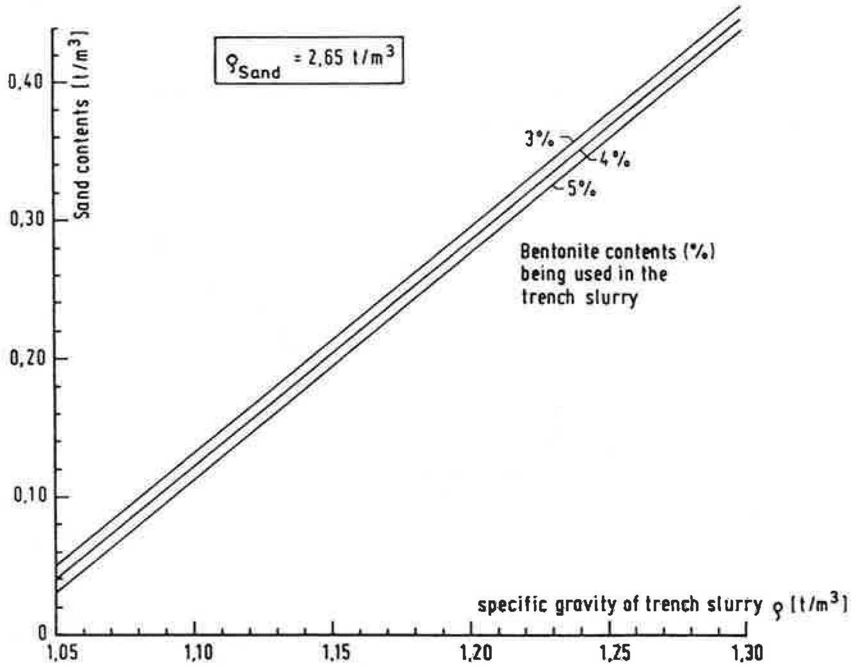


Fig. 12 Nomographs for calculating sand contents held in suspension in a trench slurry

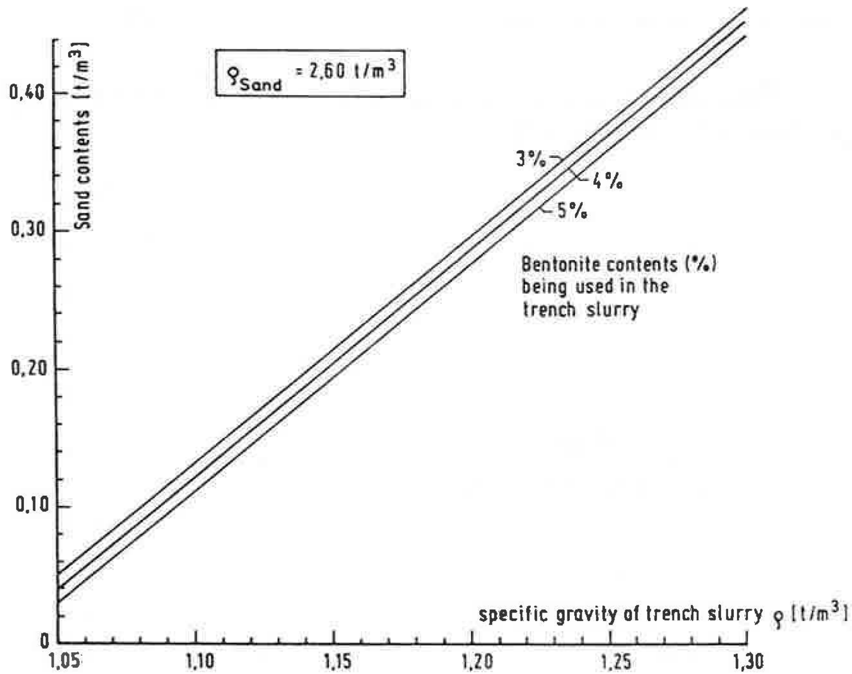


Fig. 13 Nomographs for calculating sand contents held in suspension in a trench slurry

	ρ_{sand} 2.60 t/m^3			ρ_{sand} = 2.65			ρ_{sand} = 2.70		
ρ_{sus}	α =			α =			α =		
(t/m^3)	0.03	0.04	0.05	0.03	0.04	0.05	0.03	0.04	0.05
1.05	0.051	0.041	0.031	0.051	0.041	0.031	0.050	0.040	0.030
1.10	0.133	0.124	0.114	0.132	0.122	0.113	0.130	0.121	0.111
1.15	0.216	0.206	0.197	0.213	0.204	0.194	0.211	0.201	0.192
1.20	0.298	0.289	0.280	0.294	0.285	0.276	0.291	0.282	0.273
1.25	0.380	0.371	0.363	0.375	0.367	0.356	0.371	0.363	0.354
1.30	0.462	0.454	0.445	0.457	0.448	0.440	0.451	0.443	0.435

ρ_{Bent} = 2.75 t/m^3 (value of 2.75 was held constant. When the value varies between 2.65 and 2.75 it has almost no influence on calculation of sand contents)

ρ_{sus} = the density of trench suspension whose sand contents are to be determined

α represents the ratio by weight of bentonite to water, for example 0.03 represents the 3 % neat bentonite suspension.

ρ_{sand} represents the density of sand at site. The density of sand is likely to remain within the limitsd 2.60 - 2.70 t/m^3.

Table 10 shows the quantity of sand (t/m^3) being held in suspended form in the trench slurry

The values given in the table are the quantities of sand per cubic meter of suspension. For example 0.285 (t/m^3) means a quantity of 285 kg of sand (per 1000 l suspension) is being held in suspended form.

9 Effect of mixing technique

In order to find the effect of mixing technique on the stability of the bentonite suspension experiments were performed in the laboratory on neat bentonite-water slurries.

The effect of mixing is to break up the small sized bentonite particles into even still smaller particles, increasing the specific surface area. Two types of mixers were used. One was the routine laboratory mixer with two blades (2000 rpm). The second one was a high shear Ultra Turrax with a maximum of 10000 rpm mixer (Fig. 14).

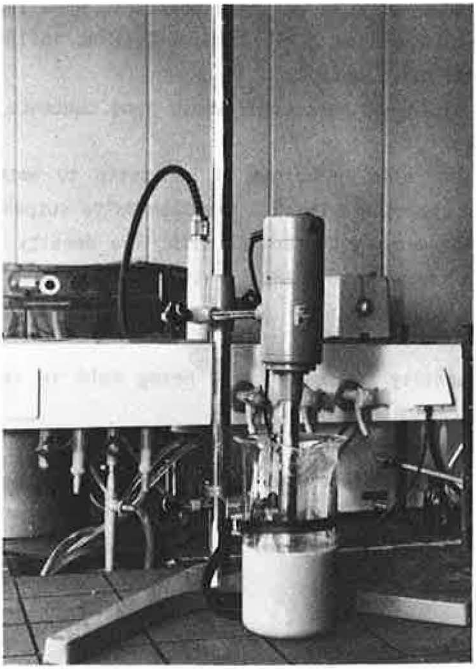


Fig. 14 Ultra Turrax: a high shear mixing apparatus

In both cases the mixing time was 5 minutes. After mixing, the suspensions were tested for two different hydration times of one hour and 24 hours. The effect of mixing shows up in the results of filter press and centrifuge tests. The results of the tests are given in Table 11.

mixing technique	hydration time	Tixoton f (cm^3)	Tixoton Z (%)	Ultragel f (cm^3)	Ultragel Z (%)	BI f (cm^3)	BI Z (%)
routine mixer	1 hr	19	6	21	9	17	2
	24 hrs	20	4	22	7	16	< 1
high shear mixer Ultra Turrax	1 hr	18	2	14	<1	16	< 1
	24 hrs	18	2	13	<1	15	< 1

Table 11 Results of tests from filter press and centrifuge for three different types of bentonites for hydration time of one hour and 24 hours

In general it can be said that when the hydration time is increased from 1 hour to 24 hours it has no influence on the results of both filter press and centrifuge. However when comparing the routine mixing with the high shear mixing of Ultra Turrax the following points can be noted:

Tixoton

Filtrate water no change.

Zentrifugal test seems to react better. It shows that the value of Z = 6 % for routine mixer, reduces to Z = 2 % when Ultra Turrax was used.

Ultragel

In the case of Ultragel the results of both filter press and centrifuge show that mixing had a decisive influence when Ultra Turrax was used. The value of f = 21 cm^3 reduces to 14 cm^3 and the value of Z = 9 % reduces to 1 %. The value of Z < 1 % denotes evaporation losses only and further that no water gets separated from the suspension.

BI

In the case of BI the mixing seems to have no significant effect in the values of either f or Z, except that centrifugal test seems to respond better than the filter press.

Comparison of at-site-mixing with laboratory mixing

While going over the results of centrifugal test and filter press tests it was mentioned that in case of Ultragel the mixing with Supraton seemed to be inadequate. A series of tests were therefore performed in which site-mixing could be compared with the high-shear mixing in the laboratory.

The mixing at site was done with Supraton mixer (2950 rpm with a capacity of 20 m^3/h), while the mixing in the laboratory was done with the high shear mixer Ultra Turrax. For the presentation of results a 4 % bentonite suspension is considered. The results are given in Table 12.

	Tixoton		Ultragel		BI	
	f(cm^3)	Z(%)	f(cm^3)	Z(%)	f(cm^3)	Z(%)
Supraton mixer (at site)	15-23	0-12	27-48	35-43	17-21	<1
Ultra Turrax (laboratory)	17-20	4-11	13-22	1-17	15-16	<1

Table 12 Values of filtrate f and separated water in centrifugal test Z for two types of mixing

In the case of Tixoton and BI there are almost no changes in the values of f and Z, between Supraton and Ultra Turrax. There is however a marked difference in case of Ultragel.

The comparison confirms therefore that in case of Tixoton and BI the Supraton mixer at site is fully effective but in case of Ultragel, as mentioned previously, extra shearing energy is needed before optimum dispersion can be utilized.

JEFFERIS (1982) has also done research on the effect of mixing on bentonite slurries. His conclusions are:

Effect of mixing speed (propeller mixer: speeds between 2000 to 10000 rpm) increases (in terms of viscosity) with increasing slurry concentration (3.5 - 5.0 - 7 %), but the effect of mixing time is similar in all three concentrations, further that remixing 24 hours after the original mixing is very effective at developing viscosity. He goes in to recommend that if any bentonite slurry must be used soon after mixing then high speed or prolonged mixing should be used. In case time is not of paramount nature then remixing produces good results.

10 Electric conduction value

The measurement of electric conduction values was not a part of the original research scheme but is added here on the basis of a follow up research. The electric conduction value will be written in short here as E.C.V. The apparatus used, is shown in Fig. 15.

pH-value represents a measure of hydrogen ionen concentration of a given suspension. The specific electric conduction value (unit is us/cm or ms/m at 20 °C) represents a measure of ion-concentration and therefore gives an idea of dissolved dissociatable substances. Because water represents a thin electrolytic solution, the valance of ions and the migration velocity of the ions is constant, the specific electric value of water-bentonite suspension can be seen simply as a measure of ion-concentration at a constant temperature.

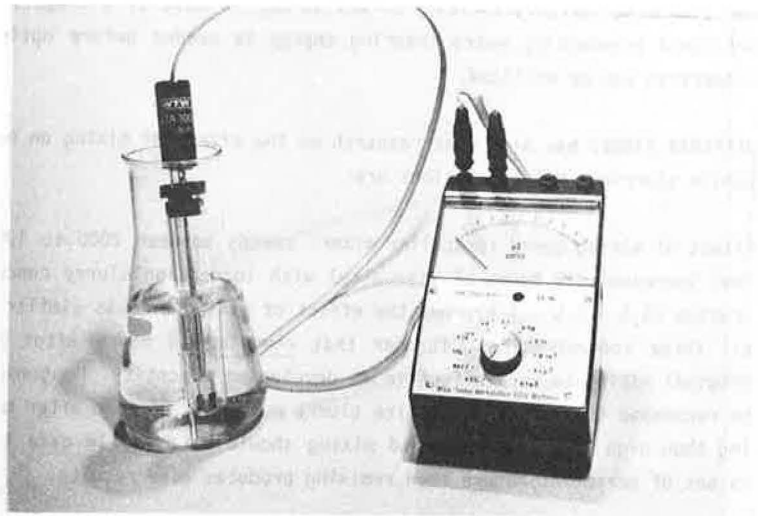


Fig. 15 Apparatus for measuring electric conduction values

In order to draw a comparison between pH- and electric conduction value (ms/m, milli Siemens/meter) 3 and 4 % bentonite suspensions were prepared in the laboratory and pH- and E.C.V.-values were measured. The results are given in Table 13.

	Tixoton		Ultragel		BI		
	3%	4%	3%	4%	3%	4%	Remarks
pH	10.9	11.1	9.2	9.3	10.7	10.3	For reference the average values for Munich water are: pH = 7.9 and ECV = 60 ms/m
ECV (ms/m)	220	247	108	128	162	194	

Table 13 showing pH- and electric conduction values for 3 and 4 % bentonite suspensions

On the basis of comparison betweeh pH- and electric conduction values it can be recommended that in future greater importance ought to be attached to electric conduction values rather than pH-values because noticeable differences exist in case of electric conduction values. For instance in case of Ultragel the pH-value changes from 9.2 to 9.3 (a very small margin) for 3 and 4 % bentonite respectively while the electric conduction values change from 108 to 128 ms/m (a clear spread). Naturally field data will have to be collected before judgement can be formed about the quality of the bentonite suspensions.

The electric conduction values (along with other properties) were keenly observed in the suspensions with additives, dealt with next.

11 Effect of two additives on general behaviour of bentonite slurries

For the construction of trench walls additives are sometimes used in the bentonite slurry in order to increase the viscosity and decrease the fluid loss. The chemical preparation generally used in Germany is "Antisol" (Wolff Walrode AG). The second additive is not used in the trench construction, but is used in grouting where the injection material may be supplemented with this additive and bears the trade name "Tricosal 181" (Chemische Fabrik, Grönau). The main purpose of grouting is to be able to fill up the smallest of the pores. The usefullness of Tricosal lies in the fact that it makes the mixture more smooth, so that the grouting material encounters less obstruction in entering the smallest of the pores. In order to see how these two additives changed the behaviour of neat suspensions, tests were performed on neat bentonite suspensions and then with suspensions additionally containing either 0.3 % Antisol or 0.1 % Tricosal 181.

The results of general properties - pH-, electric conduction value, Marsh funnel, filtrate water, filter-cake thickness and Bingham yield value - are presented in Table 14.

Bentonite Slurry	pH	Electric Conduction value ms/m	Bingham yield value τ_0 from rotational viscosimeter N/m^2	Marsh funnel t in s	Filtrate water f cm^3 for 7.5 min	Filter cake in filter press mm
Tixoton 3%	10.9	220	5.4	38	16	1.8
Tixoton 3% + 0.3% Antisol	11.1	333	2.4	51	10	0.7
Tixoton 3% + 0.1% Tricosal	10.9	189	2.0	34	20	1.3
Ultragel 3%	9.2	108	7.3	54	20	3.0
Ultragel 3% + 0.3% Antisol	9.2	232	10.5	150	15	0.9
Ultragel 3% + 0.1% Tricosal	9.2	103	4.8	48	22	2.1
BI 3%	10.7	162	1.7	34	16	0.9
BI 3% + 0.3% Antisol	10.6	279	1.8	45	11	0.6
BI 3% + 0.1% Tricosal	10.7	160	1.1	32	20	0.8
Tixoton 4%	11.1	247	8.1	42	16	2.3
Tixoton 4% + 0.3% Antisol	11.2	290	5.7	87	9	0.9
Tixoton 4% + 0.1% Tricosal	11.1	230	5.3	38	16	1.9
Ultragel 4%	9.3	128	15.4	145	15	3.0
Ultragel 4% + 0.3% Antisol	9.5	218	30.0	150	10	1.6
Ultragel 4% + 0.1% Tricosal	9.7	107	12.2	89	17	2.5
BI 4%	10.3	194	3.2	37	14	1.3
BI 4% + 0.3% Antisol	10.9	300	5.0	84	8	0.8
BI 4% + 0.1% Tricosal	10.9	190	2.3	35	18	1.2

Table 14 showing effect of additives (Antisol and Tricosal) on the properties of bentonite suspensions

Bentonite suspension with 0.3% Antisol	Bentonite suspension with 0.1% Tricosal
1. Marsh values increased markedly	1. Marsh values decreased slightly
2. Filtrate water was at its minimum	2. *Filtrate water was at its maximum
3. Very slight or no change in pH-values	3. Very slight or no change in pH-values
4. +Electric conduction values increased markedly	4. Electric conduction values decreased markedly
5. Filter cake thickness was at its minimum	5. *Filter cake thickness was between maximum and minimum
6. +Except for neat 3 and 4% Tixoton bentonite suspensions, Bingham yield value was at its maximum	6. Bingham yield value was at its minimum

<u>Remarks:</u>

Each time the comparison is made between 3 values (1) of neat suspension, (2) suspension with 0.3% Antisol and (3) suspension with 0.01% Tricosal

* It is interesting to point out that although the filtrate water was at its maximum when 0.1% Tricosal was present, the filter cake thickness was not at its maximum. The filter cake thickness was at its maximum when no additive was present

\+ Except for 3 and 4% Tixoton the tendency is that when the Electric Conduction values are greater (indicating higher ion-concentration), greater are the Bingham yield values also. Similarly when the Electric conduction values at its minimum, so are the Bingham yield values as well.

Table 15 Summary of results: Comparison between neat suspension (3 and 4%), Suspension with additive of 0.3% Antisol and suspension with additive of 0.1% Tricosal

The conclusions derived from these results are given in a concise form in Table 15.

From the view point of diaphragm construction one can say that when 0.3 % Antisol is added to the bentonite suspension it has a positive effect - marsh value increases, electric conduction value increases markedly, both filtrate water and filter-cake thickness values decrease and the Bingham yield value increases.

The results achieved are of opposite nature when 0.1 % Tricosal is added. However Tricosal is not meant to be used in the slurry for trench construction. As mentioned earlier it is supposed to be used in chemical grouting for in-place strengthening of soil mass. With the addition of 0.1 % Tricosal marsh value decreases and so does the Bingham yield value. If those results can be applied to chemical grouting it would mean that the injected material can enter and fill up the pores more easily compared to the case when Tricosal is not present. As to what effect Tricosal would have in the presence of other grouting materials is a subject by itself and cannot be dealt with here.

12 Thixotropy of bentonite suspensions

12.1 Structure of bentonite

The generally accepted structure of montmorillonite (after Hofman) consists of units composed of 3 layers, i.e. two silica tetrahedral sheets on the outside and a central alumina octahedral sheet. A montmorillonite crystal consists of 15 - 20 such laminated units (which are plate-like particles) stacked one above the other. The surface of each lamination carries a negative charge which is compensated by cations lying between the two units. When water is introduced, hydration of cations takes place, water is drawn in and the montmorillonite crystal undergoes intra crystalline swelling. If it is a calcium bentonite the distance between the plate-like particles can increase to double its original distance, but the calcium montmorillonite crystal consisting of a packet of 15 - 20 plate-like particles remains intact meaning that plate-like particles are not able to tear themselves loose from the parent crystal.

However when the calcium-ions are replaced by the sodium-ions (as is the case in converted bentonites) the force exerted by the soidum-ions in the water layer between the plate-like particles is smaller with the result that the packet is no longer able to hold itself together and each of the 15 - 20 plate-like particles becomes individual particles in the suspension. The amount of water bound to the particles is greater resulting in a stable suspension with a smaller amount of filtrate water. Furthermore this increase of individual particles is responsible for a card-house structure which extends throughout the available volume and a gel is formed. When the gel is stirred the bonds are broken and the system becomes more fluid. Such gels behave as Bingham Body Fluids and possess a Bingham yield value which in fact is a measure of number and strength of bonds in the card-house structure.

Thixotropy can be said to depend on the number and strength of bonds in such a card-house structure. Some additives would have the effect of strengthening such a structure. Other additives would have the effect of decreasing the strength of such a structure or of preventing the formation of such a structure.

The thixotropy effects determined in a rotational viscosimeter (Fig. 16) of 3 and 4 % bentonite suspension containing two different additives will be described in the next paragraphs.

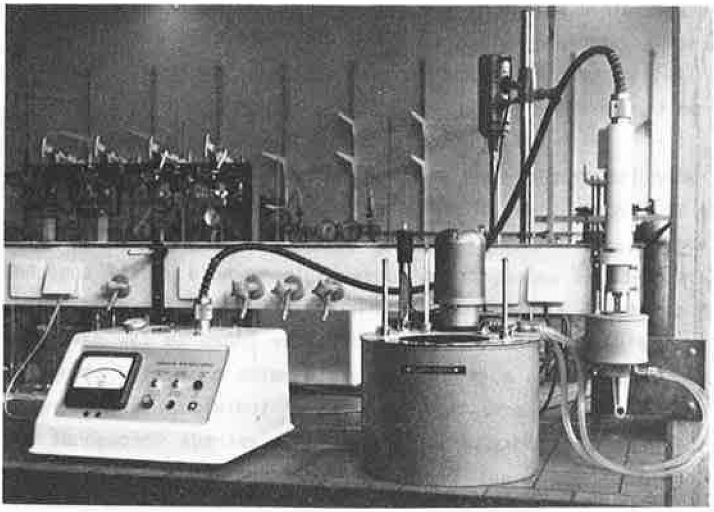


Fig. 16 Rotational viscosimeter apparatus used for tracing thixotropic loops

12.2 Thixotropic effects of additives

As is well known, thixotropy means to "change by touch". In case of bentonite suspensions the change means the change in structure. The card-house structure breaks down when stirred. Thixotropic structure has however the unique property that it will rebuild itself again if left to itself. The rebuilding of the structure is not produced instantaneously. It requires a finite time. Furthermore the whole procedure takes place isothermally.

For purposes of research the criterion of thixotropy is the hysteresis loop (hence forth called thixotropic loop). When a bentonite suspension is tested in a rotational viscosimeter and two curves are produced, an up-curve and a down-curve. The suspension is thixotropic if these curves do not coincide but form a loop. A loop forms because it consists of measurements of a structure that is being continuously broken down until the point of highest shear rate is reached. The highest shear rate is the top of the up-curve. When the down-curve is immediately run after reaching the highest shear rate, no further break down occurs and this curve therefore is linear. The result is that the two curves cannot coincide and a loop is formed.

In general it is difficult to define thixotropy as a property possessing definite dimensions. However thixotropic breakdown is a reaction the extent of which can be experimentally determined. If different suspensions are run in a rotational viscosimeter and their thixotropic loops are arranged accordingly to the area of the loops, the suspension with the largest loop area whose structure broke down the most and is therefore more thixotropic than the others.

The effect of different additives would show up in the formation of such thixotropic loops. Tests were performed with 3 and 4 % suspensions containing either 0.3 % Antisol or 0.1 % Tricosal.

Curves for 3 % and 4 % bentonite suspensions are given in Fig. 17 to Fig. 29 (Appendix C).

The results can be expressed as follows:

1. From the three bentonites tested, bentonite BI possesses the smallest thixotropy. Tixoton and Ultragel both have greater thixotropy than BI. When the bentonite percentage is increased the level of thixotropy increases correspondingly.

2. When 0.3 % Antisol was used as additive, thixotropic effects were increased (compared to the neat suspension) as indicated by larger areas of the thixotropic loops. A marked increase occurred in case of BI bentonite suspensions. The 3 and 4 % neat BI suspensions possess very small thixotropy, but when 0.3 % Antisol was added, a clear thixotropic effect could be measured.

3. When 0.1 % Tricosal was used as additive the thixotropy was decreased. This decrease went so far in the case of 3 % BI and 3 % Tixoton suspensions that those were rendered non-thixotropic because there was no trace of thixotropic loops.

Summary of results and conclusions

On the basis of testing reported herein the following points are of interest:

1. A new testing procedure in the form of centrifugal test is introduced. The results showed that sedimentation process can be accellerated and that an acceleration of 500 rpm for a duration of 10 minutes produced similar results as in a sedimentation test of a duration of one day. The test is simple to perform and after the test has run for 10 minutes one is in a position to distinguish between stable and unstable slurry.

2. For neat bentonite suspensions the limiting value of 20 cm^3 filtrate (duration of test 7.5 minutes) can be set as a criterion between stable and unstable suspensions.

3. The results of centrifugal and filter-press tests show that mixing at site with Supraton (2950 rpm with a capacity of 20 m^3/hr) is satisfactory for bentonite types of Tixoton and BI. In case of Ultragel it is inadequate and additional external shearing is required in order to unfold its optimum effectiveness.

   The results also showed that there is no difference of practical significance between a hydration time of one hour and a hydration time of one day.

4. The measurements for specific gravity of suspension along the depth of the trench showed (as expected) that the value increased directly with the depth. The detritus in the suspension is responsible for the increase in specific gravity. In order to calculate the amount of detritus present in the trench slurry, nomographs have been prepared for 3, 4 and 5 % bentonite suspensions.

   With this method no additional sand content tests are necessary as is the practice at present.

5. A comparison between pH- and electric conduction values (E.C.V.) showed that the E.C.V. deserves future attention. As as example pH-value for 3 and 4 % bentonite suspension measured were 9.2 and 9.3 respectively. The E.C.V. however increased from 108 to 128.

6. With the use of additive "Antisol" (generally used in diaphragm wall construction) both Marsh values and Bingham yield values increased. The filtrate water and filter-cake (measured in filter-press) values decreased.

7. With the use of additive "Tricosal" (generally used in grouting) both Marsh values and Bingham yield values decreased. The filtrate water and filter cake values increased.

8. The thixotropic effect of the two additives is demonstrated with the help of thixotropic loops. The addition of Antisol increased the thixotropic effect as indicated by larger thixotropic loop areas. The neat BI suspensions possess very small thixotropy but when Antisol was added a clear thixotropic effect could be measured.

   The addition of Tricosal on the other hand causes the thixotropic effect to decrease. This decrease went so far in the case of 3 % BI and Tixoton suspensions that there were rendered non-thixotropic because there was no trace of thixotropic loop.

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DIN 4126: Ortbeton-Schlitzwände

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Appendix A

Tables 1 to 4

Centrifugal test results
on 4 different bentonites

Appendix A
Table 1

Centrifugal tests

Tixoton (Bayerische Landesbank München)

+Suspension with 4,5% Bentonit otherwise 4%

Sample Nr	1 (Silo) +)				2 (Silo)				10 (Silo)				27 (Silo)			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	0,25	0,35	0,33	0,44	0,83	1,82	3,73	6,70	11,89	18,44	18,16	26,44	0,23	0,34	0,65	1,36
after 20 min	0,34	0,54	0,67	0,81	0,99	2,14	6,05	9,82	17,36	25,45	28,39	30,67	0,39	1,77	1,04	2,27
after 30 min	0,56	0,74	0,93	1,30	1,64	3,74	6,39	12,05	22,38	27,21	32,36	35,33	0,66	1,53	1,65	2,66
f (7,5 min)	11,3				16,2				17,0				15,0			
Sedimentationtest 3h-1d-3d-7d	0,0 0,0				0,0 0,0				2,87 10,62 18,72 24,11				0,0 0,0			
Sample Nr	7				11				18 +)				21			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	13,57	19,44	24,53	26,43	21,72	28,25	30,87	35,95	0,21	0,45	0,67	1,30	9,21	12,67	14,00	26,50
after 20 min	13,66	14,97	28,51	27,46	25,34	31,10	35,88	37,16	0,42	1,06	2,53	4,34	13,17	15,68	25,49	29,32
after 30 min	14,95	17,30	-	29,60	28,35	33,30	37,16	39,44	0,79	2,31	4,44	8,17	14,17	19,78	24,12	29,75
f (7,5 min)	23,5				35,8				13,0				22,0			
Sedimentationtest 3h-1d-3d-7d	2,2–12,5–19,9–21,3				5,91–21,51–24,01–24,01				– 0,0 – –				1,01–7,43–15,37–17,40			
Sample Nr	9				13				20 +)				23			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	16,12	18,97	23,45	24,40	20,15	26,41	30,21	35,32	0,25	0,41	0,42	0,80	11,25	15,28	22,29	36,79
after 20 min	18,29	24,61	24,49	-	26,89	31,32	36,45	37,73	0,46	1,06	1,80	2,66	14,75	19,01	25,80	37,12
after 30 min	19,89	26,23	25,20	26,99	28,31	32,84	37,06	39,34	0,87	1,84	3,40	5,81	15,62	19,53	26,32	37,32
f (7,5 min)	24,0				39,4				10,8				20,4			
Sedimentationtest 3h-1d-3d-7d	3,7–15,6–22,9–23,9				5,43–21,9–23,6–24,0				– – –				1,53–7,65–13,6–16,3			
Sample Nr	28 (pre-cyclone)				29 (post-cyclone)				30 (pre-cyclone)				31 (post-cyclone)			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	17,83	21,05	23,43	26,93	19,62	19,17	24,73	28,04	21,28	24,33	27,40	31,32	15,24	21,16	24,98	28,38
after 20 min	19,55	22,86	25,40	-	23,50	26,60	30,23	33,47	22,90	26,40	29,44	32,99	20,10	26,19	27,91	32,42
after 30 min	23,37	25,92	28,28	31,19	25,73	29,56	32,73	35,73	26,54	29,46	32,28	35,38	23,73	28,70	34,05	35,81
f (7,5 min)	37,2				30,8				37,5				31,8			
Sedimentationtest 3h-1d-3d-7d	5,1–16,5–17,01–17,52				1,69–8,78–15,54–17,23				5,63–17,75–19,45–19,8				1,70–9,37–15,33–16,87			

Centrifugal tests

+Suspension with 3% Bentonite

Tixoton
(Karlsplatz München)

Sample Nr	62 (Silo) +)				69 (Silo) +)				70 +)				72 +)			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	3,41	7,54	13,25	32,61	8,67	20,50	34,96	40,07	0,31	1,00	1,83	4,46	2,31	10,67	13,60	15,24
after 20 min	-	-	-	-	-	-	-	-								
after 30 min	7,12	15,85	25,50	40,13	21,48	34,07	41,15	47,00	1,01	2,05	4,53	11,72	6,99	15,14	15,83	21,36
f (7,5 min)	17,9				23,0				16,2				17,8			
Sedimentationtest 3h - 1d - 3d - 7d	0,0 – 1,78 – 2,14 – 6,05				1,36 – 3,06 – 5,95 – 8,16				0,0 – 0,54 – 1,43 – 1,79				0,36 – 0,71 – 3,91 – 5,69			

Sample Nr	58 +)				61 +)				65 +)				68 +)			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	1,16	1,63	4,13	11,14	5,12	7,17	12,12	14,89	19,28	25,51	28,31	32,89	21,56	30,03	30,91	34,54
after 20 min																
after 30 min	6,74	8,69	14,54	17,89	11,89	18,59	16,23	20,71	28,63	32,45	34,12	37,78	30,06	32,86	34,51	37,67
f (7,5 min)	15,8				15,9				32,0				32,8			
Sedimentationtest 3h - 1d - 3d - 7d	0,0 – 0,85 – 1,69 – 3,05				0,0 – 1,12 – 2,79 – 5,58				2,49 – 14,41 – 21,74 – 22,06				5,38 – 20,43 – 22,94 – 23,30			

Sample Nr	56 +)				59 +)				63 +)				66 +)			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	0,85	6,24	6,19	12,13	6,42	11,12	12,96	17,41	20,54	26,73	30,31	34,96	21,58	28,69	32,27	36,21
after 20 min																
after 30 min	6,87	7,30	19,35	20,61	14,00	15,11	20,95	21,30	28,25	32,24	34,95	37,92	30,18	34,85	35,99	40,20
f (7,5 min)	15,0				16,2				36				34,8			
Sedimentationtest 3h - 1d - 3d - 7d	0,0 – 0,34 – 1,55 – 2,92				0,0 – 1,02 – 2,20 – 5,42				4,08 – 18,03 – 21,26 – 21,77				7,38 – 21,1 – 22,98 – 23,16			

Centrifugal tests

Ultragel
(Bayerische Landesbank
München)

Sample Nr	42 (Silo)				49 (Silo)				47				Mixed in Laboratory			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	34,80	40,68	47,97	49,64	42,79	47,11	52,91	56,16	16,64				0,23			
after 20 min	38,72	44,26	48,50	53,14	43,98	50,17	56,13	57,25	23,98				-			
after 30 min	40,40	47,48	51,74	52,94	43,78	53,80	55,93	58,84	26,59				0,63			
f (7,5 min)	26,8				47,5				15,0				13,2			
Sedimentationtest 3h - 1d - 3d - 7d	7,72 – 22,30 – 25,21 – 26,59				21,63 – 28,55 – 30,85 – 30,85				– 8,4 – – 28,1				– – –			
Sample Nr	40 (pre-cyclone)				41 (post-cyclone)				43				50			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	22,57	25,41	28,56	32,45	17,16	25,05	30,87	34,31	18,36	21,41	23,58	26,07	26,06	31,85	34,99	37,77
after 20 min	25,53	27,13	-	33,45	25,71	29,16	32,25	36,66	20,92	-	24,48	26,30	29,39	35,30	36,77	40,04
after 30 min	27,73	28,61	32,10	35,55	27,51	31,33	33,88	40,52	20,33	22,31	24,12	26,38	31,98	35,86	37,08	41,26
f (7,5 min)	51,0				47,5				74,0				48,2			
Sedimentationtest 3h - 1d - 3d - 7d	3,54 – 15,18 – 16,69 – 16,86				2,65 – 11,66 – 14,31 – 14,66				4,12 – 11,15 – 12,04 12,01				11,05 – 28,23 – 29,08 – 29,93			
Sample Nr	34 (Tix. + Ult.)				35 (pre-cyclone)				36 (post-cyclone)				37			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	10,29	14,61	18,21	22,17	18,51	23,05	26,30	29,54	14,12	19,30	22,93	26,86	23,28	27,69	31,52	35,65
after 20 min	16,21	-	24,25	28,36	-	25,85	29,37	33,36	21,43	-	28,52	32,97	27,82	31,30	33,42	36,67
after 30 min	19,57	23,01	26,57	30,96	24,46	27,53	31,09	34,45	24,51	28,56	31,49	36,43	29,22	31,75	35,25	38,10
f (7,5 min)	13,5				39,8				32,8				53,0			
Sedimentationtest 3h - 1d - 3d - 7d	0,54 – 2,33 – 6,27 – 13,80				3,40 – 14,97 – 18,03 – 19,22				0,89 – 6,75 – 14,21 – 16,52				5,25 – 20,47 – 21,66 – 21,83			

Transitional period from Tixoton to Ultragel

Centrifugal tests

Erbslöh BI
(Karlsplatz München)

Sample Nr	74				78				82				86			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	0,21	0,30	0,36	0,74	20,37	26,25	-	31,70	17,12	25,15	31,64	35,90	18,34	27,79	32,69	36,30
after 20 min																
after 30 min	1,00	1,11	1,28	2,05	31,36	34,62	-	35,71	29,21	34,36	38,15	41,40	27,74	34,37	37,71	42,80
f (7,5 min)	18,2				29,8				24,4				25,9			
Sedimentationtest 3h-1d-3d-7d	0.0								0,86 –2,23–6,69–13,38				0,0–1,89–7,95–14,77			

Sample Nr	90				91				94				95			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	20,32	30,93	36,98	40,90	22,07	28,35	31,35	33,10	28,02	34,61	40,10	44,17	20,21	25,37	27,53	31,96
after 20 min																
after 30 min	34,10	40,13	43,85	47,50	28,94	33,48	33,75	34,70	38,65	42,96	44,05	47,87	27,59	32,05	32,51	35,26
f (7,5 min)	38,0				73,8				44,5				43,9			
Sedimentationtest 3h-1d-3d-7d	3,91–22,1–32,4–32,7				7,04–26,6–31,5–33,1				4,1–24,5–31,9–32,4				4,7–21,8–26,7–26,9			

Sample Nr	73 (Silo)				77 (Silo)				81 (Silo)				85 (Silo)			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	0,20	0,24	0,32	0,78	0,19	0,27	1,18	2,29	0,16	0,26	0,31	1,00	0,21	0,29	0,61	4,22
after 20 min																
after 30 min	0,45	0,66	0,97	1,68	0,58	1,22	3,17	29,70	0,45	0,69	1,33	5,10	0,58	1,43	1,66	33,70
f (7,5 min)	17,4				21,0				20,8				18,5			
Sedimentationtest 3h-1d-3d-7d	0.0				0.0				0.0				0.0			

Sample Nr	76				80				84				88			
U/rpm	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250	500	750	1000	1250
after 10 min	12,84	17,47	-	25,32	14,31	-	-	26,21	20,13	27,43	32,92	36,70	23,19	29,10	32,29	36,24
after 20 min																
after 30 min	18,31	22,73	-	26,27	20,71	-	-	27,80	30,50	35,04	38,72	42,00	30,79	34,02	36,79	38,50
f (7,5 min)	29,2				29,5				39,0				46,6			
Sedimentationtest 3h-1d-3d-7d					1,42–11,72–16,87–17,23				3,06–19,6–27,21–27,89				6,41–25,8–29,51–29,68			

Appendix B

Complete List of test results

Karlsplatz München   B I

Sample Nr.	Panel Nr. / Sampling depth Nr./m	Density of slurry ρ_F t/m³	pH	Bingham yield value τ_0 N/m²	Sand contents t/m³	Filtrate water cm³	Centrifugal test r.p.m 500/10 %	Centrifugal test r.p.m 500/30 %	Marsh Funnel t_{1000} s	Marsh Funnel t_{500} s	Sedimentation after 1 day d=5,92cm %	Sedimentation after 1 day d=12,85cm %	Sedimentation after 7 days d=5,92cm %
73	Silo	1.018	10.1	3.1	-	17.4	0.20	.45	34	23	0.0	0.0	1.0
74	8/0,1	1.044	11.6	0.2	.03	18.2	0.21	1.36	35	25	0.9	-	2.2
75	8/8,0	1.107	11.9	1.6	.13	16.8	0.23	0.97	44	34	0.0	-	0.5
76	8/15,0	1.217	12.5	10.0	.31	29.2	12.84	18.31	50	40	-	-	-
77	Silo	1.015	9.8	0.5	-	21.0	0.19	0.59	32	22	0.0	0.0	0.0
78	9/0,1	1.084	12.2	1.5	.10	29.8	20.37	31.36	36	25	-	-	-
79	9/12,0	1.204	12.5	5.3	.29	31.0	15.25	23.90	41	29	12.5	14.5	18.9
80	9/24,0	1.228	12.5	8.0	.33	29.5	-	-	46	31	11.7	-	17.2
81	Silo	1.016	9.9	0.5	-	20.8	0.15	0.45	33	21	0.0	0.0	0.5
82	15/0,1	1.061	12.0	0.3	.06	24.4	17.12	29.21	35	23	2.2	3.1	13.4
83	15/9,0	1.114	12.2	1.3	.15	39.2	22.94	33.54	34	23	26.9	-	30.1
84	15/18,0	1.134	12.5	3.3	.18	39.0	20.13	30.50	37	25	19.6	19.4	27.9
85	Silo 3,5 %	1.017	10.0	0.4	-	18.5	0.21	.58	33	21	0.0	0.0	1.7
86	13/0,1 3,5 %	1.055	12.1	0.4	.05	25.9	18.34	27.74	35	23	1.9	1.9	14.8
87	13/0,5 3,5 %	1.182	12.4	2.4	.26	40.0	19.25	28.62	34	24	25.9	-	31.6
88	13/13,0 3,5 %	1.215	12.5	2.9	.31	46.6	23.19	30.79	36	23	25.8	28.5	29.7
89	Silo 3 %	1.015	10.1	0.0	-	19.9	.23	0.57	32	21	0.0	-	0.0
90	10/0,1 3 %	1.106	12.2	0.6	.13	38.0	20.32	34.10	34	22	22.1	-	32.7
91	10/6,5 3 %	1.220	12.6	3.2	.32	73.8	22.07	28.94	36	24	26.6	-	33.1
92	10/13 3 %	1.330	12.7	5.8	.50	89.8	18.96	23.08	41	30	22,3	-	23.1

Karlsplatz München Tixoton

Sample Nr.	Panel Nr. / Sampling depth Nr./m	Density of slurry ϱ_F t/m^3	pH	Bingham yield value τ_0 N/m^2	Sand contents t/m^3	Filtrate water cm^3	Centrifugal test r.p.m 500/10 %	Centrifugal test r.p.m 500/30 %	Marsh Funnel t_{1000} s	Marsh Funnel t_{500} s	Sedimentation after 1 day $d=5,92 cm$ %	Sedimentation after 1 day $d=12,85 cm$ %	Sedimentation after 7 days $d=5,92 cm$ %
53	6/2	1.174	9.6	5.2	.24	10.0	0.20	0.48	52	49	0.0	0.0	0.0
54	6/15	1.205	9.6	5.1	.29	9.8	0.22	0.54	53	54	0.0	0.0	0.0
55	6/30	1.214	9.8	5.0	.31	9.8	0.20	0.60	54	58	0.0	0.0	0.0
56	8/0,5	1.185	11.8	6.2	.26	15.0	0.85	6.87	47	42	0.3	0.4	2.9
57	8/15	1.194	11.9	6.7	.28	16.0	2.31	6.31	49	43	0.5	0.4	6.4
58	8/30	1.187	11.8	5.0	.26	16.0	1.16	6.74	46	40	0.9	0.4	3.0
59	9/0,5	1.175	11.8	5.2	.24	16.2	6.42	14.00	46	45	1.0	0.4	5.4
60	9/15	1.207	11.9	9.5	.29	15.8	3.06	7.28	64	84	0.4	0.4	4.7
61	9/33	1.197	11.9	7.9	.28	15.9	5.12	11.89	58	66	1.1	0.4	5.6
62	Silo	1.021	10.3	4.4	-	17.9	3.41	7.12	36	26	1.8	0.8	6.0
63	11/0,5	1.176	12.3	6.8	.24	36.0	20.54	28.25	41	27	18.0	19.8	21.8
64	11/15	1.242	12.3	17.7	.35	32.2	17.12	24.04	47	35	10.0	0.1	17.2
65	11/33	1.174	12.3	9.0	.24	32.0	19.28	28.63	40	27	14.4	7.6	22.1
66	10/0,5	1.111	12.2	3.3	.14	34.8	21.58	30.18	38	25	21.1	21.2	23.2
67	10/15	1.122	12.3	3.2	.16	34.0	23.62	30.68	38	25	21.3	22.4	25.2
68	10/33	1.147	12.3	3.5	.20	32.8	21.56	30.06	38	26	20.4	19.3	23.3
69	Silo	1.019	10.4	3.2	-	23.0	8.67	21.48	36	25	3.1	2.7	8.2
70	3/0,5	1.145	11.6	2.1	.20	16.2	0.31	1.01	44	33	0.5	0.4	1.8
71	3/16	1.197	11.8	5.2	.28	15.6	4.81	8.21	60	71	0.3	0.4	5.9

Bayerische Landesbank München

Ultragel

Sample Nr.	Panel Nr. / Sampling depth Nr. / m	Density of slurry ϱ_F t/m^3	pH	Bingham yield value τ_0 N/m^2	Sand contents t/m^3	Filtrate water cm^3	Centrifugal test r.p.m 500 / 10 %	Centrifugal test r.p.m 500 / 30 %	Marsh Funnel t_{1000} s	Marsh Funnel t_{500} s	Sedimentation after 1 day d = 5,92 cm %	Sedimentation after 1 day d = 12,85 cm %	Sedimentation after 7 days d = 5,92 cm %
40	Pre-cyclone	1.179	12.0	10.4	.25	51.0	22.57	27.73	54	57	15.2	17.1	16.9
41	Post-cyclone	1.137	12.0	9.0	.18	47.5	17.16	27.51	66	71	11.7	12.4	14.7
42	Silo	1.018	9.5	3.0	-	26.8	34.80	40.40	42	32	22.3	23.6	26.9
43	60/3,5	1.221	12.0	10.6	.32	74.0	18.36	20.33	155	-	11.2	12.5	12.0
44	60/7	1.229	12.0	11.0	.33	76.0	-	-	176	-	10.5	11.0	11.0
45	60/14	1.220	12.0	11.1	.32	75.0	-	-	135	-	11.4	12.9	11.9
46	137/3,5	1.136	9.0	5.3	.18	16.2	-	-	46	36	10.4	9.1	28.9
47	137/7	1.135	9.0	5.3	.18	15.0	16.64	26.59	46	36	8.4	9.7	28.1
48	137/14	1.134	9.5	5.2	.18	15.5	-	-	46	35	17.1	9.9	29.7
49	Silo	1.017	9.5	2.1	-	47.5	42.79	43.78	38	30	28.6	31.1	30.9
50	4/3,5	1.165	11.5	4.2	.23	48.2	26.06	31.98	40	31	28.2	29.7	29.9
51	4/7	1.167	11.0	4.0	.23	48.5	-	-	40	31	28.3	28.7	30.1
52	4/14	1.169	11.0	4.0	.23	52.5	-	-	40	36	27.1	27.9	28.8

Bayerische Landesbank München

Transition from Tixoton to Ultragel

Sample Nr.	Panel Nr. / Sampling depth Nr./m	Density of slurry ρ_F t/m^3	pH	Bingham yield value τ_o N/m^2	Sand contents t/m^3	Filtrate water cm^3	Centrifugal test r.p.m 500/10 %	Centrifugal test r.p.m 500/30 %	Marsh Funnel t_{1000} s	Marsh Funnel t_{500} s	Sedimentation after 1 day d=5,92cm %	Sedimentation after 1 day d=12,85cm %	Sedimentation after 7 days d=5,92cm %
21	77/3,5	1.156	12.2	11.9	.21	22.0	7.05	17.82	44	24	7.4	6.9	17.4
22	77/7	1.156	12.2	10.7	.21	22.0	-	-	44	24	6.8	6.8	17.0
23	77/14	1.148	12.2	10.5	.20	20.4	11.25	15.62	44	23	7.7	7.2	16.3
24	11/3,5	1.155	11.7	0.9	.21	12.0	-	-	43	27	0.7	0.8	0.9
25	11/7	1.164	11.8	0.7	.23	12.8	-	-	42	28	0.7	0.8	0.9
26	11/14	1.173	12.0	1.8	.24	13.6	-	-	42	32	0.5	0.8	0.7
27	Silo	1.024	10.5	4.1	-	15.0	0.23	0.66	35	25	0.5	1.2	0.7
28	Pre-cyclone	1.176	12.3	9.3	.25	37.2	17.83	23.37	55	63	16.5	16.4	17.5
29	Post-cyclone	1.129	-	10.1	.17	30.8	-	25.73	51	52	8.8	10.6	17.2
30	Pre-cyclone	1.148	12.2	11.7	.20	37.5	21.28	26.54	56	53	17.8	17.1	19.8
31	Post-cyclone	1.113	12.2	12.9	.14	31.8	15.24	23.73	65	71	9.4	7.6	16.9
32	70/3,5	1.118	10.5	9.6	.15	13.8	12.34	21.01	61	65	2.3	2.7	14.6
33	70/7	1.116	10.5	9.2	.15	13.6	-	-	62	66	3.5	2.7	15.8
34	70/14	1.125	10.6	9.3	.16	13.5	10.29	19.57	63	64	2.3	1.1	13.8
35	Pre-cyclone	1.186	12.0	9.5	.26	39.8	18.51	24.46	52	52	15.0	16.4	19.2
36	Post-cyclone	1.121	11.5	12.3	.16	32.8	14.12	24.51	60	71	6.8	6.4	16.5
37	52/3,5	1.159	12.0	6.1	.22	53.0	23.28	29.22	45	26	20.5	21.3	21.8
38	52/7	1.162	12.0	5.7	.22	57.0	-	-	44	35	19.6	21.4	21.1
39	52/14	1.150	12.0	6.4	.20	57.0	-	-	44	39	18.9	20.5	20.3

Bayerische Landesbank München Tixoton

Sample Nr.	Panel Nr. / Sampling depth Nr./m	Density of slurry ϱ_F t/m^3	pH	Bingham yield value τ_o N/m^2	Sand contents t/m^3	Filtrate water cm^3	Centrifugal test r.p.m 500/10 %	Centrifugal test r.p.m 500/30 %	Marsh Funnel t_{1000} s	Marsh Funnel t_{500} s	Sedimentation after 1 day d=5,92cm %	Sedimentation after 1 day d=12,85cm %	Sedimentation after 7 days d=5,92cm %
1	Silo - 4,5 %	1.025	11.6	11.3	-	11.3	.25	.56	43	30	0.0	.4	0.0
2	Silo 4,0 %	1.020	10.4	4.4	-	16.2	.83	1.64	33	22	0.0	.2	0.0
3	116/5	1.158	12.4	5.2	.22	33.5	-	-	40	26	18.1	17.5	23.5
4	116/10	1.177	12.2	6.7	.25	33.0	16.67	24.93	41	26	18.9	17.1	24.0
5	116/20	1.167	12.2	5.4	.23	32.5	-	-	41	27	15.7	16.7	22.8
6	storage tank	1.135	12.3	5.9	-	30.5	-	-	38	26	15.0	17.4	-
7	107/5	1.165	12.2	6.5	.23	23.5	8.32	16.70	41	27	12.5	11.6	21.3
8	107/10	1.167	12.2	7.9	.23	22.5	-	-	40	27	11.4	11.2	21.0
9	107/18	1.173	12.2	7.2	.24	24.0	16.12	19.89	41	27	15.6	13.2	23.9
10	Silo	1.020	10.5	2.2	-	17.0	11.89	22.38	34	24	10.6	10.6	24.1
11	80/3,5	1.128	12.2	3.4	.17	35.8	19.63	28.23	39	29	21.5	22.1	24.0
12	80/7	1.131	12.2	3.6	.17	36.5	-	-	39	29	21.8	22.1	23.8
13	80/13,5	1.160	12.2	3.6	.22	39.4	20.15	28.31	40	29	21.9	22.2	24.0
14	17/3,5	1.142	12.1	5.2	.19	28.0	18.71	22.66	38	26	15.6	16.7	25.0
15	17/7	1.144	12.2	5.5	.19	28.0	-	-	38	26	15.0	18.3	25.2
16	17/14	1.152	12.2	5.9	.21	28.0	-	-	39	26	13.0	24.5	23.6
17	storage tank	1.110	12.2	2.0	-	45.5	-	-	36	23	26.1	27.1	-
18	49/5 5 %	1.100	10.9	6.6	.12	13.0	0.54	0.64	39	27	0.3	0.8	0.7
19	49/10 5 %	1.105	10.8	5.9	.13	12.2	-	-	41	27	1.0	0.4	1.0
20	49/20 5 %	1.112	10.8	6.9	.14	10.8	0.25	0.87	41	27	0.5	0.4	0.7

Appendix C

Rotational viscometer tests
for the determination of thixotropic loops

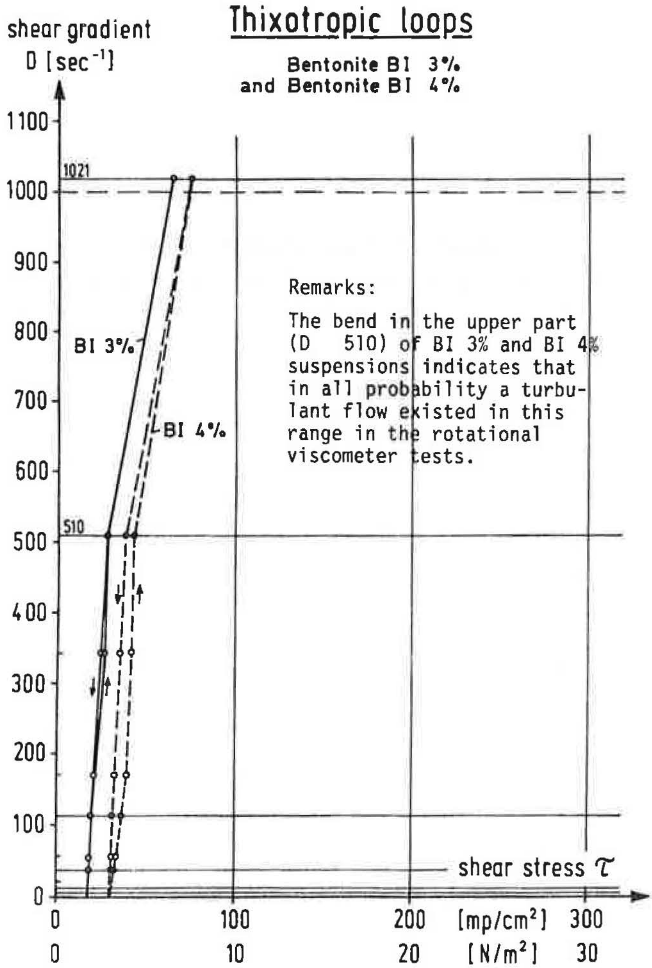

Fig. 17 Rotational viscometer test

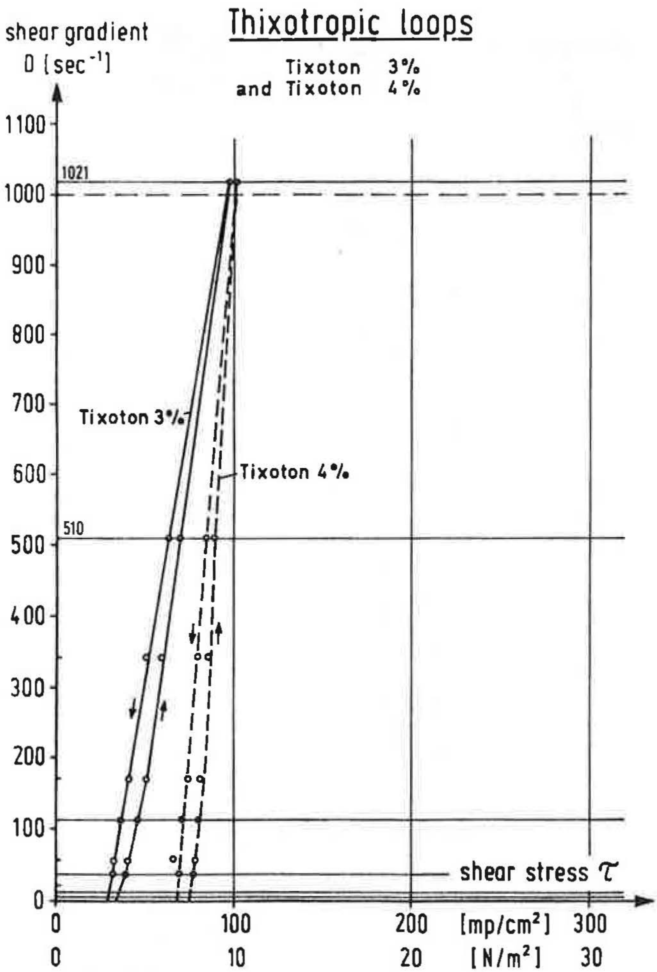

Fig. 18 Rotational viscometer test

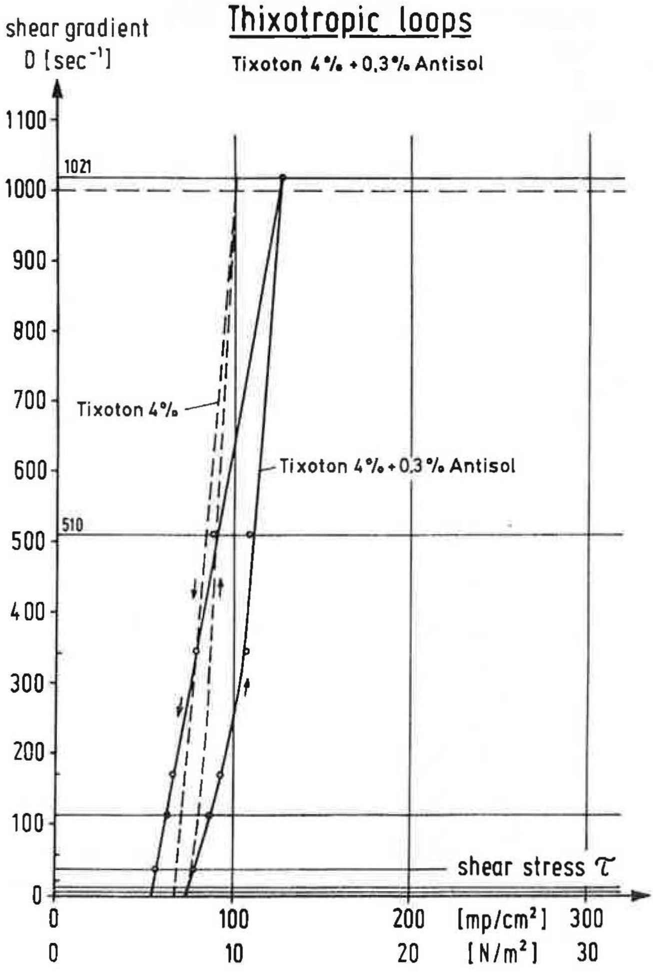

Fig. 19 Rotational viscometer test

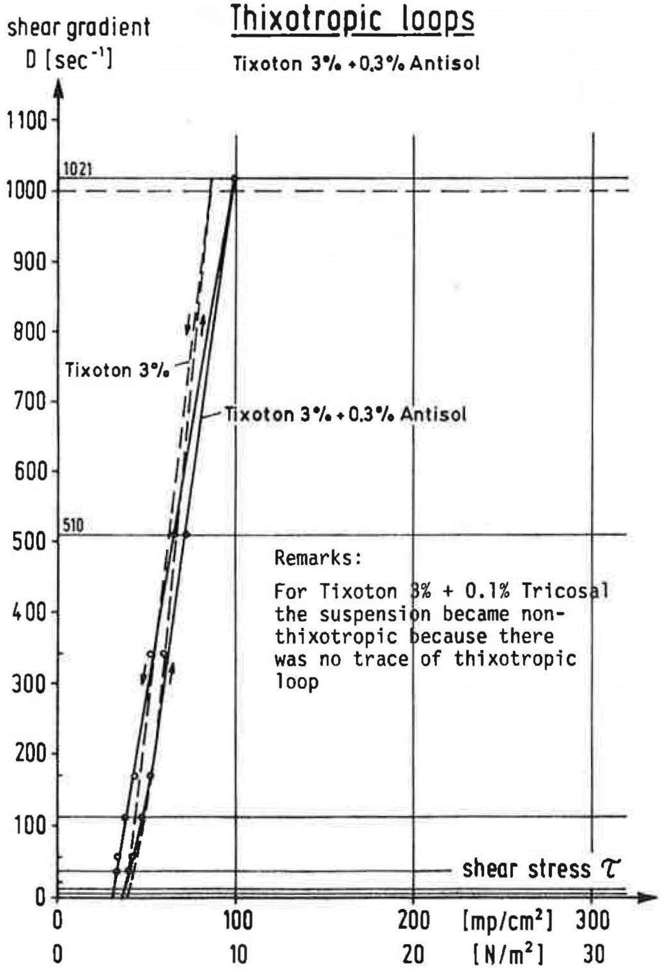

Fig. 20 Rotational viscometer test

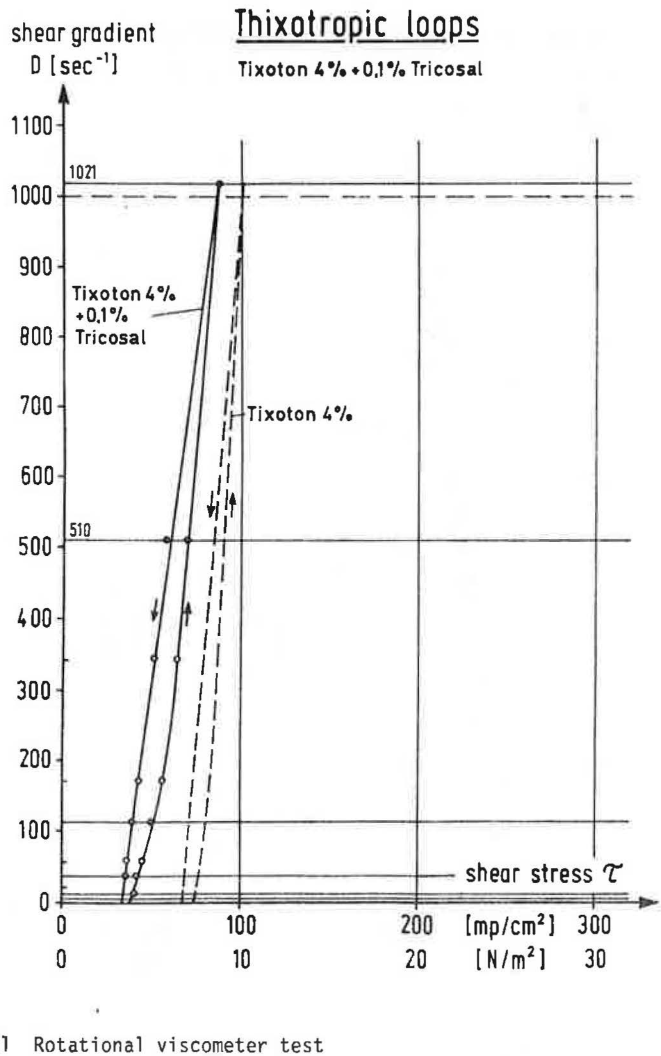

Fig. 21 Rotational viscometer test

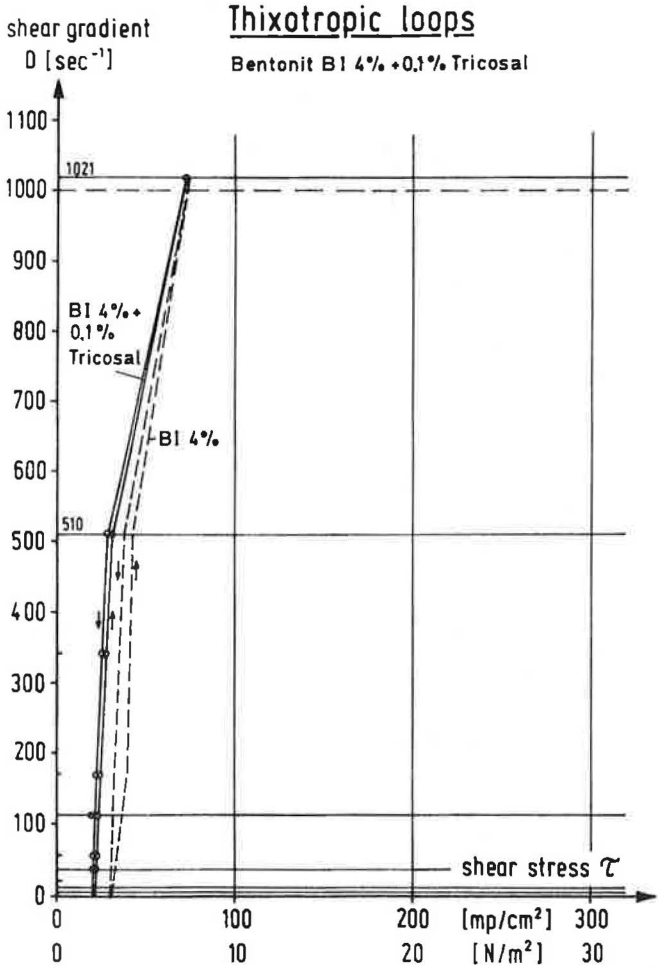

Fig. 22 Rotational viscometer test

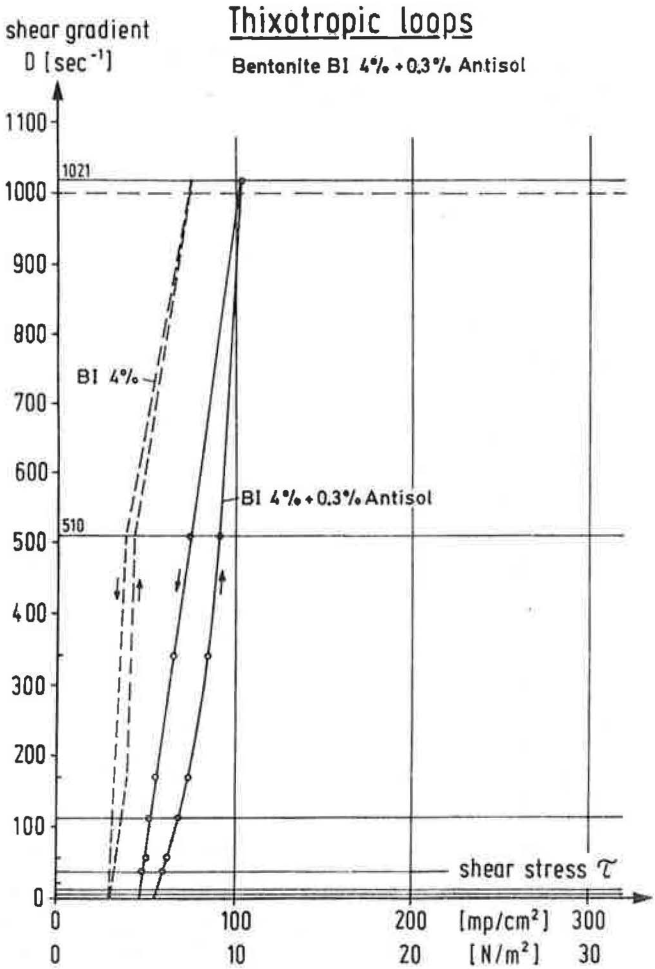

Fig. 23 Rotational viscometer test

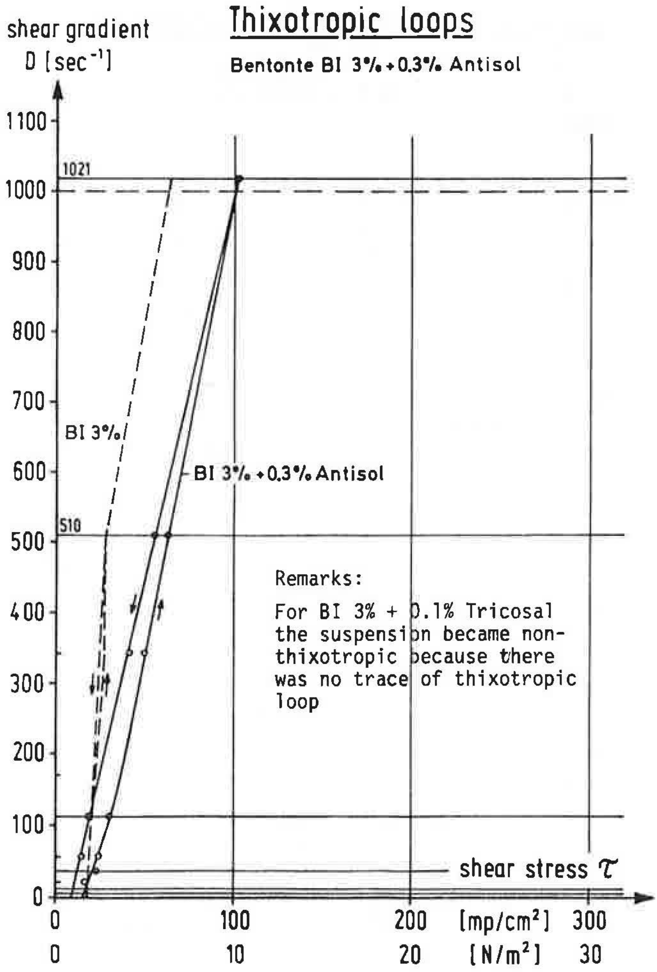

Fig. 24 Rotational viscometer test

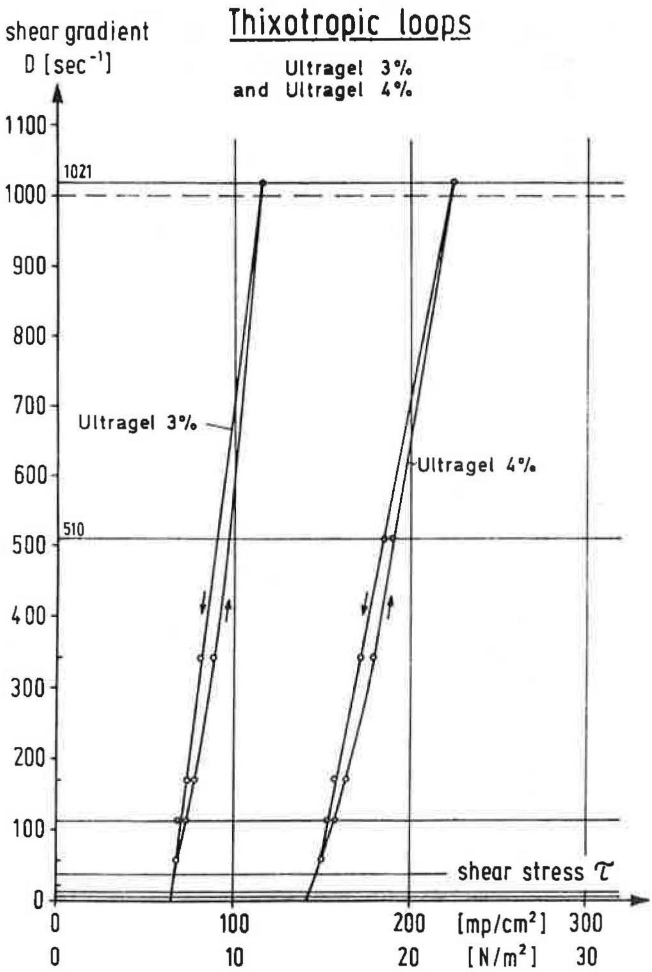

Fig. 25 Rotational viscometer test

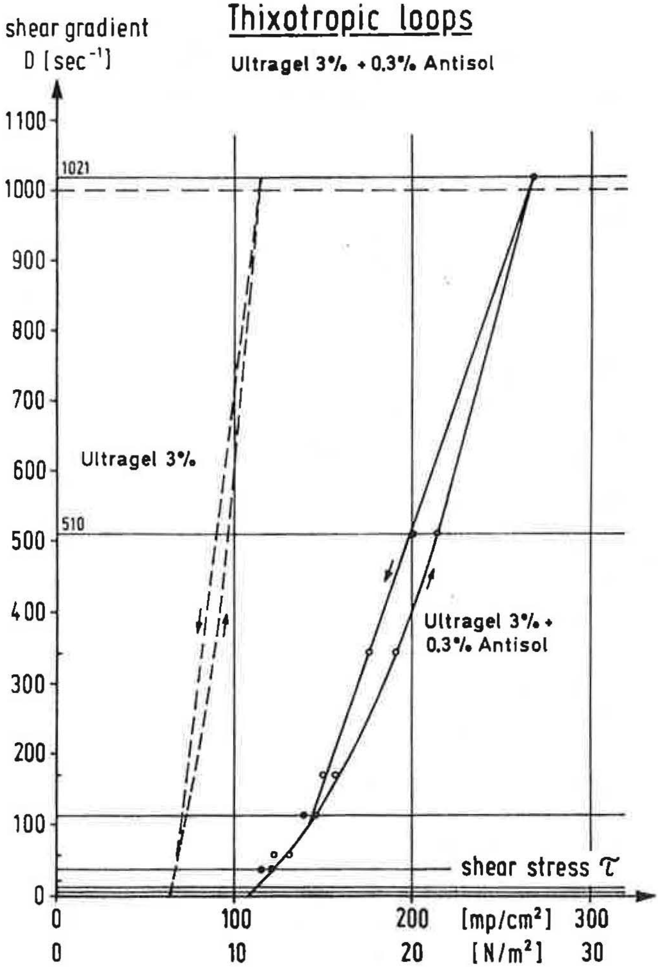

Fig. 26 Rotational viscometer test

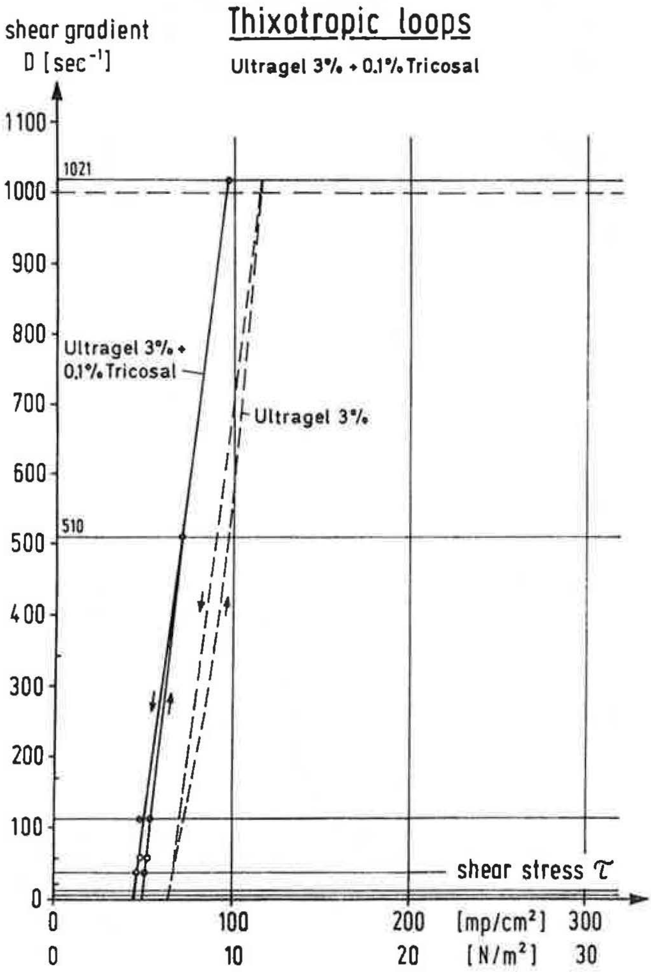

Fig. 27 Rotational viscometer test

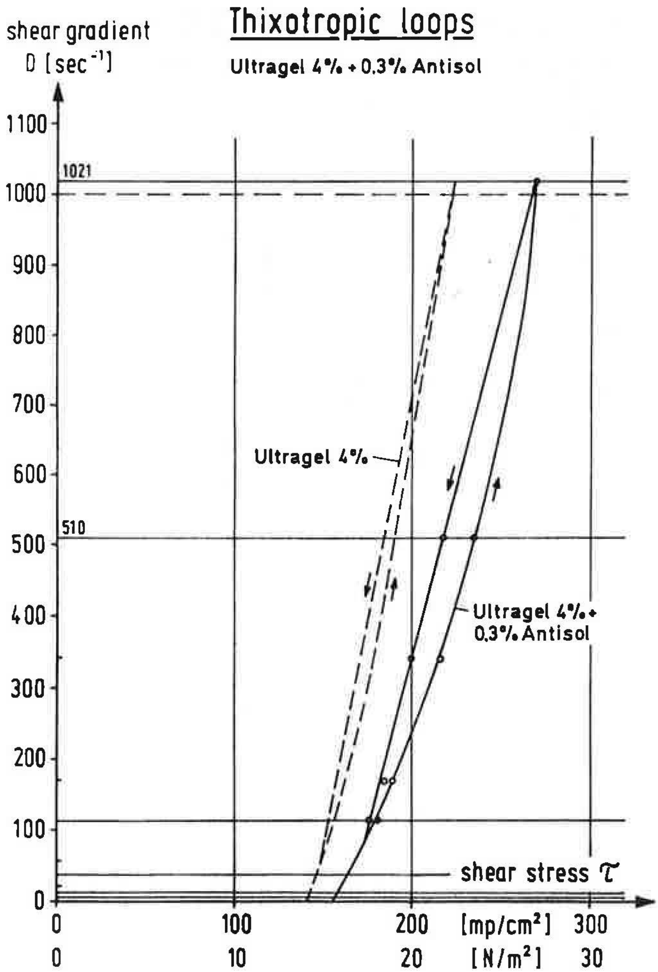

Fig. 28 Rotational viscometer test

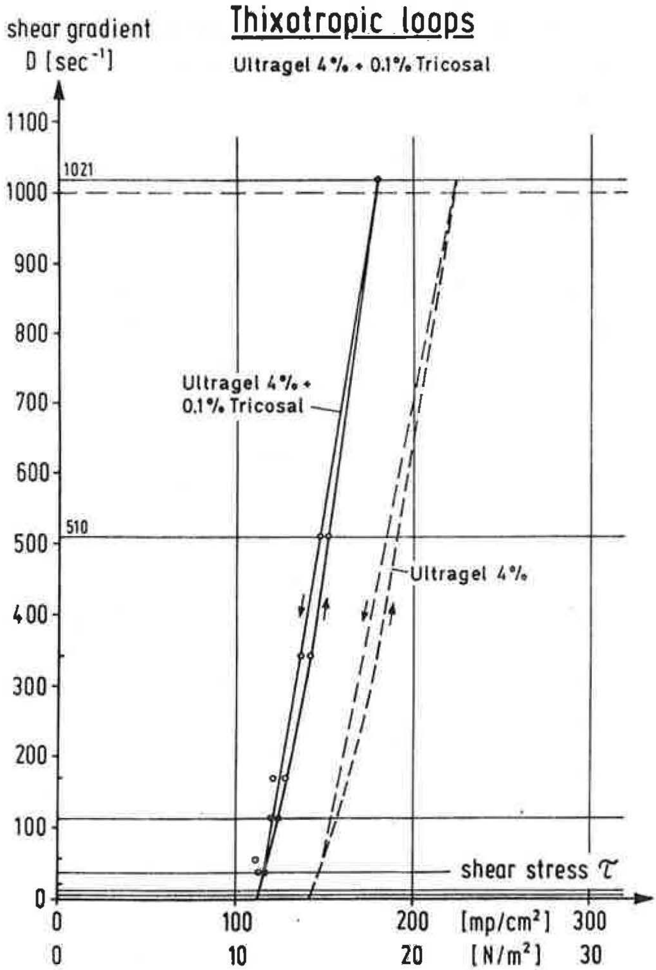

Fig. 29 Rotational viscometer test

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