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SLURRY CUT-OFF WALLS
DESIGN PARAMETERS AND FINAL PROPERTIES
AN INTERIM REPORT

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ABSTRACT

Slurry characteristics and the final in-place properties of slurry cut-off walls are described, including discussions of bentonite hydration, cement-bentonite slurry behavior, and the permeability, strength and compressibility of completed walls. A distinction is drawn between technical and economic factors in the construction process. The recommendation is made that technical specifications should isolate factors important to the quality of the finished product and give the contractor the widest latitude in economic decisions.

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INTRODUCTION

Slurry cut-off walls have been in use in the United States for over twenty years. Worldwide, there have been several hundred applications on projects involving seepage cut-offs, dewatering, pollution control, etc. In spite of this large experience with different types of walls under varying environmental conditions, there has been little data collected on the behavior of slurries during the construction process and on the performance of completed slurry walls.

The main reasons for the paucity of data are the variety of methods and products used, plus the difficulty of testing underground structures which cannot be uncovered and which are too soft to be easily sampled. As discussed below, there are two ways to construct a slurry cut-off wall; each method involves different materials and results in an end product with substantially different properties. Field data seem to indicate that final properties are not too sensitive to variations in materials; however, test results on the slurries during construction can be significantly affected. For example, within a given technique, there may be up to a one hundred percent difference in the quantity of bentonite consumed in slurries of equal viscosity made up from different bentonites. Other materials added to the slurry to form the finished product can also vary. In the case of soil-bentonite (S-B) walls, the soil aggregate can range from well-graded gravel with silt to poorly graded medium-fine sand. Sources for aggregate have varied from custom-blended materials meeting tight specifications to strip mine spoil. In the case of the cement-bentonite (C-B) technique, Portland cements have been used consistently in the United States because of their wide availability. However, other types of cement
(e.g. slag cements) have been shown to yield higher strengths for a
given cement:slurry ratio. In Europe, where several types of cements
are in common use, the French originators of this technique have
expended considerable research effort to determine the relative behaviors
of different cements when mixed in a bentonite-water slurry (Caron, 1972).
When, in addition to the variety of materials used, the difficulty
of testing the completed product, is considered, the reasons for the
lack of data from field installations begin to become clear. Slurry
cut-off walls, by their nature, are relatively weak, flexible membranes
which require support from the surrounding soil, and therefore are always
underground. Many installations are further buried under dams, dikes, or
other surface structures. Opportunities to excavate and observe the
completed walls are infrequent. Soil sampling techniques are of little
use because of the soft nature of the backfill, particularly in the case
of S-B walls. Field tests to measure the most important characteristic,
permeability, are difficult because the permeabilities are typically so
low that complete slurry trench boxes must be constructed to eliminate
outside variables. Because of the high cost of such testing, the number
of instances where it has been carried out are few.

There are a number of drawbacks due to the low availability
of performance data on slurry cut-off wall construction. These
are all due to the difficulty of writing specifications for a product whose
behavior is not well understood. Many engineers are reluctant to use
the technique for the first time, in spite of the successful history of
slurry wall installations. Others tend to repeat the same specification
on a following project after their initial exposure, even though the appli-
cation or soil conditions may differ substantially. In many cases, well-
intentioned specifications have led to problems of basic feasibility or to conflicts with good practice. Due to the lack of testing standards keyed to slurry wall methods, oil well drilling fluid standards are frequently cited. In many cases, this has led to emphasis on the wrong aspects of behavior for controlling slurry cut-off wall construction.

In an attempt to investigate some of the basic parameters of slurry wall construction, this paper examines three topics: bentonite-water slurries; the effect of the addition of cement to bentonite-water slurries; and the final in-place properties of the completed product. The emphasis has been placed on data gathered under field conditions on slurries batched in high-speed operations. Since the data contained here represent only a few combinations of bentonite type, soil conditions and other important variables, the value of the data is somewhat limited. However, as additional data on the basic relationships are gathered, there will evolve a greater understanding than is contained in this interim report.

CONSTRUCTION METHODS

In this section, a brief overview of slurry cut-off wall construction methods, a discussion of their relative advantages, and a description of the main applications of this type of construction are presented. A more detailed discussion of these subjects was presented in an earlier paper (Ryan, 1976) and in some of the other publications cited on the attached reference list.

All of the techniques discussed herein involve excavating a trench which is kept filled with slurry, whose primary ingredients are bentonite clay and water, and whose function is to keep the trench open with vertical sides, even below the water table. The excavation is carried out from the ground surface using any equipment capable of the trench widths and depths required.
After the trench has been excavated under a bentonite slurry, more slurry is mixed adjacent to the trench with the soil backfill. A bulldozer is used to work the material to a smooth consistency; it is then pushed into the trench so that a wave of the backfill displaces the bentonite slurry forward. Excavation and backfilling are phased to make the operation continuous with relatively small quantities of new slurry required to keep the trench full and to mix backfill. This type of construction is called a Soil-Bentonite (S-B) slurry cut-off wall and is otherwise known as the "American method." The S-B technique has the advantage of being most economical in situations where backfill material can be obtained from the trench or from a nearby borrow area.

With a variation on the above technique called a Cement-Bentonite (C-B) slurry trench or "European method," cement is added to the bentonite slurry just before it is introduced into the trench. The resultant slurry has properties substantially similar to normal bentonite slurry with respect to maintaining the sides of the trench. However, once excavation is complete, the C-B slurry remains in the trench, sets up, and forms the permanent watertight wall.

This technique is more expensive due to the higher cost of incorporated materials. However, the backfilling operation is eliminated and the technique provides several technical and construction advantages which may make the use of a C-B wall economical under appropriate circumstances. The advantages include:

- no dependence on the availability or quality of backfill material,
- better suited for excavations in areas prone to failure,
• easier to key sections of wall into one another,
• higher strength to support construction loadings or future structures
• better and more homogeneous quality of the permanent backfill material,
• no requirement for mixing areas, so more suitable for work in confined areas (e.g. dike crests),
• less mess than the S-B method.

Given the relative advantages between the two systems, the project requirements should be evaluated to determine the best method to be selected.

Where possible, it may be most economical to specify both methods and allow the contractor to bid with the least expensive system.

Slurry cut-off walls have been in use in the United States for approximately twenty years. In dewatering applications, where a slurry wall can key into an underlying impervious layer, the amount of water inflow into an open excavation can be dramatically reduced. Slurry walls eliminate many of the problems encountered with systems involving pumping; i.e., no system maintenance or power costs, no headers to interfere with site work, no risks due to breakdowns or strikes, and no water table drawdown in areas adjacent to the site.

Slurry cut-off walls have been used as seepage barriers under dams to reduce water flow under the dam and to reduce downstream pore pressures. They have also been applied to a number of problems where the groundwater table was polluted by various contaminants, including chemical wastes, sanitary landfills, flyash ponds, petroleum, and many others. In some cases, the contaminants have been so concentrated that specially treated bentonite is required to prevent deterioration of the wall.
BENTONITE SLURRY

Bentonite slurries have three required functions in slurry cut-off wall construction. They are:

- To hold the trench open. The slurry must have the properties required to maintain a stable excavation. Experience has shown that keeping above a minimum viscosity of the in-trench fluid is of primary importance.

- To be workable. The slurry must be fluid enough to permit passage of excavating equipment and to allow displacement by backfill. The most important factors are staying below a maximum in-trench viscosity and a maximum unit weight.

- To be impermeable. Once the trench is complete, portions of the slurry remain in place and serve as the primary water stop. The imperviousness of soil-bentonite slurry walls appears to be related to the existence of a "filter cake" and the quantity of bentonite present in the backfill.

In the following section, data is presented on the mixing, hydration and use of bentonite slurry. Some attempt is made to note factors that are related only to the cost of construction. The recommendation is made that contract specifications treat only the technical aspects (as outlined above), and that the widest latitude be given to the contractor over economic aspects.

Hydration of bentonite slurry is the process that begins the instant when the bentonite clay is mixed with water. The duration of hydration is dependent on the mixing system used, length of mixing time, grade of bentonite, chemical properties of the water and numerous other factors. Hydration is also called "swelling" and, in simplified terms, constitutes the attachment of water molecules to the bentonite platelets through electrical bonding. During the hydration process, several important properties of the bentonite-water slurry change. In the following paragraphs,
methods of measuring hydration are discussed, and factors controlling hydration under field mixing conditions are explored.

Two tests are commonly used to measure hydration. Both tests are derived from standards published by the American Petroleum Institute (API). The first is the Marsh-funnel viscosity. In this test, a known volume of slurry is allowed to flow out of a funnel of standard dimensions, and the viscosity measured in seconds. A normal slurry has a 42 second viscosity. Marsh-funnel viscosities have great importance because they have been found empirically to relate to trench stability. Trenches will seldom fail if the viscosity is maintained above 38 seconds. In general, hydration time seems to be, for a given bentonite, independent of bentonite quantity; however, the increase in Marsh-funnel viscosity during hydration is normally greater for higher bentonite quantities. The second measure of hydration is the filtrate test. In this test, a sample of slurry is subjected to a constant pressure and squeezed through filter paper. The volume of water escaping (milliliters) is inversely affected by both degree of hydration and bentonite quantity. Hydration time measured by the two techniques may vary substantially. For example, for Ultragel 180 samples mixed under field conditions on the same site, Marsh-funnel viscosities increase and stabilize after less than one hour while filtrate tests show a decrease and eventual stability after about eight hours (Figs. 1 and 4).

The terms "filtrate loss" and "filter cake" will be used throughout the rest of this paper. It is important at this point to discuss the inter-relationship between the two terms and what is known about their contributions to the final impervious quality of the wall. In the trench, water under pressure leaves the slurry and exits through the sides of the trench. This filtrate loss causes a buildup of a bentonite paste on the walls of the trench called a filter cake. Greater filtrate loss causes a thicker cake. There has so far been no data to show that, if all other
conditions are equal, lower filtrate loss yields a more impervious wall. In fact, since the cake is thicker with high filtrate loss, the effect may be the opposite. The reasons for the concern of API specifications (written for deep drilling) with filtrate loss have no pertinence to slurry trenching. In deep drilling, pressures are many times greater than in slurry trenching, so filter cakes will be thicker; a thick cake will impede the passage of return drill fluids and possibly even interfere with the rotation or withdrawal of drill tools. These conditions do not affect slurry trenching.

Two kinds of mixing systems are commonly used on slurry wall sites. The first type is essentially a batch system. Water and bentonite are measured into a tank with a volume normally of two to five cubic yards, and subjected to high-speed agitation by a circulation pump or paddle mixer. Agitation is continued until hydration is complete, normally a matter of minutes and the slurry is then ready for use. Because of the relatively low output of this type of mixer, its use is normally confined to structural slurry wall sites or to smaller cut-off walls sites. The second type of mixing system is a flash mixer, also called a venturi mixer. In this system, water is forced at a constant rate through a nozzle and bentonite is fed constantly into the stream. The resultant mix is then stored in a circulating pond until hydration is complete, normally overnight. Hydration takes longer because the slurry is subjected to high-shear mixing for only a fraction of a second. Productivity, however, is high; bentonite can be mixed at rates as high as 25 tons per hour. Since most cut-off walls require high production mixing, most sites currently use flash mixers. All the field data contained in this report were obtained from flash mixing systems unless otherwise noted.
The grade of bentonite used makes a significant difference in hydration time. Since the grade of bentonite also affects bentonite consumption, filtrate loss results are also affected. American Colloid manufactures three principal types of bentonite for slurry trenching: SPV 200, Premium Gel 125, and Ultragel 180. A fourth type, Saline Seal 100, is used in toxic underground conditions and is roughly equivalent to Premium Gel 125 in efficiency. Consumption of bentonite per cubic yard of slurry to yield a hydrated 40-second slurry for the listed bentonites can vary from as low as 50 lbs for the peptized Ultragel 180 to as high as 120 lbs for SPV 200, depending on water quality. Figure 1 shows the difference in hydration time for two bentonites mixed under similar conditions. The variation of filtrate loss versus viscosity is plotted in Figure 2. The significant difference in hydrated filtrate losses is primarily due to the difference in the bentonite quantity per unit volume.

One area in which many technical specifications in current use are especially deficient is in sections pertaining to bentonite consumption. On almost all projects, the cost of bentonite incorporated together with slurry losses is paid by the contractor. It is therefore in the contractor's interest to minimize slurry losses and it is not necessary for written specifications to address this problem. It is also true that on most permanent slurry wall installations and on almost all temporary applications, the most important factor is to use a construction procedure that will provide a continuous wall, and the grade of bentonite used has no significant effect on the performance of the finished product. In spite of this, specifications frequently contain language that rules out use of more efficient bentonites. For example, there are frequent references to minimum pounds per barrel and also to maximum filtrate loss. In some
cases, certain bentonites are specified together with a minimum bentonite/water ratio that would yield an unworkable slurry. Filtrate losses as low as 16 ml are specified. As seen on Figure 2, the super-efficient Ultragel 180 can never meet this strictly a requirement.

The recommendation of the author is that specifications concentrate on the in-trench viscosity; an ideal working range should be specified together with a maximum deviation outside this range. Where possible, consistent with the bentonite manufacturer's recommendations, the use of peptized bentonites should be allowed. This type of specification will yield the lowest cost and will not cause unnecessary conflicts during construction.

The effect of water temperature on hydration characteristics is somewhat confused. According to the proceedings of the Symposium on Grouts and Drilling Methods (1963), warm water aids bentonite hydration. Figure 3 shows the results of a series of recent laboratory tests which were run in an attempt to verify this. Samples of bentonite/water slurry were mixed and maintained at three temperatures: near freezing, room temperature, and near boiling. The coldest sample seemed to hydrate more quickly and more completely, according to viscosity measurements. Afterwards, all samples were returned to room temperature—the heated samples' viscosity rose and the cooled samples' dropped. The results are unclear, but the conclusion can be made that, within the range of temperatures normally found on site, there is no great difference due to water temperature in either bentonite consumption or hydration characteristics.
A site variable which has a tremendous impact on both bentonite consumption and on hydration is water quality. Even water suitable for drinking may be totally impossible to mix with bentonite if it is too hard or if it has high concentrations of electrolytes. While no data is presented in this paper, it is certainly true that water which is acid, salty or hard has a significant impact. Poor water will cause higher bentonite consumption and usually shows up in lumpy slurry with above-average free water. Free water escapes from the slurry, rising to the top of the trench or pond, and eventually is lost. Various chemicals can be added to bad water to bring it within workable limits.

CEMENT-BENTONITE SLURRY

The C-B slurry cut-off wall requires that cement be added to the bentonite slurry. Normal cement dosage is about 300 lb/yd. The functions of the C-B slurry are the same as for bentonite slurry: to hold the trench open, to be workable, and to be impermeable. There are two important differences (between S-B and C-B walls) in the factors which affect the above functions. First, since there is not separate backfilling operation, the C-B slurry may be more viscous and heavier, provided that the excavating equipment can still dig. Second, the imperviousness of the final wall is related only to the material proportions present in the in-place slurry. The addition of cement to the slurry has certain effects on the slurry properties. In this section the behavior of cement-bentonite slurry is described, and the important variables are discussed.

Any specification on cement-bentonite slurries should recognize that the fluid will set. A normal mixture subjected to typical trenching operations begins to set after a few hours and has a consistency similar to lard after 12 hours. The second day, the C-B slurry can usually be
walked on. Final set is normally taken at 90 days rather than the 28 days used for concrete. The setting phenomenon makes in-trench viscosity rather difficult to control, although a minimum viscosity should be maintained to keep the trench stable.

The change in viscosity due to the addition of cement seems to depend on the mixing method. Using batch mixers, the bentonite-water slurry is hydrated for several minutes and then the cement is added. Normally the Marsh-funnel viscosity remains approximately constant or drops slightly. When cement is mixed with hydrated bentonite-water slurry after flash mixing, the viscosity normally rises significantly. The difference seems to be that the flash mixing plus storage actually hydrates the bentonite better than batch mixing. In batch mixing, the tendency of the addition of solids to thicken the mix is probably offset by the chemical activity of the cement interfering with the hydration of the bentonite.

There have been several examples of specifications that place almost impossible requirements on the mixing process. The bentonite-water mix may have a specified minimum viscosity and the cement-bentonite a specified maximum viscosity which is too low. Other specifications have a working range for cement-bentonite slurry that is so low that the bentonite slurry must be mixed too thin. In general, on jobs where flash mixing is to be used, the ideal range for the cement-bentonite slurry Marsh-funnel reading should be 45–55 seconds. Where batch mixing is to be used, the range can be lower, 40–45 seconds. Since no replacement of the slurry by backfill is necessary, the thicker mix can have no negative effects.

Another aspect of C-B slurry behavior is a high filtrate loss. Figure 4 shows that, for Ultragel 180 bentonite slurry, the filtrate loss decreases to a constant after about eight hours. Upon the addition of
cement, the filtrate loss increases dramatically and continues to increase with time until the setting process takes over. Specifications on filtrate loss for C-B slurries therefore have little meaning unless related to time.

The question of filtrate loss in C-B slurries has caused severe contractual problems on several sites where maximum filtrate losses have been specified. The fact is that a higher filtrate loss is related to a greater loss of water through the walls of the trench, resulting in a higher solids content in the finished product. There is no evidence that this is detrimental to the final properties. Studying one aspect of this behavior, Caron (1973) reversed the normal mixing process and added bentonite to maintain a constant viscosity. He reported that the strength of samples where cement was mixed first, bentonite second, was the same as samples with equivalent cement-water ratios that were mixed in the normal manner.

In a current experiment with two different bentonites, the mixing order was reversed, and the resultant bentonite and cement proportions kept constant, and the resultant slurries allowed to set in a vertical cylinder. The difference in free water was dramatic. Samples containing Ultrage 180 lost almost sixty percent of their volume in free water and samples containing Premium Gel 125 lost about fifty percent. In contrast, samples where the cement was mixed in the same proportions with well-hydrated bentonite slurries, free water losses were seven and three percent, respectively. These samples will be tested for comparative strength and permeability.

If, as expected, these samples have strengths and permeabilities that are equivalent to or better than the normal samples, there is an important conclusion to be drawn. Clearly the method of mixing cement first is the worst possible method and yields the highest filtrate loss and greatest loss of materials. However, if the finished product is acceptable, the
only problem is economic and therefore the filtrate loss should not be treated in technical specifications. A contractor should control hydration to minimize his own costs, but should not be compelled to waste slurry that occasionally does not meet a tight specification. The current testing will have to be completed and probably additional testing carried out before this finding can be confirmed.

FINAL PROPERTIES

The principal properties of concern in their usual order of importance, are permeability, strength, and compressibility. In this section measurements of values for these three properties are presented. Emphasis is on data measured in the field and on laboratory data on field samples. In a few instances, laboratory-prepared samples are discussed to illustrate certain points.

A fourth parameter, durability, has implicit importance in permanent installations. Little data is available, but slurry trenches are installed in many situations where permanence is a requirement. Bentonite is stable under most environmental conditions. In the case of C-B slurry, cement may be subject to attack by sulphates or other chemicals in the groundwater. The depth of penetration under low flow conditions in a chemically hostile environment, and its subsequent effect on a wall which has a substantial bentonite content has not been studied in detail. There have been no reported failures of slurry cut-off walls in the U. S. Caron (1973) reports that numerous field samples of old C-B walls showed no evidence of deterioration.

Permeability has been the subject of numerous field and laboratory studies. In a full scale test for a Midwestern utility company
a square box 60 ft. on a side and 70 ft. deep was constructed of C-B slurry. Then a diagonal of S-B slurry wall was constructed through the box. Sufficient instrumentation was installed inside and outside the test area to monitor behavior. Heads were varied by pumping internally from deep wells. The results showed the C-B wall to have a permeability of $3 \times 10^{-6}$ and the S-B wall to have a permeability of $6 \times 10^{-7}$ cm/sec.

In a separate test program, block samples were taken from the top of a completed C-B Slurry wall. The mix was 75 lbs of Ultragel 180 and 234 lbs of cement per yd of slurry. Permeabilities measured 2 months after construction and on laboratory samples ranged from 5 to $20 \times 10^{-7}$ cm/sec. Some sample disturbance of the field samples was suspected. Although there is some buildup of concentration near the edges of the trench, cement-bentonite does not form a cake. The permeability derives from the concentration of solids in the completed wall. The relationship between the quantity of solids (i.e., cement bentonite) and the eventual permeability of the wall has not been well documented.

A recent series of laboratory tests was made to try to understand the factors that contribute to the impermeability of a soil-bentonite wall. A pure bentonite cake had a measured permeability of about $10^{-8}$ cm/sec. The thickness of cake may be less than a centimeter, but this is still a significant contribution towards impermeability. Two types of sand backfill were tested, with natural permeabilities in the range of $10^{-4}$ to $10^{-5}$ cm/sec. Upon mixing with bentonite slurry, the permeabilities dropped to $2 - 6 \times 10^{-7}$ cm/sec in laboratory measurements. The conclusions reached were that the impermeability of backfill is first dependent on the quantity of bentonite (dry weight) and second on the presence of some fines in the backfill.
material. Since the quantity of bentonite is the most important factor in the backfill, this should be specified. In situations where the natural water content of the backfill material is high, a thicker slurry may be used to avoid making the backfill too soupy. The gradation of backfill is also important. Preliminary test data show that the percentage of minus 200 sieve material has a secondary relationship with impermeability. A range of 10 – 30 percent is recommended, where possible. The balance of the backfill material should ideally be well graded sand and gravel. This type of material will achieve a better final strength and provides a more stable matrix to contain the bentonite particles.

The strength of slurry walls is an important factor where loads of future structures or construction equipment are to be applied. Soil-bentonite walls are extremely hard to sample because of their soft nature. Some walls never set up, and will always maintain a consistency like butter (Sherard, 1963). There have been some cases where S-B walls have attained unconfined strengths in the range of 10 – 15 psi. C-B walls are more easily sampled and tested. Figure 5 shows a series of laboratory results for various C/W ratios, and on the same graph are plotted results of tests on field samples. For typical cement contents used currently in the U. S. of 2 1/2 – 3 1/2 bags per yard, unconfined strengths normally lie between 10 and 20 psi. As shown in the next section, the strength increases substantially under confining pressure and under drained shear conditions.

A requirement that is frequently placed on slurry cut-off walls is that they be flexible, move with surrounding ground, and not crack or create hard spots under future structures. In both the case of S-B and C-B walls, flexibility far exceeds the possible deformations
of ground under typical loading conditions. Figure 6 shows stress strain curves for C-B slurry samples taken from an actual installation, and tested two months after construction. A high deformability is apparent. The consolidated-drain test was carried to 28 percent strain without peaking in shear stress. By varying the bentonite and cement quantities, flexibility can be designed into the wall.

CONCLUSIONS

Slurry cut-off walls are coming into increasing application on projects where a positive barrier to groundwater flow is required. In recent years the number of times that slurry walls have been chosen for dewatering and combatting groundwater pollution has been rising rapidly. A constant problem in slurry cut-off wall design and construction is the lack of information relating slurry composition and behavior to the final design properties. The type of information presented in this paper can show a few basic trends and, when combined with similar data on other projects, will form the basis of a rational design process. A second side to the problem is to make the information available so that design engineers can assess the requirements for their projects and use the data to write technical specifications which will assure that the final product will serve adequately. There is little purpose in overdesigning installations beyond requirements, and the resultant cost penalties can be substantial. The principal conclusions or trends that can be inferred at this time are listed below. The first section deals with technical factors that relate to the final properties of the completed wall.

- In S-B cut-off walls, the impermeability is primarily related to the bentonite content of the backfill and the cake (which has a permeability at least an order of magnitude
lower). A secondary effect is attributable to the percentage of fine soil particles in the backfill. The permeability is normally in the range of $10^{-6}$ cm/sec.

- Since the concentration of bentonite in the backfill is important, the slurry that is mixed with the backfill soil may have to have a different viscosity (percentage of bentonite) than the bentonite used in the trench. The exact amount should be determined by the desired workability of the backfill mix and the initial water content of the backfill soil.

- The gradation of the backfill has importance with respect to the in-place strength of the material. A well-graded backfill with gravel particles will yield the most rigid mix.

- The permeability of cement-bentonite slurry walls appears to depend primarily on the concentrations of the constituent materials. Filtrate losses appear not to cause the formation of a cake but apparently do result in a more or less equal increase in concentration of the C-B mix across the width of the trench. Permeabilities generally range about $10^{-6}$ cm/sec and below.

- The strength of C-B slurry walls depends primarily on the in-place cement:water ratio. There is sufficient reason to believe that this ratio increases by at least ten to twenty percent after mixing, due to filtrate losses. Soil particles in suspension may cause a further increase in strength.

- The primary specification on the slurry during trenching should relate to workability, i.e. viscosity. In the case of C-B slurry the maximum is related to the ability of the backfill material to replace the slurry. In the case of the C-B slurry the maximum viscosity relates to the ability to dig. In the case of S-B slurry, a maximum unit weight is desirable. For C-B slurry, this is usually important only in the case where excavation is carried out by equipment suspended on cables.

- Permeability of both types of wall depends primarily on the percentage of incorporated materials: the importance of degree of hydration as measured by viscosity or filtrate loss with respect to permeability is not known. In fact there is some
reasonable to believe that high filtrate losses actually improve permeability.

- Slurry trenching is an inexact art. Specifications should recognize the existence of normal variations in slurry properties during trenching. The imposition of strict limits on slurry properties can increase costs without substantially improving performance.

The conclusions listed below apply primarily to slurry behavior as it relates to the economics of slurry trenching. There is an implicit assumption that increased consumption is beneficial to wall performance from a technical standpoint. In fact, this is not always true. For example, some C-B installations have had strict minimum requirements on deformability. A cement:water ratio that increases more than expected during trenching may yield a more rigid product.

- The primary purpose of controlling the proper hydration of bentonite slurries is to reduce consumption. Poorly hydrated slurries lose more water by sedimentation and filtrate loss. The losses are even worse with cement-bentonite slurry.

- Simple lab tests have shown that the temperature of mixing water has no significant impact on hydration characteristics of bentonite slurry. The trend, however, seems to be the opposite of what would be expected -- colder water leads to a faster increase in viscosity and a higher hydrated viscosity.

- There are substantial differences in bentonite consumption for the various grades of bentonite available. Study of cost and loss factors will lead to the choice of the most economical bentonite for a given project.

- To assess proper hydration, both filtrate loss tests and viscosity measurements should be made. Hydration time measured by these two methods can differ substantially.
Slurry cut-off walls will undoubtedly continue to see
a wider range of applications. Proper understanding by the design
engineer of technical factors important to design and proper consider-
ation by the contractor of economic factors will lead to the optimum
product at lowest cost. Continued collection of data on these subjects
is essential to this purpose.
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FIG. 1  TYPICAL HYDRATION CURVES
VISCOITY Vs. TIME
BENTONITE / WATER SLURRY

NOTES:
1. ALL SAMPLES ARE BUCKET SAMPLES TAKEN AT MIXER OUTLET.
2. B/W SLURRY MIXED IN FLASH MIXER ON SITE.
FIG. 2  VISCOSITY VS. FILTRATE LOSS  BENTONITE/WATER SLURRY
NOTE:
LABORATORY SAMPLES MIXED FOR ONE MINUTE IN HIGH SPEED PADDLE MIXER.

FIG. 3  EFFECTS OF TEMPERATURE ON HYDRATION
NOTES:
1. (40) — INITIAL VISCOSITY MEASUREMENTS.
2. POINTS CONNECTED BY LINES ARE TESTS ON THE SAME SAMPLE.
3. BENTONITE - WATER MIXED IN ON-SITE FLASH MIXER, STORED IN BUCKET.
4. CEMENT - BENTONITE MIXED IN ON-SITE 12 YARD BATCHER.

FIG. 4 FILTRATE LOSS VERSUS TIME FOR BENTONITE AND CEMENT-BENTONITE SLURRIES
FIG. 5 UNCONFINED COMPRESSION TESTS ON CEMENT-BENTONITE SLURRY
NOTES
1. ALL TESTS ON 60 DAY OLD C-B SLURRY.
2. C/W RATIO = 0.11
3. 70 LBS./YD. ULTRAGEL BENTONITE

FIG. 6 TRIAXIAL TESTS ON CEMENT-BENTONITE SLURRY