CHAPTER 7

DRILLING FLUIDS IN DRILLED SHAFT CONSTRUCTION

7.1 INTRODUCTION AND BACKGROUND

Drilling fluid is employed in the wet method of construction, as described in Chapter 4, and may also be used with the casing method of construction. Drilling fluid therefore plays an important role in drilled shaft construction and its proper use must be understood by both contractors and engineers. When a drilled shaft is to be installed through potentially caving soils or below groundwater, filling of the excavation with properly-mixed drilling fluid allows the excavation to be made without caving. As described in Chapter 4, once the excavation has been completed through the potentially caving layer, construction typically proceeds in one of two ways. In one procedure, a casing is installed and sealed into impermeable soil or rock. The fluid is then bailed or pumped from inside the casing. The shaft can be excavated in the dry to greater depth, followed by placement of the concrete. The second procedure is to maintain fluid in the excavation until the final depth is achieved. Concrete is then placed by tremie starting at the bottom of the borehole, so that the rising column of fluid concrete completely displaces the drilling fluid (slurry-displacement method). In either of these procedures the drilling fluid must have the proper characteristics during the drilling operations and, for the slurry-displacement method, at the time of concrete placement. The required characteristics of the drilling fluid and proper procedures for handling the fluid are the topics of this chapter.

Water alone is sometimes used as a drilling fluid and may be quite effective where the formations being penetrated are permeable but will not slough or erode when exposed to water in the borehole. Examples of formations suitable for using water include permeable sandstone and cemented sands. The level of water in the excavation should be kept above the piezometric surface in the natural formation so that any seepage is from the excavation into the formation, and not from the formation into the excavation. Inward seepage (into the excavation) is likely to cause sloughing of the sides of the borehole.

During the 1950's and 1960's it was common practice for drilled shaft contractors to create a slurry by mixing water with on-site clayey soils, primarily for use with the casing method. The resulting fluid has properties that are difficult to control and suffers from the fact that it is unstable -- that soil particles are continuously falling out of suspension -- which makes cleaning of the borehole difficult and which can lead to soil settling from the slurry column into the fluid concrete during concrete placement if the wet method of construction is used. For this reason the use of drilling fluids made from on-site materials, referred to as uncontrolled slurry, is not normally recommended for drilled shaft construction.

Drilling fluids are made from several different types of materials which when mixed with water can be controlled in a manner that makes them highly effective for the support of boreholes. Suitable materials include several naturally occurring clay minerals, and polymers. Bentonite is the common name for a type of processed powdered clay consisting predominately of the mineral montmorillonite, a member of the smectite group. Technologies pertaining to the use of mineral slurries as drilling fluids have been developed extensively by the petroleum industry, and many references on bentonite slurries are available; for example, Chilingarian and Vorabutr (1981) and Gray et al. (1980). While these references are useful, this information must be balanced by knowledge gained through field experience pertaining specifically to drilled shaft construction. Other processed, powdered clay minerals, notably attapulgite and sepiolite, are occasionally used in place of bentonite, typically in saline groundwater conditions. Any drilling fluid that is made from one of these clay minerals is referred to as mineral slurry.

A second group of materials used to make drilling slurry is polymers [from Greek *polymeres*, having many parts: poly + merous]. The term polymer refers to any of numerous natural and synthetic compounds, usually of high molecular weight, consisting of individual units (monomers) linked in a chain-like structure. Synthetic polymer slurries made from acrylamide and acrylic acid, specifically termed anionic polyacrylamide or PAM, entered the drilled shaft market beginning in the 1980's. More recently, advanced polymers made by combining polyacrylamides with other chemicals have been introduced in an effort to improve performance while minimizing the need for additives.

A growing trend of increasingly strict regulations governing the disposal of drilling fluids has become an important issue for drilled shaft contractors. Mineral slurries must be handled carefully, not allowed to flow into surface water or sewers, and disposed of in an approved facility at the end of a project. These requirements generally force the contractor to handle mineral slurries in a closed loop process -- that is, to condition slurry continuously and re-use it from borehole to borehole in order to eliminate the need to spoil the slurry on the site and to minimize the amount of slurry that has to be disposed of at the end of the project. Such careful handling obviously adds to the cost of excavating with mineral slurry. Handling and disposal of polymer slurries may also be subject to environmental regulations. Some jurisdictions require waste polymer slurry to be transported to a waste water treatment plant after obtaining the plant's approval. Concerns have also been raised over the potential effects of polymer-based slurries on drinking water aquifers.

While drilling fluids have proved effective in advancing boreholes through many types of unstable soil and rock, the use of drilling fluid of any type should be avoided for economic reasons unless it is necessary for the completion of a borehole. The additional cost on a job can be considerable for drilling fluid materials, handling, mixing, placing, recovering, cleaning, testing, and disposal.

7.2 PRINCIPLES OF DRILLING FLUID PERFORMANCE FOR DRILLED SHAFTS

With proper use and handling, both mineral and polymer slurries are effective in meeting the principal objectives of (1) maintaining a stable excavation, and (2) allowing clean displacement by fluid concrete. However, the mechanisms controlling the performance characteristics of each type of slurry are different.
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7.2.1 Mineral Slurries

Bentonite and other clay minerals, when mixed with water in a proper manner, form suspensions of microscopic, plate-like solids within the water. When introduced into a drilled shaft excavation, this solid-water suspension, or slurry, contributes to borehole stability through two mechanisms:

1. formation of a filter cake (or "mudcake"), which effectively acts as a membrane on the sidewalls of the borehole
2. a positive fluid pressure acting against the filter cake membrane and borehole sidewalls

The concept is illustrated in Figure 7-1. For the filter cake to be established, fluid pressures within the slurry column in the borehole must exceed the groundwater pressures in the permeable formation (*i.e.*, positive fluid pressure), causing the slurry to penetrate the formation and depositing suspended clay particles on the surface of the borehole. The action of clay particle transport and deposition is termed "filtration" and once the filter cake is formed filtration gradually stops. At this point, a positive fluid pressure must be maintained to provide continued stability. As shown in the figure, it is necessary to maintain a slurry head inside the borehole so that the fluid pressure on the inside surface of the filter cake exceeds the fluid pressure in the pores of the soil in the formation. This differential pressure and the resulting seepage into the formation cause a positive effective stress against the walls of the borehole, which acts to hold the membrane in place. It is the combination of membrane formation and positive fluid pressure against the borehole wall that enables a mineral slurry to stabilize a drilled shaft excavation. Unless the contractor continuously maintains a positive head difference, however, the borehole could collapse, because backflushing of the filter cake can occur if the head in the slurry column becomes less than the head in the formation, even for a short period of time.

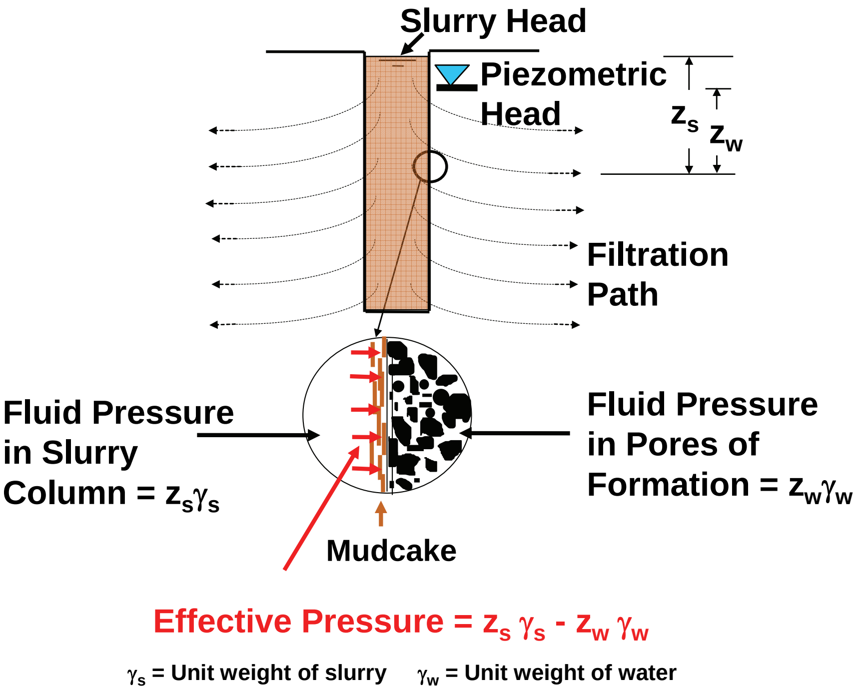


Figure 7-1 Formation of Filter Cake and Positive Effective Pressure, Mineral Slurry in Sand Formation

Several important factors can impact the ability of bentonite slurry to function as intended. The most important of these are: (1) proper hydration, (2) pore size distribution of the permeable formation, and (3) suspension of solids derived from the excavated materials. Each of these is discussed below.

In order for bentonite slurry to form a proper filter cake and suspend cuttings, the individual clay particles must be fully hydrated. Hydration refers to the formation of an electrochemically bound layer of water surrounding each particle. Once formed, the colloidal suspension promotes repulsion of the bentonite particles, referred to as dispersion, and keeps the bentonite in suspension almost indefinitely. A properly hydrated and dispersed slurry exhibits a smooth, lump-free consistency. Proper hydration requires both mixing effort (shearing) and time. One of the cardinal rules of drilling with bentonite slurry is that all newly mixed bentonite must be allowed to hydrate fully before final mixing and introduction into a borehole. Standard industry practice is to hydrate bentonite slurry for 24 hours prior to its use in drilled shaft construction. Bentonite slurry should be added to the borehole only after its viscosity stabilizes, which is an indication that the bentonite has become fully hydrated.

When the pore sizes in the formation being excavated are large (as in gravelly soils or poorly graded coarse sands) the filter cake may be replaced by a deep zone of clay platelet deposition within the pores that may or may not be effective in producing a stable borehole. This effect is illustrated in Figure 7-2. Nash (1974) notes that a bentonite slurry penetrating into a gravel quickly seals the gravel if there are no enormous voids. He notes that the main factors involved in the ability of the slurry to seal the voids in gravel are: (1) the differential hydrostatic pressures between the slurry and the groundwater, (2) the grain-size distribution of the gravel, and (3) the shearing strength of the slurry. It is obvious that slurry will penetrate a greater distance into an "open" gravel than into one with smaller voids. As the velocity of flow of the slurry into the soil voids is reduced due to drag from the surfaces of the soil particles, a thixotropic gelling of the slurry will take place in the void spaces, which may afford some measure of stability. If the bentonitic slurry proves ineffective, special techniques (for example, use of casings, other types of drilling slurry, or grouting of the formation) may have to be used to stabilize the borehole.

After mixing, mineral slurries have unit weights that are slightly higher than the unit weight of the mixing water. Their specific gravities, with proper dosages of solids, are typically about 1.03 - 1.05 after initial mixing. During excavation, particles of the soil or rock being excavated will be mixed into the slurry and become suspended. Below a certain concentration the soil particles will stay in suspension long enough for the slurry to be pumped out of the borehole and/or for the slurry (with suspended cuttings) to be completely displaced by an upward flowing column of high-slump fluid concrete. However, as drilling progresses and the slurry picks up more soil, its unit weight and viscosity will increase. This is not detrimental up to a point; however, excessive unit weight and viscosity will eventually have to be corrected by the contractor if mineral slurry is re-used or prior to concrete placement. During construction, measurements of slurry unit weight, viscosity, and sand content are used to determine whether corrections are needed. These tests are covered later in this chapter.

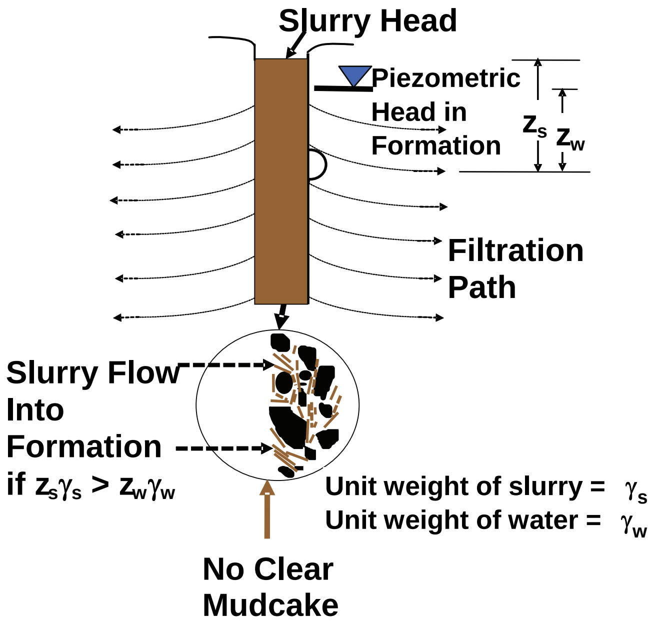


Figure 7-2 Mineral Slurry Plates in Pores of Open-Pored Formation (Modified after Fleming and Sliwinski, 1977)

Bentonite slurry is not suitable for all ground conditions. Bentonite use should be restricted when constructing a drilled shaft in smooth-drilling rock (*e.g.*, generally uniform sandstone) in which bond between the concrete and the rock is achieved by penetration of cement paste into the pores of the rock (Pells et al., 1978). Bentonite will usually inhibit such a bond from forming and will produce values of side resistance that will be lower than would be predicted by the design methods suggested in this manual. Another situation where bentonite may be problematic is where groundwater is high in salt content, which may cause flocculation and failure of the particles to remain in suspension. Bentonite can sometimes be used for limited periods of time in saline water by first mixing it with fresh water and then mixing the resulting fluid with additives such as potassium acetate to impede the migration of salt into the hydrated zone around the clay plates, sometimes referred to as the "diffuse double layer". With time, however, the salts in salt water will slowly attack the bentonite and cause it to begin to flocculate and settle out of suspension. Therefore, in this application, careful observation of the slurry for signs of flocculation (attraction of many bentonite particles into clumps) should be made continuously, and the contractor should be prepared to exchange the used slurry for conditioned slurry as necessary.

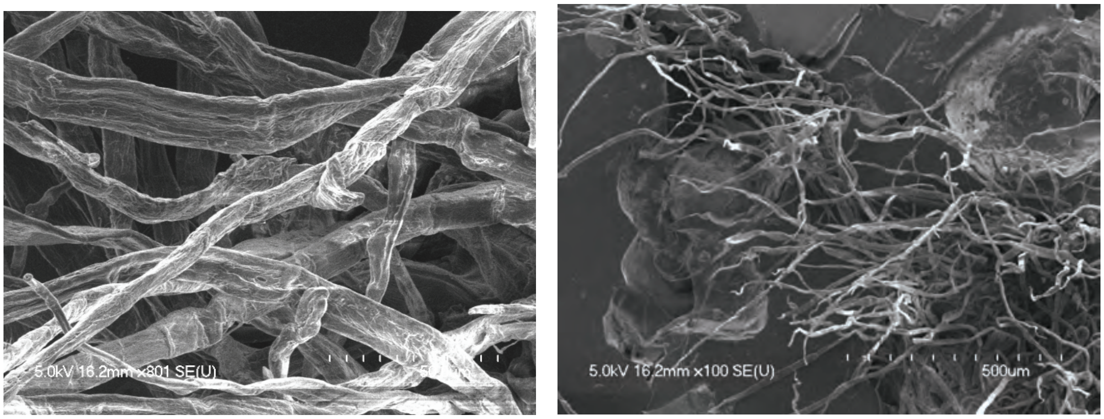
Minerals other than bentonite are used in limited amounts under certain circumstances. The most common are the minerals attapulgite and sepiolite. Typically, these are used for drilling in permeable soils in saline environments at sites near the sources of the minerals (*e.g*., Georgia, Florida, and Nevada), where transportation costs are relatively 1ow. Unlike bentonite, attapulgite and sepiolite are not hydrated by water and therefore do not tend to flocculate in saline environments. These minerals do not tend to stay in suspension as long as bentonite and require very vigorous mixing and continual remixing to place and keep the clay in suspension. However, since hydration is not a factor, the slurries can be added to the borehole as soon as mixing is complete. They do not form solid mudcakes, as does bentonite, but they do tend to form relatively soft, thick zones of clay on the borehole wall, which are generally effective at controlling filtration and which appear to be relatively easy to scour off the sides of the borehole with the rising column of concrete. It should always be verified by testing or experience that the mineral selected for slurry is compatible with the groundwater chemistry, especially at sites with low pH or contamination.

Properly prepared mineral slurry, in addition to keeping the borehole stable, also acts as a lubricant and reduces the soil resistance when a casing is installed. The wear of drilling tools is reduced when slurry is employed.

7.2.2 Polymer Slurries

Suitable mixtures of polymers and water represent the other major category of drilling fluids used for drilled shaft construction. Polymer slurries have become popular for use in all types of soil profiles because, compared to bentonite slurries, they require less processing before re-use and the costs of disposal can be less. However, as noted previously, there appears to be growing concern over the potential environmental effects of polymers and increasingly more strict requirements pertaining to its use and disposal.

The term “polymers” covers a very broad spectrum of materials and technologies. Synthetic polymers, derived from petroleum, exhibit a wide a range of chemistries and characteristics. The polymers used in drilling slurries consist of long, chain-like hydrocarbon molecules which behave, in some respects, like clay mineral particles in their interactions with each other and in the way in which they stabilize a borehole. Figure 7-3a is a scanning electron micro-photograph of a polymer slurry magnified to 800 times its actual size. The polymeric strands form a three-dimensional lattice or web-like structure. This organizational structure, in combination with various other physical and performance characteristics of the polymer slurry, allow it to form a polymeric membrane on the excavation sidewall. The membrane allows for fluid loss control and for positive pressure to be exerted against the excavation sidewall, provided the head in the slurry column exceeds the piezometric head in the formation being drilled.



(a) (b)

Figure 7-3 PAM Polymer Slurry ; (a) Polymer Slurry, 800x; (b) Slurry Interacting with Ottowa Sand, 100x (Photos courtesy of Likos, Loehr, and Akunuri, University of Missouri – Columbia)

When polymer slurry is introduced, there is an initial fluid loss into the formation. This penetration of polymer slurry into a porous formation allows the polymer to interact with the soil particles by chemical adhesion, creating a bonding effect and improving stability. The strength of adhesion varies significantly between polymer types and can be affected by various additives. Depending on the specific polymer and additives, the overall effect can range from a small strength increase to something approaching a true chemical grout effect.

The polymer chains within PAM's (polyacrylamide) are intended to remain separate from one another in the slurry through electrical repulsion, and therefore remain in suspension in the makeup water. Particle repulsion is achieved by imparting a negative electrical charge around the edges of the backbones of the polymer chains. Clean polymer slurries continuously penetrate into permeable formations (sand, silt, and permeable rock) at a linear rate of fluid loss determined by the viscosity of the slurry. As long as the head of the polymer slurry in the column exceeds the piezometric head in the formation being drilled, the excavation is typically stable. Since the polymer molecules are hair-shaped strands and not plate-shaped, they do not form a filter cake unless the slurry has ample entrained colloidal fines. Rather, borehole stability is produced through continual filtration of the slurry through the zone containing the polymer strands, in combination with the adhesion and three-dimensional structure described above (Figure 7-4). The drag forces and cohesion formed through the binding of the soil particles with the polymer strands and colloidal fines tend to keep the soil particles in place. Eventually, if enough fluid with entrained colloidal fines is deposited, filtration may cease due to the viscous drag effects coupled with the construction of a colloidal filter cake in the soil near the borehole and on the excavation surface. Colloids are drilled fines which have become suspended within the slurry.

Polymer slurries designed to perform as described above, through filtration, are continuously being lost to the formation. The contractor must be diligent in maintaining a positive head in the slurry column with respect to the piezometric surface in the formation at all times so that filtration and borehole stability continue. This often means continually adding slurry stock to the borehole to replace slurry lost by seepage into the formation. Since the unit weights of PAM slurries in proper operational condition are essentially equal to that of water, allowing the head in a polymer slurry column to drop to the piezometric level in the formation, even momentarily, may initiate hole sloughing. A good rule of thumb is to keep the level of polymer slurry at least 10 ft above the piezometric surface at all times. An equally good rule is to place the slurry in the borehole before the piezometric level is reached so that sloughing or raveling does not have a chance to start. Some of the more advanced polymeric technologies are designed to limit filtration losses, but it is still imperative to maintain positive fluid pressure on the borehole sidewalls for sidewall stability.

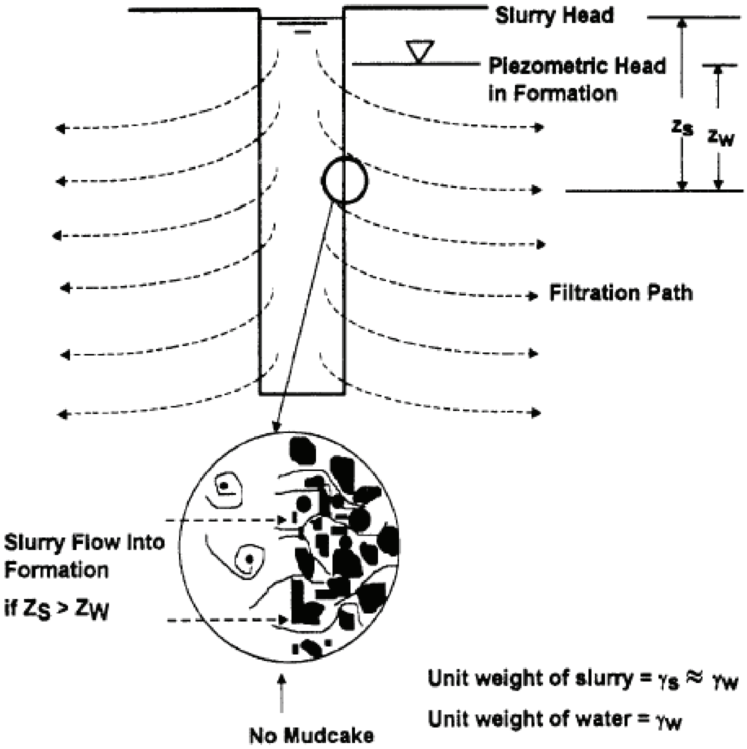


Figure 7-4 Stabilization of Borehole by the Use of Polymer Drilling Slurries

Long-chain PAM molecules tend to wrap around clay and silt particles that are mixed into the slurry during the drilling process. This behavior is illustrated in Figure 7-3b. The polymers attach first to the more active clays in the cuttings, producing small groups of fine particles which then bond to less active clay minerals, such as illites and kaolinites, and then finally to silts. The resulting agglomerated particles tend to settle out of suspension slowly and accumulate as mushy sediments on or near the bottom of the borehole. Some of the agglomerated particles also tend to float on the surface of the slurry or stay in suspension, at least temporarily, and may appear as a bulky material that some observers have termed "oatmeal”. Requiring a period of time after completion of the excavation prior to final cleanout allows this material to settle to the bottom of the slurry column where it can then be removed. This period can range from about 30 minutes up to several hours. If the sediments are not properly cleaned from the excavation they will be at least partially lifted upward by the initial charge of concrete and will appear at the surface on top of the concrete. When drilling in silty soils, some ‘oatmeal’ is inevitable, and in some types of polymers this process appears to be accelerated by excessive hardness in the slurry water.

Some of the recently-introduced advanced polymer slurries provide for more efficient settlement of colloidal fines. The three-dimensional lattice structure allows colloidal fines, silts, and fine sands to continuously wrap into larger agglomerated masses. These agglomerates fall rapidly to the base of the shaft throughout the excavation process. Being larger masses they are readily removed from the slurry column. The degree of water hardness that can be tolerated by various polymer products depends on the specific design of the product; therefore, the manufacturer should be consulted regarding how water hardness should be controlled. Control of makeup water hardness is discussed briefly in Section 7.3.2.

A fundamental difference between polymer and bentonite slurries is that a polymer slurry will not suspend colloidal fines or particles of sand size or larger for any significant time. In some types of synthetic slurries, in particular PAM's, these coarse-grained particles will settle to the bottom of the slurry column (referred to as sedimentation) and must be removed prior to placement of concrete. This behavior is not a disadvantage or problem, but it must be understood and the appropriate cleanout techniques must be employed to ensure proper placement of concrete under polymer slurry. In most cases, it is sufficient to allow the slurry properties, discussed later, to reach a steady state at mid-height and in the bottom 6 ft of the borehole before final clean-out and placement of the rebar cage and concrete.

Any situation that results in entrapment of excessive silt in a polymer slurry creates the potential for poor slurry displacement when concrete is placed. Some contractors report that sand content tests do not predict the occurrence of silt entrapment. Increases in slurry density and color change are usually the key indicators. A practical solution for silt entrapment in polymer slurry is to replace the slurry completely just prior to concreting. Slurry which has been replaced can then be treated in tanks for further use.

Disposal of synthetic polymer slurries must conform to all applicable local regulations governing the safe disposal of job-site materials. In some cases it is possible to obtain permission from the local municipality to dispose of polymer slurry through the sewer system or to transport the slurry directly to the waste water treatement plant. Either of these options typically requires sending a representative sample to a testing lab to certify its composition and then contacting officials with the waste water treatment plant where the waste stream will be treated, to obtain permission. Polymer slurry may require treatment prior to disposal. The simplest form of treatment is dilution with water. Some agencies may require the slurry to be depolymerized (or 'broken') which can be achieved by the addition of an oxidizer, such as calcium hypochlorite. In the past, sodium hypochlorite has been used as an oxidizer, but the resulting chemical reaction can produce secondary contaminants, and the amount of oxidizer required is 10 to 12 times the amount of calcium hypochlorite needed to achieve the same result. Another possible disposal scenario is for the polymer slurry to be covered under the permit of the general contractor for waste materials to be disposed of on-site. This may also require dilution with water, and is also subject to restrictions pertaining to the slurry entering surface water, such as lakes and streams. In all cases, it is the responsibility of the contractor to determine the applicable regulations, obtain the necessary permits, and to dispose of the polymer slurry appropriately.

7.2.3 Blended Slurries

Blended slurries consist of mixtures of minerals (generally bentonite) and polymers. In some situations blended slurries can be designed and used in a manner that takes advantage of the beneficial characteristics of each. However, this is a specialty field that requires expertise beyond what is normally available on most drilled shaft projects. Specifications developed for mineral slurries or commercially available polymer slurries likely will not be suitable for blended slurries. Blending is not recommended unless those involved have the knowledge and experience to determine appropriate specifications and quality control/quality assurance procedures for its use, given the site-specific ground conditions.

Blended bentonite and polymers are also available as packaged products that are marketed as "extended" bentonites. The polymer additive helps less bentonite produce a given amount of slurry, which is an economic consideration, since high-quality bentonite is becoming harder to find. However, the properties of extended bentonites can be affected significantly by the type of polymer used, and it is important for the end user (contractor) to work closely with the bentonite supplier to understand the composition and the behavior of the resulting slurry.

7.2.4 Example Applications and Limitations of Drilling Fluids in Drilled Shaft Construction

As with all drilled shaft construction methods and materials, success depends upon proper execution by the contractor and on the suitability of the methods and materials for the ground conditions. Competent contractors experienced in the use of drilling fluids are best-qualified for assessing whether slurry methods are appropriate for a specific project and for selecting the most suitable type of slurry. Nevertheless, engineers and owners should be well-informed on issues important to construction with drilling fluids, such as the general suitability of a site for slurry, and potential problems. For example, use of drilling fluid in certain geologic environments, such as karstic limestone or basalt with lava tubes, could result in the loss of large quantities of fluid into cavities. The program of subsurface exploration should reveal whether such geologic conditions exist, and the appropriate construction planning should be done in the event the chance for encountering such features is high. It is also important to recognize that use of drilling fluids is both a science and an art. Mistakes can be made in the application of mineral, polymer, or blended slurries, as with any method of construction of deep foundations, and the last section in this chapter discusses some of the common mistakes and methods of avoiding them. However, there are numerous examples of circumstances where drilling slurry has been used with outstanding success. A few are given here.

1. A site was encountered where the soil consisted of very silty clay, which was not sufficiently stable to permit the construction of drilled shafts by the dry method. Bentonite slurry was used, and shafts up to 4 ft in diameter and 90 ft long were installed successfully despite the fact that claystone boulders were encountered near the bottoms of the shaft excavations.
2. A mineral slurry was used to penetrate a soil profile that consisted of interbedded silts, sands, and clays to a depth of about 105 ft, where soft rock was encountered. Drilled shafts with diameters of 4 ft were successfully installed down to the soft rock. A loading test was performed, and the test shaft sustained a load of over 1,000 tons, with little permanent settlement.
3. Three test shafts were constructed with bentonitic drilling slurry in a soil profile containing alternating layers of stiff clay, clayey silt, and fine sand below the water table. These test shafts were all instrumented to measure side and base resistance during the loading tests, which were found to be comparable to the resistances that would have been achieved had the dry method of construction been used. The test shafts were later exhumed, and it was found that the geometry of the constructed shafts was excellent. The information obtained in this test program was then used to design foundations for a large freeway interchange.
4. Two instrumented test shafts, 30 inches in diameter, were installed with PAM polymer slurry in a mixed profile of stiff, silty clay, clayey silt, lignite, and dense sand to depths of up to 51 ft at a freeway interchange site. The contractor allowed the sand in the slurry columns to settle out of suspension for 30 minutes after completing the excavations before cleaning the bases with a clean-out bucket and concreting. The shafts were tested to failure, and the measured side and base resistances were comparable to the values that would have been anticipated in this soil profile with bentonitic drilling slurry.

These are only four examples of the use of drilling slurry in the construction of drilled shafts. To date, tens of thousands of large-diameter drilled shafts have been constructed worldwide with drilling slurry and are performing successfully.

While much is known about the properties of drilling slurries and their effects, success in maintaining borehole stability with a given slurry depends on many factors that are understood qualitatively but not all of which are readily quantified. Some of these are:

- Density of the granular soil being retained. Soils of higher relative density are retained more easily than soils of lower relative density (loose).
- Grain-size distribution of the granular soil being retained. Well-graded soils are retained more easily than poorly graded soils.
- Fines content of the granular soil being retained. Silt or clay within the matrix of sand or gravel assists in maintaining stability, especially with polymer slurries, but fines can become mixed with the slurry, causing its properties to deteriorate. Some contractors look for a fines content of at least 8 percent in order for polymer slurries to perform well.
- Maintenance of positive fluid pressure in the slurry column at all times (Figure 7-1 and Figure 7-2). This factor is especially important with polymer slurries, which have unit weights that are lower than those of mineral slurries and thus produce smaller effective stresses against borehole walls for a given differential head.
- Diameter of the borehole. Stability is more difficult to maintain in large-diameter boreholes than in small-diameter boreholes because of a reduction in arching action in the soil, and because more passes of the drilling tool often must be made to excavate a given depth of soil or rock compared with excavation of a smaller-diameter borehole. Such excess tool activity tends to promote instability.
- Depth of the borehole. For various reasons, the deeper the borehole, the more difficult it is to assure stability. Evidence suggests that difficulties have occurred using PAM polymer slurries at some sites where granular soils were encountered at depths greater than 80 ft. However, some of the newer polymer systems have been used successfully at greater depths. It is the responsibility of the user to insure that they are incorporating a polymer system designed for the conditions being encountered.
- Time the borehole remains open. Boreholes in granular soil have been kept open and stable for weeks with the newer polymer slurries as compared to days with bentonite and PAM polymer slurries. However, in general, stability decreases with time. Ground stresses, which affect axial resistance in the completed drilled shaft, decrease with time as long as the borehole remains open, regardless of whether the borehole remains stable.

7.3 MATERIAL CHARACTERISTICS AND SLURRY MIX DESIGN

The general principles important to the use of drilling fluids were introduced in the previous section. This section provides a more in-depth description of the most widely-used slurry materials, bentonite and synthetic polymers, with a focus on properties that are most important in material selection and slurry mix design, and their influence on the performance of drilling fluids for drilled shaft construction.

7.3.1 Bentonite

Bentonite has been used extensively for making drilling fluid used in drilled shaft construction and continues to be used widely in some parts of the U.S. Because bentonite is a naturally-occurring material which is mined and then subjected to varying degrees of processing before being supplied commercially, its properties can vary. It becomes important to consider the source of the bentonite and to conduct screening tests to establish the proper mix of bentonite, water, and additives for a given project. For the interested reader, several excellent references are available in which the chemistry of bentonite and slurries made from bentonite are covered thoroughly (*e.g.*, Darley and Gray, 1988). The focus here is on the practical aspects of bentonite slurry used for drilled shaft construction. The following general observations pertaining to bentonite (and other slurry minerals) will prove to be useful.

- The materials to be selected for a particular job will depend on the requirements of the drilling operation. Different types of drilling fluids are required to drill through different types of formations. Some of the factors that influence the selection of drilling fluid are economics, contamination, available make-up water, pressure, temperature, hole depth, and the materials being penetrated, especially pore sizes and the chemistry of the soil or rock and the groundwater.
- An economic consideration for the contractor is the "yield" of the mineral used to make the slurry. The yield is the number of barrels (42 gallons) of liquid slurry that can be made per ton of the dry mineral added to achieve a slurry with a viscosity of 15 cP (described later).
- The best yield comes from sodium smectite ("Wyoming bentonite"). Other natural clays give very low yield and, for reasons discussed previously, are typically not used in drilled shaft construction. Calcium smectite yields a lesser amount of slurry per unit of weight than Wyoming bentonite because it is hydrated by only about one fourth as much water as Wyoming bentonite.
- The yield of Wyoming bentonite has been dropping due to the depletion of high-quality deposits in the areas where it is mined. The yield of some pure bentonite products is now as low as 50 barrels of slurry per ton of dry bentonite. High-quality Wyoming bentonite that will produce a yield of 100 bbl./ton is still available, but at a premium price. In recent years, suppliers have been producing Wyoming bentonite mixed with polymer "extenders" to increase the yield. In fact, most bentonite products available today are actually mixes of bentonite and some type of polymer, ranging from natural polymers such as cellulose derived as a waste product of paper and pulp processing, to synthetic polymers. Some suppliers are also chemically modifying calcium smectite to give it essentially the same properties as Wyoming bentonite, but the resulting products are relatively expensive.
- The quality of the water that is used to make drilling slurry is important. For bentonitic slurries potable water should be used. Saline water can be used for slurry if attapulgite or sepiolite clay is used instead of bentonite. These clays derive their viscosity from being vigorously sheared by specialized mixing equipment designed to accelerate the suspension of such clays. As described previously, bentonite, with proper preparation, can be used for limited periods of time while drilling in salt water if the makeup water is fresh and if additives are applied to inhibit migration of salt. They key is that makeup water should be uncontaminated.

The detailed design of a bentonite slurry (particle size, additives, mixing water, mixing technique, and time) and the interaction of the slurry with the chemicals in the makeup water, as modified by the conditions in the ground through which the shaft is drilled, affect the thickness and hardness of the filter cake that is built up, as well as the gel strength of the fluid slurry. It is good practice for the contractor to conduct tests on trial mixes of the proposed mineral slurry to determine these properties. The test and device used to determine cake thickness and filtration loss is standardized by the American Petroleum Institute (API) and is referred to as the API filter press (API, 2003). A small amount of slurry is forced through a standard piece of filter paper under a differential pressure of 100 psi for a fixed period of time (typically 30 minutes). It is advisable that the resulting filter cake be no more than about 1/8 inch thick and that the filtration loss (amount of slurry passing through the filter paper) be less than about 10 mL. Higher values of cake thickness from this standard test may indicate that a substantial thickness of filter cake will remain on the sides of the borehole, and will perhaps attach to the rebar, after the concrete has been placed. This condition is undesirable, as it will reduce the load transfer between the drilled shaft and the soil formation to a magnitude below that which will be calculated using the procedures in Chapter 13. Filtration loss is a measure of the effectiveness of the mineral slurry in controlling loss of fluid to the formation, which is an economic factor for the contractor, but in and of itself is not critical to the drilled shaft as long as the borehole remains stable. Some slurry suppliers recommend deviating from the API standardized procedure for drilled shaft applications, because the high magnitude of pressure (100 psi) causes a thin, highly compressed filter cake. Conducting the test at pressures in the range of 8 to 14 psi may model the field conditions of drilled shaft construction more realistically.

The gel strength of bentonite slurry should also be measured and adjusted as necessary as the trial mix is being prepared. The gel strength is the shear strength of the unagitated slurry after hydration with water, has taken place. Measurement of slurry gel strength using a viscometer is described in Section 7.4.4.2. As a standard, the gel strength is measured 10 minutes after vigorous mixing is completed. High gel strength is necessary if it is desired that the slurry be used to transport solids, as in direct or reverse circulation drilling, in which the cuttings are transported to the surface by suspending them in the slurry and pumping the slurry to the surface where the cuttings are removed. However, high gel strengths can be a problem when concrete is being used to displace the slurry. Lower gel strength should be used if the purpose of the drilling slurry is only to maintain borehole stability and to maintain a minimal volume of cuttings in suspension, which is the usual objective of mineral slurries for drilled shaft construction, since the cuttings are usually lifted mechanically. Ordinarily, for this purpose, 10 minute gel strength should be between about 0.2 and 0.9 lb/100 ft^2. Measurement of gel strength is described in Section 7.4.4.2.

Gel strength, cake thickness, and filtration loss are not usually measured during construction operations unless the slurry begins to perform poorly. Instead, they are monitored indirectly by measuring the viscosity of the slurry by means of a rheometer or "viscometer" (Section 7.4.4.2) or a Marsh funnel, the results of which relate crudely to slurry viscosity.

The unit weight of slurry made from high-quality Wyoming bentonite upon mixing should be between about 64.3 and 66 lb/ft^3 in order to achieve the proper viscosity. Since the unit weight of fresh water is 62.4 lb/ft^3, about 1.9 to 3.6 lb. of bentonite needs to be added to every cubic foot of makeup water (or about 0.2 to 0.4 lb. per gallon) to produce slurry of proper consistency. Use of less mineral solids in the initial mix will likely make the slurry ineffective at maintaining borehole stability, and use of more mineral solids will produce too much gel strength (excessive viscosity) for the slurry to be flushed effectively by the fluid concrete. The dosage of attapulgite in a slurry mix should be about the same as for bentonite, but the dosage of bentonite from sources other than Wyoming needs to be about four times as high as for Wyoming bentonite.

Mineral slurry can be improved in some instances by chemical additives. For such cases, the supplier of the bentonite or other product can usually be helpful and should be consulted. A technical representative of the slurry product supplier should be present at the beginning of any important project to ensure that the properties of the slurry are appropriate for the excavation of soils and rocks at the specific site involved, even if special additives are not contemplated by the contractor. The following is a general description of additives available for use with bentonite slurries (LCPC 1986):

- Cake thinners Reduce the free-water content, thus thinning the cake and enhancing its resistance to contamination, and increasing the viscosity of the slurry somewhat. These additives also act as filtrate reducers (below).
- Filtrate reducers Reduce loss of slurry to the formation.

- Anti-hydrating-agent Inhibit the erosion of dispersive clays and clay-based rocks into the slurry and the expansion of expansive clays.
- pH reducers Pyrophosphate acid can be added to lower the pH of the slurry. This additive is of special interest when excavating certain expansive marls in which hydration, which occurs when the drilling slurry is highly basic ($pH > 11$), can be limited by maintaining the pH value between 7.5 and 8. Maintaining pH below 11 is also necessary to maintain good characteristics of bentonite slurries.
- Weighting agents Barite (barium sulfate), hematite, pyrite, siderite, or galenite may be added to the slurry when it is necessary to resist the intrusion of water under pressure or flowing subsurface water. The specific gravity of the slurry, which is normally around 1.03 to 1.05 upon mixing, may be increased to 2.0 or even greater with these agents, without appreciably affecting the other properties of the slurry (for example, its gel strength and viscosity).

Additives may also affect the yield of the slurry to varying degrees. Again, the assistance of a technical representative of the supplier of the slurry solids and additives is important to ensure that the desired properties are achieved, at least in the initial mixing of the slurry.

Bentonite slurry is strongly affected by the presence of excessive concentrations of positive ions, as are found in very hard water and acidic groundwater, by excessive chlorides concentrations, as are found in sea water, and by organics. Acidic conditions are indicated by pH values that are lower than 7. Some commercial bentonites are packaged with additives that raise the pH of the bentonite-water mixture to 8 to 9 to counteract the effects of minor acid contamination, but excessive acid contamination can lower the pH to a point where the bentonite will flocculate. Bentonite can be used sparingly at low pH (acidic) for short periods of time (pH down to about 5). One function of the manufacturer's technical representative would be to measure the hardness, acidity, chlorides content, and organic content of the mixing water and the groundwater, if necessary, and to recommend conditioners in the event the water is not suited to mixing with the bentonite without modification.

If the soil being excavated is organic, acidic, or saline, the bentonitic slurry may be "killed" (flocculate). The addition of de-flocculants or other measures will be required to maintain proper consistency. Therefore, the critical factor in regard to the materials is that specifications be written to control the slurry as it is manufactured and as it is being used during excavation. Suggestions are given in Section 7.4.5 on the preparation of specifications for mineral slurry.

7.3.2 Polymers

Two general categories of polymers have been used in slurries for drilling applications: natural (or semi-synthetic) and synthetic. Naturally-occurring polymers include starches, guar/xanthan gum, welan gums, scleroglucan, and cellulose. For a variety of reasons, most of these materials are not well-suited for producing slurry to be used in drilled shaft construction. Cellulosic polymers (which are a waste by-product of paper manufacturing) are sometimes blended with bentonite to extend the bentonite yield or as additives to reduce the filtration rate of bentonitic slurry (fluid loss into the formation) and inhibit swelling and consequent erosion of clays and shales. Aside from their use as additives, natural polymers are not commonly used in drilled shaft construction. The vast majority of polymer slurries used for foundation drilling today are made with purely synthetic (*i.e.*, manufactured) polymers.

Synthetic polymers used in the drilled shaft industry can be further divided into two broad groups. The first consists of various forms of the hydrocarbon-derived family of chemicals called polyacrylamides, or PAM. These materials are manufactured by combining individual acrylamide molecules (monomers) through various chemical processes into long chains, hence the term polyacrylamide. In the manufacturing process, negative electrical charge is created on the backbones of the chains through a variety of processes. When these products were first introduced, the process used to adjust the charge density was partial hydrolyzation (addition of OH^- molecules) and the resulting drilling polymer was referred to as a partially-hydrolyzed polyacrylamide, or "PHPA". However, the processing techniques have changed and partial hydrolyzation is no longer used. The chemical industry term for polyacrylamide is “PAM”. The purpose of the negative charge is to promote molecular repulsion, restrict agglomeration (attraction of many molecules into large masses), and keep the molecules in suspension once mixed with water. Polymers used for drilled shaft excavation do not have all of the possible positions for negative charges filled because the surfaces of the polymer chains would be so negatively charged as to be repelled by the soil they are intended to penetrate.

The second category of synthetic polymers used in drilled shaft slurries is highly engineered polymeric materials that involve combinations of acrylamide molecules with other chemicals to form new molecules whose properties are designed to optimize their performance as drilling slurries. These products typically are proprietary and covered by patents. It is not possible to provide detailed information on the composition of these products; however, it must be recognized that these products will exhibit different behaviors than slurries made from PAM products. The specifications used to control properties of slurries made from proprietary polymers may differ from those applicable to PAM slurries. For details of polymer chemistry for any drilling product and for recommended specifications, the contractor should work closely with the manufacturer's technical representatives and/or literature.

Commercial polymer products vary in physical form (dry powder, granules, or liquids) and in the details of the chemistry of the hydrocarbon molecules (molecular weight, molecule length, surface charge density, etc.). No one formulation is likely to be superior in all cases. Many polymer slurry suppliers market several formulations that can be customized for a given site. For this reason, as with mineral slurry drilling, the drilling contractor should employ a technical representative of the polymer supplier to advise on the specific formulation that is best suited for the job at hand. That representative should be present for the drilling of technique shafts and/or the first few production shafts to make sure that the slurry is working as intended and, if not, to make such modifications to the slurry mix and procedures as necessary.

The simpler PAM slurries are especially sensitive to the presence of free calcium and magnesium in the mixing water or groundwater. Excess calcium and magnesium produce what is commonly called "hard water". The total hardness of the slurry mixing water should be reduced to a value in the range of 50 parts per million or less (varies with the specific product used) unless the polymer has been modified chemically to remain stable in high-hardness conditions. If the hardness is too high, polymer chains lose their repulsion and can begin to attract one another and agglomerate, causing the polymer to be ineffective. Total hardness of the slurry can be checked easily by a titration process, in which one or two chemicals are added to a known volume of slurry to change its color and another chemical is titrated into the colored slurry. When the color of the slurry again changes (typically from purple to blue), the volume of the final chemical added to the slurry is read, and the hardness is obtained from a simple calibration chart. Some simpler, though more approximate, methods can also be used for field control of hardness.

Excessive hardness is reduced by thoroughly mixing sodium carbonate ("soda ash") with the slurry until the hardness is within the desired range. Manufacturers of proprietary polymers may supply other softening agents for use with their slurries. Hardness is not usually monitored routinely during construction due to the effort involved; however, pH, which can be measured quickly and easily, should be monitored. The agent that is used to lower hardness also raises pH, so that a check on pH is an indirect check on hardness.

Chlorides also have a negative effect on PAM slurry. PAM slurries tend not to be effective in water having chloride content greater than about 1500 parts per million. Therefore, they are not usually effective in sea water. Sometimes, suppliers' technical representatives can recommend additives or devise mixing procedures to allow the use of polymer slurry in brackish water. The newer polymers tend to be less sensitive to chloride content.

7.4 CONTROL OF DRILLING FLUID DURING CONSTRUCTION

7.4.1 Mixing and Handling of Mineral Slurry

A variety of procedures are employed for the mixing and handling of mineral slurry. The principal concern is that the slurry characteristics are appropriate during the excavation of the borehole and during concrete placement. The mixing equipment and procedures must satisfy two general requirements: (1) adequate mixing of the mineral with the makeup water, and (2) adequate hydration to form a dispersed, lump-free suspension. A schematic diagram of a complete, appropriate system for mixing and handling bentonite slurry for drilled shafts is shown in Figure 7-5. Two acceptable types of mixers are shown in Figure 7-5b. The mixer identified by b_1 consists of a funnel into which dry bentonite is fed into a jet of water directed at right angles to the flow of the bentonite (a "venturi"). The mixture is then pumped to a holding tank. The mixer identified by b_2 consists of an electric motor, with or without speed controls, that drives a vertical shaft. The shaft has blades attached that operate at a circumferential speed of up to about 260 ft/s and provides excellent mixing of bentonite with water.

Freshly-mixed slurry should be held in storage for a period of time to allow complete hydration. The stored slurry can be re-mixed, if necessary, by pumps, mechanical agitation, or compressed air. The mixed slurry should not be used in drilling until the viscosity has completely stabilized, which usually requires several hours following initial mixing. It is recommended that bentonite be hydrated for 24 hours prior to its introduction to a drilled shaft excavation. Less time, but more vigorous mixing, is required for attapulgite or sepiolite slurries.

Figure 7-5d depicts the common "static" (non-circulation) mineral slurry drilling process. The slurry stored in the storage tank (Figure 7-5c) is carried to the borehole by pump or by gravity with the slurry level in the borehole kept continuously above the level of the piezometric surface in the formation during drilling. When soils with significant amounts of granular material (sand or silt) are being excavated, the slurry may quickly thicken as the particulate matter is placed in suspension. This is not desirable, because (a) the slurry becomes incapable of suspending additional particulate matter, the consequence of which is that the additional particulate matter may slowly settle out of suspension after the borehole is cleaned and as the concrete is being placed, and (b) the slurry may become too viscous to be displaced by rising fluid concrete. This condition can be identified by measuring the sand content, density, and viscosity of the slurry at the bottom of the borehole before concrete placement. Slurry with excessive sand or viscosity must be pumped from the bottom of the borehole to a treatment unit located on the surface for removal of the particulate matter. Simultaneously, fresh slurry meeting all of the sand content, density, and viscosity requirements is pumped from a holding tank on the surface and introduced at the top of the borehole, keeping the level of slurry in the borehole constant.

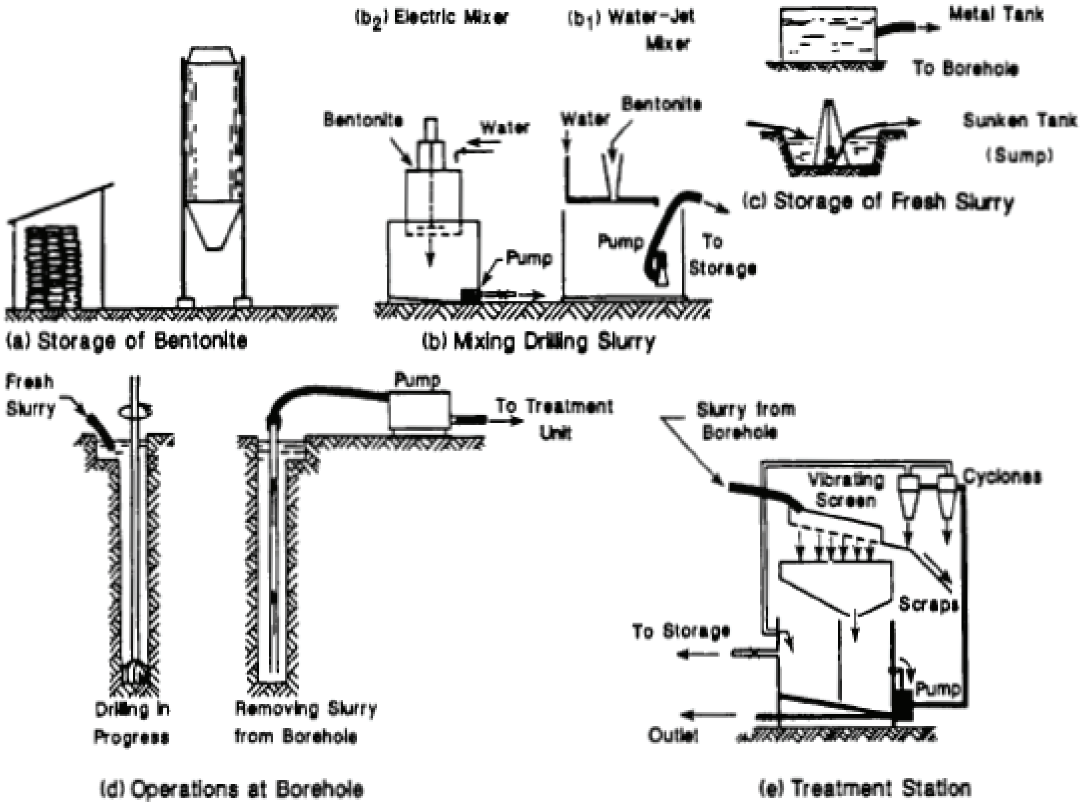


Figure 7-5 Schematic Diagram of Unit for Mixing and Treating Mineral Slurry (after Le Laboratorie Central des Ponts et Chaussees, 1986)

A common procedure for removing the slurry from the bottom of the borehole is to use an airlift. A jet of air at low pressure and high volume is introduced near the bottom of an open pipe, which is placed near the bottom of the borehole. As the air flows upward, the reduced pressure in the pipe causes slurry to enter and a mixture of air and slurry will be blown up the pipe to the surface by the air lift. Air lifting is also effective in cleaning loose sediments and agglomerated slurry from the bottom of the borehole if a diffuser plate is placed on the bottom of the pipe to distribute the suction equally around the bottom of the borehole. A submersible pump can also be used for this purpose. With either method, the rate of the fluid flow should lift all sediments in the slurry from the borehole.

When the hole is advanced through primarily cohesive soil, the slurry may not thicken appreciably during drilling, unless the clay erodes. In such a case, exchange of the slurry in the borehole may not be necessary. However, agitation of the slurry (as with the auger) is still desirable to ensure that particulate matter stays in suspension. This action is especially important with attapulgite or sepiolite, which do not suspend solids as readily as bentonite. In this case, the slurry needs to be recovered from the hole only once (as the concrete is placed) and directed to the treatment unit before reuse or discarded.

The contaminated mineral slurry is moved to a treatment unit, Figure 7-5e, consisting of screens and hydrocyclones. The slurry first passes through the screens (usually No. 4 size), where the large-sized sediments are removed, and then is pumped through the cyclone unit where the small-sized material is removed by vigorously spinning the slurry. Most hydrocyclones are capable of removing virtually all sand-sized particles. Some units are equipped with smaller hydrocyclones that also remove silt, although several passes through the hydrocyclones may be necessary. Silt removal can be just as important as sand removal for reused mineral or blended slurries, because suspended silt can cause the viscosity, density, and filtration rate to increase, rendering the slurry ineffective.

The cleaned ("desanded") slurry is pumped back to a holding tank where it should be tested. Since slurry drilling ordinarily involves some loss of slurry to the formation, some amount of fresh slurry is usually mixed with the desanded slurry at this point. If the used slurry is to be discarded without treatment, it is essential that approved methods be used for disposing of the slurry.

For a small job where it is uneconomical to bring in a full treatment unit to the jobsite, the contractor may wish to fabricate a screen system that can be cleaned by hand and to obtain a small cyclone unit to do the final cleaning. As stated earlier, another procedure that can be employed on some jobs where relatively little sand is present in the formation being drilled is to employ the static drilling process, without any treatment of the slurry, as long as the sand and silt content in the slurry do not become excessive. A clean-out bucket can be lowered to the bottom of the borehole and rotated to pick up sediments that have settled out of the slurry. This kind of cleaning operation, although time-consuming, is necessary to prevent significant amounts of sediment from either being trapped beneath the concrete as it is introduced into the borehole or from collecting at the top of the concrete column during concrete placement. The slurry that is flushed out by the placement of the fluid concrete can sometimes be reused several times if the specified ranges for density, viscosity, sand content and pH can be maintained. Attapulgite and sepiolite slurries are treated much like bentonite slurries, except that very vigorous mixing for a long period of time is required. Once the mineral is thoroughly mixed with the makeup water, the slurry can be introduced directly into the borehole, as these minerals do not hydrate with water and so do not need to be held for several hours for hydration, like bentonite, before introducing them into the borehole.

Certain procedures have no place in drilled shaft construction; for example, dumping dry bentonite into a water-filled excavation and stirring the mixture with the auger. This procedure produces an ineffective slurry that contains clods of dry, sticky bentonite that fail to stabilize the borehole because the individual bentonite plates are not available to form the mudcake. Furthermore, the clods can become lodged in the rebar or against the borehole wall and produce a defective drilled shaft.

7.4.2 Mixing and Handling of Polymer Slurry

Methods for mixing of polymer slurries can vary and the supplier should always be consulted for recommendations. Emulsified PAM products can be mixed by circulating between tanks, as shown in Figure 7-6. High-shear mixing of polymers results in “chopping” of the long-chain molecules, rendering the slurry ineffective, and should be avoided. Additional measures that help to minimize the potential for damage to polymer slurries include in-line mixing (Figure 7-7a) and the use of splash plates for transporting between tanks (Figure 7-7b). For pumping, diaphragm pumps are recommended. It is strongly recommended that a technique shaft be constructed to test the effectiveness of the polymer slurry prior to constructing production shafts.

Soda ash or another hydroxide hardness reducer is almost always added to the makeup water during mixing to control the hardness of the water, which simultaneously adjusts the pH of the polymer slurry to a high value. Note that soda ash should not be used with certain proprietary polymer products, and the supplier should be consulted on proper treatment of mixing water.

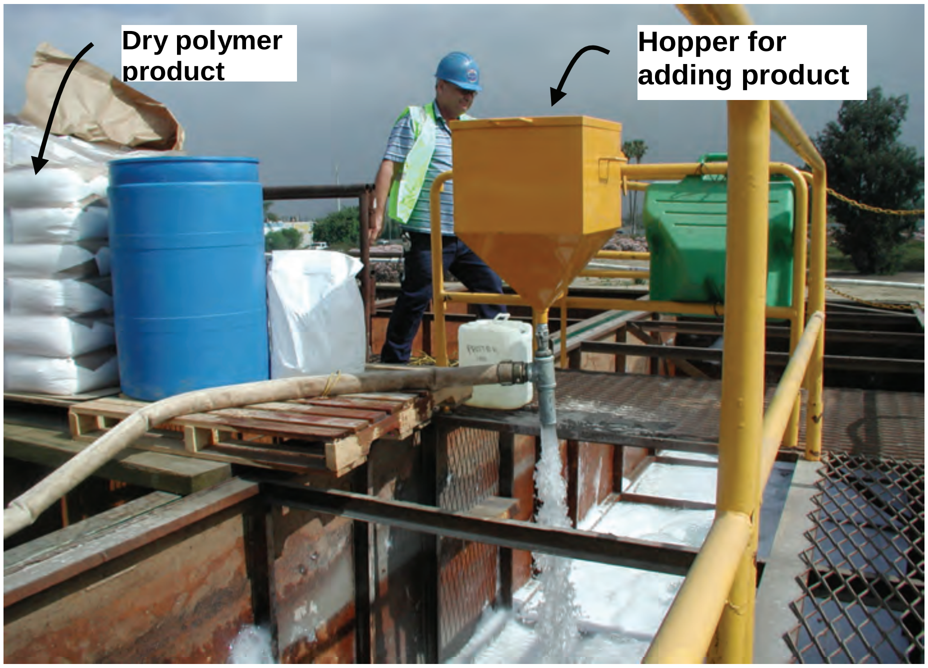


Figure 7-6 Field Mixing Polymer Slurry by Circulating Between Tanks

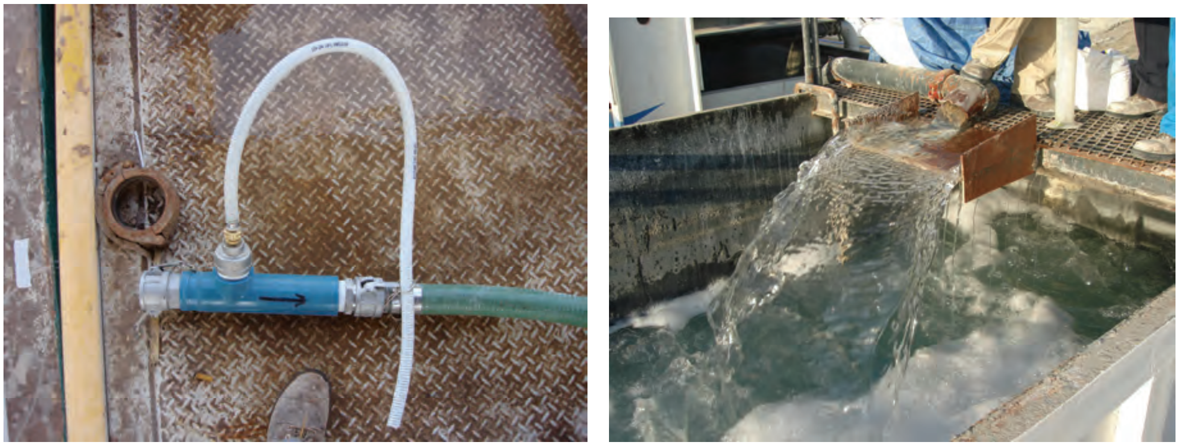

(a) (b)

Figure 7-7 Techniques for Handling Polymer Slurry; (a) In-line Mixing Device for Adding Polymer; (b) Splash Plate for Transporting Slurry

Polymer slurries cannot be cleaned effectively using the equipment intended for mineral slurries, shown in Figure 7-5. The polymer strands are broken down by vigorous mixing in hydrocyclones, and polymers tend to "gum up" the components of the treatment plant. Instead, the cleaning process is adapted to the concept that polymer slurries do not suspend soil particles. By allowing sedimentation to occur, soil particles are concentrated at the bottom of the slurry column. The sand content at the bottom of the borehole will stabilize at a small value (usually less than 1 per cent by volume) after the slurry column is allowed to stand without agitation for a period of time, for example, about 30 minutes to 2 hours in boreholes less than 65 ft deep. The sediments collected at the bottom of the slurry column are then removed with a clean-out bucket or airlift. Slurry that is subsequently flushed out of the borehole by the rising column of fluid concrete is then essentially clean, although good practice is to store it for a few hours in a tank on the surface to permit small amounts of solids still in suspension to settle out. The supernatant polymer can then be reused in drilling subsequent boreholes after checking its properties and adding fresh slurry, if necessary.

High silt content can be a challenge in some polymer slurries. Silt particles may remain in suspension for a longer period of time than sand and other coarse-grained particles, and silt may be difficult to remove using the cleanout procedure described in the preceding paragraph. Excess silt in the slurry column creates the potential for poor displacement of slurry by the fluid concrete. Two procedures are common. The first is to completely replace the slurry column with clean slurry prior to placement of concrete. The second is to use additives or specialized polymer products that result in agglomeration of silt and other fines, creating larger particles that will settle to the base of the slurry column where they can be removed by the cleanout techniques described above. Some of the more-recently developed proprietary polymers are designed to agglomerate silt and colloidal particles in order to promote rapid sedimentation. Suppliers and manufacturers of these products should be consulted for project-specific applications.

Full circulation drilling, referred to as either direct or reverse circulation drilling, in which the cuttings are transported by pumping the slurry from the cutting face of the drilling tool continuously to the surface, is possible with mineral slurry. It is not very effective with polymer slurries without special additives since the current generation of polymer slurries do not effectively suspend particulates (cuttings).

Diaphragm-type pumps are generally best for moving polymer slurries from tank to borehole and back. Diaphragm pumps do not damage the polymer chains as severely as centrifugal or piston-type pumps. Any form of mechanical agitation, however, damages the polymer chains to some extent, such that a given batch of polymer slurry cannot be reused indefinitely. This includes air lifting, since the highly turbulent flow of the lifting mechanism can shear the polymer chains excessively. For this reason, air lifting of polymer slurries should be used only for limited durations if the slurry is to be re-used.

Mixing of either polymer or bentonite slurry with Portland cement at any time in the construction process can be detrimental to the slurry because the hydration of Portland cement releases calcium ions in such concentration that the hardness of the slurry may become very high. For this reason the contractor must be very diligent to keep cement out of the slurry and should also minimize the time that the slurry is in contact with the rising column of concrete in the wet method of construction by charging the borehole with concrete at a steady rate. The contractor should use pump lines for polymer or mineral slurry that have either never been used for pumping concrete or have been thoroughly cleaned of concrete.

7.4.3 Sampling and Testing

As stated above and discussed further in Section 7.4.4, mineral and polymer slurries will have certain desirable characteristics which are controlled on the job site according to specifications. Therefore, key properties must be measured to ensure that these characteristics are within the specified range. Sampling and testing will be necessary just before the slurry is introduced into the borehole, during the drilling operation, and always before concrete is placed.

Freshly mixed slurry is sampled from the slurry tanks immediately prior to its introduction into the drilled hole. For this purpose, satisfactory samples may be taken from almost anywhere in the storage tank. The important point is to obtain a sample that is representative of the mixture. During drilling, it is highly recommended (and should be required by appropriate specifications) that slurry be sampled from the borehole and tested at least every two hours after its introduction. Typically, samples are taken from mid-height and near the bottom of the borehole. Several types of sampling tools are available to obtain a representative sample from the desired location in the slurry column. A device used for this purpose is shown in Figure 7-8. When the sampler is brought to the surface, its contents are usually poured into a plastic slurry cup for subsequent testing.

The following sections describe several items of testing equipment, which can be obtained from any of several oil-field service companies or from bentonite and polymer suppliers.

7.4.3.1 Density

A mud balance (lever-arm scale) is typically used to measure the density, or unit weight, of the slurry. A metal cup that will hold a small quantity of slurry is carefully filled out of the slurry cup and cleaned of excess slurry on its exterior. It is then balanced by moving a sliding weight on a balance beam (Figure 7-9). The density of the slurry is read directly from a scale on the beam in several forms [unit weight (lb/cubic foot, lb/gallon), specific gravity]. The scale should be properly calibrated with water in the cup before making slurry density readings. This device is accurate, and readings can be taken rapidly. The only problem is to obtain a representative sample because the quantity of the slurry that is tested is small in relation to the quantity in a borehole. Therefore, multiple tests are recommended.

Figure 7-8 Device for Downhole Sampling of Slurry (Courtesy of Cetco).

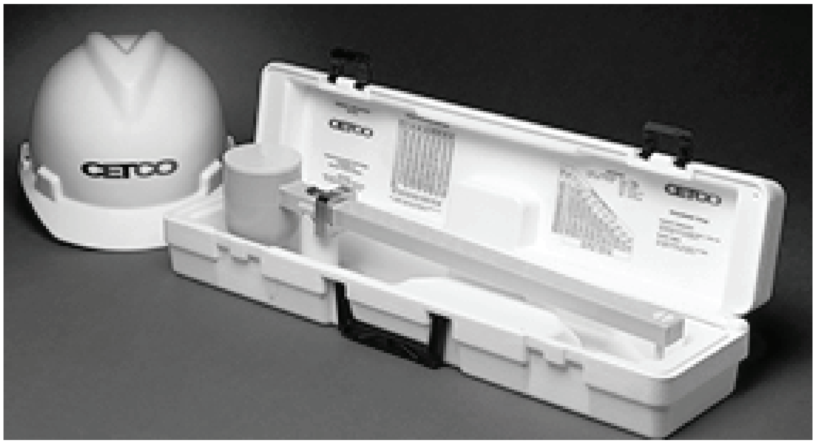


Figure 7-9 Mud Density Balance for Field Measurement of Slurry Density

7.4.3.2 Viscosity

Several measures of viscosity are used in specifications. A simple and expedient measurement is made with the Marsh funnel, a simple funnel with a small orifice at its bottom end. The Marsh funnel test provides an index of viscosity rather than a measurement of true viscosity. The test, shown in Figure 7-10, is performed by placing a finger over the tip of the small orifice at the bottom of the funnel (after making sure that the orifice is clean) and filling the funnel with slurry to a line at the base of a screen located near the top of the funnel. When filling the funnel, slurry should be poured through the screen to filter out large solid fragments. The slurry then is allowed to flow out of the funnel through the orifice back into an empty slurry cup, which has a mark denoting one quart, and the number of seconds required for one quart of the slurry to drain from the funnel into the cup is recorded. It should be noted that not all of the slurry will have flowed out of the Marsh funnel at the time one quart has accumulated in the slurry cup. This measure of time, in seconds, is the "Marsh funnel viscosity". Many specifications for drilling slurry rely on the Marsh funnel, and the device allows adequate control of slurry for many jobs.

For slurry mix design, and occasionally on drilled shaft construction projects, a more rigorous and exact measurement of slurry viscosity properties may be required. True viscosity is defined as the shear stress in a fluid divided by the shearing strain rate. The unit of viscosity in the metric system is the poise, defined as stress in dynes per square centimeter required to produce a difference in velocity of one centimeter per second between two layers one centimeter apart. A centipoise (cP) is one hundredth of a poise. An instrument referred to as a "rheometer" or "viscometer," that can be used to measure viscosity of drilling slurries is shown schematically in Figure 7-11. Slurry is contained in the annular space between two cylinders. The outer cylinder is rotated at a known velocity. The viscous drag exerted by the slurry creates a torque on the inner cylinder or bob. This torque is transmitted to a precision spring where its deflection is measured and related to shearing stress. On some commercially-available instruments, shear stress is read directly from a calibrated scale.

The information obtained from a viscometer test is illustrated in Figure 7-12, which shows results from tests on a polymer slurry as presented by Ata and O’Neill (1997). The shear rate is read directly in revolutions per minute (rpm) but can be converted to shear strain rate in 1/seconds by multiplying the number of rpm's by 1.703. The shear stress is read in lb/100 sq. ft. This value is converted to dynes/sq. cm by multiplying the shear stress reading in lb/100 sq. ft by 4.79. Measurements of shear stress are made at varying strain rates, starting at 3 rpm (5.11 sec^{-1}), to progressively higher rates, including 300 rpm (511 sec^{-1}) and 600 rpm (1022 sec^{-1}), which are the standard rates for testing bentonitic slurries.

Figure 7-10 Marsh Funnel Test for Field Evaluation of Slurry Viscosity

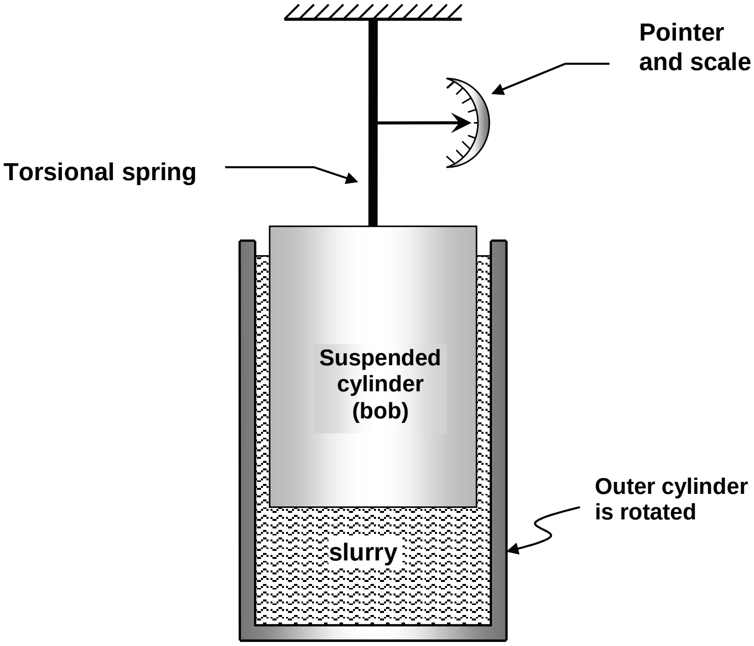


Figure 7-11 Schematic of Slurry Viscometer

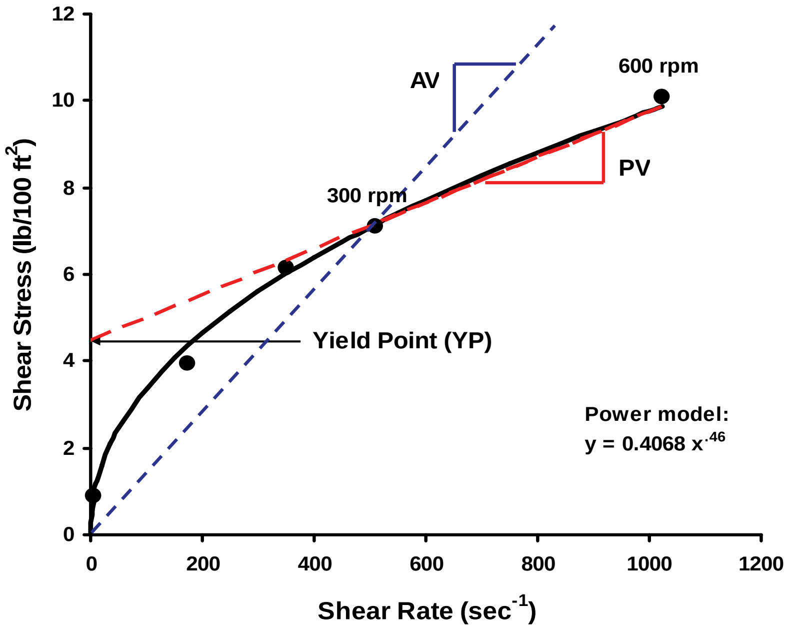


Figure 7-12 Interpretation of Data from a Viscometer Test (after Ata and O’Neill, 1997)

As the shear strain rate is increased by increasing the rpm of the container, the shear stress increases. The resulting relationship between shear strain rate and shear stress, shown by the solid line in Figure 7-12, is usually nonlinear and can be approximated by a simple power function equation. For the example in Figure 7-12 a best-fit relationship is presented in which y is the shear stress in lb/100 sq. ft, and x is the shear stain rate in sec^{-1}. This power function model of the curve is termed a "rheological" relationship. It is usually more highly nonlinear for polymer slurries than for bentonitic slurries. The exponent, in this case 0.46, is referred to as the "*n*" value for the slurry.

The following additional parameters are determined from the rheological curve as measured in a viscometer test:

- Yield Point (YP): a straight line is drawn between the two points on the curve corresponding to rotational speeds of 300 rpm (strain rate = 511 sec^{-1}) and 600 rpm (strain rate = 1022 sec^{-1}). This straight line presumes that the slurry obeys a "Bingham plastic model" law, which is approximately correct for mineral slurries, and is the dashed red line in Figure 7-12. This line is projected back to zero strain rate, and the intercept with the ordinate defines the yield point, or the apparent shear stress at zero strain rate.
- Plastic Viscosity (PV): slope of the straight line used to determine the yield point; normally expressed in units of centipoise (cP), Equation 7-1 can be used to obtain the PV in cP.

$$\text{PV}\,(\text{cP}) = \left[\frac{\left(\tau_{600} - \tau_{300}\right)\ 4.79}{511\text{sec}^{-1}}\right] \times 100 \approx \tau_{600} - \tau_{300} \qquad \text{7-1}$$

in which τ_{600} = shear stress measured at 600 rpm and τ_{300} = shear stress measured at 300 rpm. The units for τ in Equation 7-1 are lb/100 ft^2 (as read from the viscometer).

- Apparent Viscosity (AV): slope of a straight line drawn through the origin to a specified point on the curve (at 300 rpm as shown in Figure 7-12, or more commonly at 600 rpm on a direct-reading viscometer). The AV is also expressed in cP and is calculated as follows:

$$\mathrm{AV}(\mathrm{cP}) = \frac{4.79 \times \tau_{desired\,strain\,rate}}{strain\;rate\;in\;\mathrm{sec}^{-1}} \times 100 \qquad 7\text{-}2$$

  where τ is the shear stress (lb/100 ft^2) at the same strain rate as in the denominator.

- Gel Strength: the shear stress generated at a rotational speed of 3 rpm by testing the slurry after it has been allowed to stand unagitated for a given period of time, usually ten minutes. In some mineral slurries the 10-minute gel strength can be near the yield point, but the 10-minute gel strength is always considerably less than the yield point in synthetic polymer slurries.

The slurry shown in Figure 7-12 exhibits the following rheological properties:

n = 0.46
YP = 4.48 lb/100 ft^2
PV = 2.69 lb/100 ft^2
AV = 97 cP @ 3 rpm
AV = 4.7 cP @ 600 rpm
gel strength = 0.86 lb/100 ft^2.

This same slurry also exhibited a Marsh funnel viscosity of 44 sec/quart and was used successfully to excavate 70-ft deep, 3-ft diameter boreholes for drilled shafts that subsequently exhibited values of unit side resistance that equaled or exceeded the predicted values obtained from the design methods in Chapter 13. The subsurface consisted of overconsolidated stiff clay to stiff very silty clay and medium dense silty sand with water table depths of about 10 ft (Ata and O'Neill 1997).

Traditionally, when viscometers have been used to monitor the rheological properties of mineral slurries for drilled shaft construction, the slurry properties that are controlled are the 10-minute gel strength and/or the YP, and occasionally the PV.

Beresford et al. (1989) suggest that polymer slurries should be controlled by monitoring n and the AV's at 3 rpm (corresponding to the gel strength) and 600 rpm. The value of n for polymer slurries should be relatively low, which indicates that the slurry tends to thin rapidly on the application of increased shear strain rates. Beresford et al. also suggest that the AV of the slurry at 3 rpm be as high as 250 cP in order to maintain hole stability with the polymer slurry in a static condition in the borehole. However, they do not present evidence that such high values of AV in the drilling slurry result in acceptable magnitudes of unit side shear in completed drilled shafts. Beresford et al. also suggest that the AV at 600 rpm be no greater than about 12 cP so that the slurry will flow readily to the top of the borehole when displaced by the fluid concrete.

7.4.3.3 pH Value

The pH of the slurry is an indicator of the degree of acidity or alkalinity of the slurry. Maintenance of a proper range of pH is important to the proper functioning of the slurry and is an indicator of the effectiveness of anti-hardness additives. For example, neutral-to-acid pH (7.0 or lower) can reflect conditions in a borehole that is being drilled through an acidic fill and that a bentonite-based slurry may be in danger of flocculating, or it could indicate that a polymer slurry is mixing with acidic groundwater and is in danger of agglomerating. Values for the allowable range of pH are presented in Section 7.4.5. The pH can be determined readily by the use of pH paper or by a pocket pH meter. The pocket pH meter, which is the size of a large pencil, is more accurate and is easy to use, but it must be calibrated often against a standard buffer solution.

7.4.3.4 Sand Content

The material retained on a No. 200 screen (74 microns) is defined as sand. Prior to concrete placement, sand content of mineral slurry should not exceed 4 percent by volume. Sand content is measured using a standard API (American Petroleum Institute) sand content kit by taking a slurry sample of 100 mL. A photograph of an API sand content test kit is shown in Figure 7-13. The sample is usually taken from the slurry cup after stirring vigorously to make sure all of the sand in the original sample in the cup is uniformly distributed in the suspension from which the 100 mL sample is taken. The slurry sample is diluted with water and then passed through a No. 200 stainless steel screen. The sand from the slurry is retained on the screen. That sand is then backwashed from the screen into a burette with a graduated, conical base, and the sand content in percent by volume is obtained by reading the scale on the burette.

When testing polymer slurries for sand content, particularly if the soil being drilled contains dispersive clay or silt that can be put in suspension temporarily during drilling and become entangled with the polymer strands, it is important that the slurry be washed over the No. 200 screen with a mixture of household bleach containing sodium hypochlorite and water (perhaps 50/50 by volume), several times if necessary, to detach the polymer strands from the soil. Otherwise, the clay/silt-polymer assemblages will be registered as sand. In any event, it is important that the final wash water in the burette be clear. Otherwise, the washing process should be repeated until the wash water becomes clear before making the sand content reading.

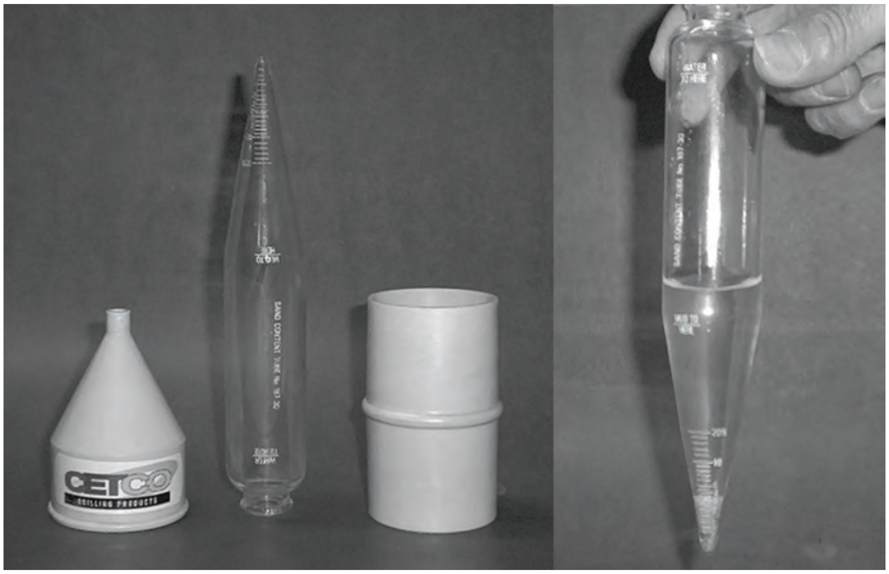


Figure 7-13 Photograph of Sand Content Test Apparatus (Courtesy of J. Berry)

7.4.3.5 Hardness

Hardness of mixing water or groundwater is measured by a titration process using a standard API kit that can be obtained for this purpose. A small sample of the water is put into an evaporating dish, and chemicals are added to change its color, usually to purple. An amount of another chemical sufficient to turn the color of the water to a target color, usually blue, is then released from a graduated burette (titrated) into the water, and the volume required for the color change measured. The hardness is then determined from a table provided with the kit from the measured volume of the titrated chemical. A simpler, but less accurate, field kit for hardness is also available. This kit requires that only one chemical be added to the water in order to estimate hardness.

7.4.3.6 Free Water and Cake Thickness

A device called a filter-press is commonly used for this test. The device consists of a small slurry reservoir that is installed in a frame, a filtration device, a system for collecting and measuring a quantity of free water, and a pressure source. The test is performed by forcing slurry through a piece of filter paper under a pressure of 100 psi for a period of 30 minutes. The free water that is recovered is measured in cubic centimeters, and the thickness of the cake that is formed is measured to the nearest millimeter. Before measuring the cake thickness, any superficial slurry that is not part of the filter cake is washed away.

7.4.3.7 Shear Strength

The shear strength of mineral slurry is influenced by the percentage of mineral that is present, by the thoroughness of mixing, and by the amount of time since agitation. The shear strength at a given time can be measured by use of a device called a shearometer. A determination by the shearometer merely involves the rate at which a thin-walled cylinder will settle in a beaker of slurry. While the shearometer is easy to use, Holden (1984) reports that it is difficult to obtain repeatable readings. The shear strength test is not commonly performed for drilled shaft slurries but can be of aid in diagnosing problems on occasion.

7.4.3.8 Comments on Field Testing of Drilling Slurries

The purposes of field tests on drilling slurries are to assure that the drilling slurry has the necessary properties to

- Maintain hole stability
- Minimize relaxation of ground stresses
- Leave the sides and base of the borehole in a condition of minimum contamination.

Overall, the field testing of drilling slurries is not difficult. The tests and the skills can easily be mastered by most State DOT inspectors, or the tests can be performed by the contractor's personnel with oversight by a State inspector. Testing personnel should be familiar with published standardized procedures (API 2003).

Not all of the tests described above need to be performed on every drilled shaft on every project. Some of the tests for slurry are time-consuming and in some cases could actually result in poor work because of the inevitable delays that would result as testing is being done. In an ideal situation, all or most of the tests described above would be conducted on trial batches of slurry made from the makeup water available on a given site, using the particular type and brand of slurry material being considered for the drilling operation, and perhaps adding site soils to the slurry mix to determine if mixing the site soils with the slurry affects the slurry's properties. Then, considering the job-specific requirements (drilling in large-grained, open-pored soils; drilling in rock; drilling in clean, loose sand; equipment available, etc.), job-specific specifications are developed. Typically, however, standard specifications that work in most cases are followed, and the tests required by those specifications are conducted to monitor the slurry. The user of standard slurry specifications should be aware that occasionally soil and/or water conditions could exist at any site, or slight changes in formulation of the drilling slurry product being used may occur that may render the standard specifications, and the test values required by the specifications, invalid. The user of the slurry, ordinarily the drilled shaft contractor, should then be prepared to design the slurry to accommodate the soil and water conditions at the jobsite and to arrive at job-specific specifications, perhaps through modification of the standard specifications that will need to be approved by the agency.

Once acceptable slurry mixes and job-specific specifications have been developed for a particular project, testing is ordinarily performed during production drilling, on representative samples, to assure that slurry properties, once established, do not change, and these tests are generally minimal. Tests performed for monitoring production drilling are generally the density test, the Marsh funnel viscosity test, the pH test, and the sand content test.

7.4.4 Specifications for Drilling Slurry

A number of agencies and writers have made recommendations about the desirable properties for bentonitic slurries for drilled shafts. Valuable references on the subject of bentonite slurries include those developed by engineers with Cementation, Ltd., in the United Kingdom (Fleming and Sliwinski, 1977), and a detailed set of recommendations given by the Federation of Piling Specialists (1975), also in the United Kingdom. The FPS specifications have been adopted by a number of owners as being adequate for most jobs involving the use of drilling slurry. Other detailed sets of bentonite slurry specifications are given by Hutchinson et al. (1975), Hodgeson (1979), and Majano et al. (1994).

The following point is emphasized: no “standardized” set of slurry specifications, including those presented in this manual, are applicable to every set of conditions encountered in drilled shaft construction. Specifications should be tailored to fit the requirements of a particular job at a particular location. Standardized specifications, however, are still useful in that they reflect the collective experience of the drilled shaft industry and provide a starting point for agencies with little experience in slurry construction. The ranges of properties specified in standardized recommendations are sufficiently wide to cover a wide range of conditions typically encountered in practice.

TABLE 7-1 and Table 7-2 present general specifications for use with mineral slurries (TABLE 7-1) and PAM-derived polymer slurries (Table 7-2). These tables are adapted from the AASHTO Construction Specifications (AASHTO, 2008) and they also appear in the drilled shaft construction specifications described in Chapter 18. The specifications in TABLE 7-1 apply to either sodium smectite (bentonite) or attapulgite and sepiolite slurries. Attention is again called to the fact that these specifications may need to be modified for job-specific requirements. For example, the specification in TABLE 7-1 for sand content up to 4 percent prior to concrete placement is appropriate in most cases, but in larger shafts (> 6 ft diameter) 4 percent may be too high to permit full displacement by concrete. One simple, although not always sufficient, axiom to follow is that the most important characteristic of a mineral slurry is its density and that the slurry should be only dense enough to maintain a stable borehole.

With particular reference to Table 7-2, a wide range of polymer products is available and the range of properties specified in the table is typical for many of the PAM products on the market at the present time (2009). Adjustments may be necessary and appropriate, based on recommendations provided by the polymer supplier or manufacturer, and taking into account job-specific conditions and new products. For example, some of the proprietary polymers now on the market operate optimally at Marsh funnel viscosities up to 150.

TABLE 7-1 RECOMMENDED MINERAL SLURRY SPECIFICATIONS FOR DRILLED SHAFT CONSTRUCTION (AASHTO, 2008)

Property of Slurry (units)	Requirement	Test Method (API Standard Method)
Density (lb/ft3)	64.3 to 72	Mud Weight Density Balance (API 13B-1)
Viscosity (sec/quart)	28 to 50	Marsh Funnel and Cup (API 13B-1)
pH	8 to 11	Glass electrode pH meter or pH paper strips
Sand Content immediately prior to concrete placement (percent by volume)	≤ 4.0	Sand Content (API 13B-1)

TABLE 7-2 RECOMMENDED POLYMER (PAM) SLURRY SPECIFICATIONS FOR DRILLED SHAFT CONSTRUCTION (AASHTO, 2008)

Property of Slurry (units)	Requirement	Test Method (API Standard Method)
Density (lb/ft3)	≤ 64	Mud Weight Density Balance (API 13B-1)
Viscosity (sec/quart)	32 to 135	Marsh Funnel and Cup (API 13B-1)
pH	8 to 11.5	Glass electrode pH meter or pH paper strips
Sand Content immediately prior to concrete placement (percent by volume)	≤ 1.0	Sand Content (API 13B-1)

Water is sometimes used to maintain stability by simply offsetting the hydrostatic or artesian groundwater pressure, thereby preventing inflow of groundwater to the borehole. For example, a borehole in sand that is cased could have basal stability issues as groundwater from outside the casing seeps upward. Maintaining water levels inside the casing above the hydrostatic or artesian level can prevent this type of bottom disturbance. Water is sometimes used in rock to prevent inflow at the base and along the side of the borehole. However, the addition of water to rock that will swell or soften in the presence of water is not recommended. When water is used as a drilling fluid, it should be kept as clean as possible, and should conform to specifications that limit its density (by mud balance) to 64 pcf and sand content to a maximum of 1.0 percent.

7.5 ADDITIONAL DESIGN AND CONSTRUCTION CONSIDERATIONS

7.5.1 Borehole Inspection Under Drilling Fluids

Construction of a drilled shaft with drilling fluids makes it difficult to inspect the borehole conditions directly, for example, compared to the dry method of construction. However, several tools are available that provide information on borehole conditions. A downhole shaft inspection device, or SID, can be used to provide a remote image of the borehole. The SID is equipped with an underwater camera that can view the bottom of a shaft excavation that is filled with slurry. The SID is described further in Section 19.2.4.

Knowledge of the excavated borehole geometry can be useful for estimating the required volume of concrete, for identifying the locations of over-excavation or caving, assessing the vertical alignment of the shaft, and for the proper interpretation of load test results. Two complimentary tools are available for this purpose. The first is to employ a borehole caliper that can be used to measure the shape of the borehole as a function of depth. Several different types of calipers and their use are described in Chapter 17 on load testing (Section 17.2.1.5). The second involves preparation of a graph showing the actual volume of concrete that is placed versus anticipated volume for small increments of depth (development of a "concreting curve"). Details of constructing such a plot are described in Chapter 9 (Section 9.3.4). This concreting curve will allow the engineer to make a judgment about the possible loss of concrete in an undiscovered cavity and about the possible collapse of the excavation during concrete placement. Such a plot is useful regardless of the method of construction, but the technique is mentioned here because of its particular importance with regard to the slurry methods, in which neither the finished borehole nor the placement of concrete can be observed visually.

The depth of the borehole should be measured immediately after the base is cleaned and compared to the depth attained by the cleaning tools to determine if sloughing has occurred from the borehole walls. Another depth sounding should be made immediately prior to placing concrete, after the cage is placed in the borehole, to ascertain whether soil that has been in suspension has settled to the bottom of the borehole. If such is the case, it would be necessary to remove the cage and re-clean the base of the borehole.

A subsequent plot of the actual volume of concrete placed per increment of depth versus the expected volume computed from the planned shaft dimensions or from the caliper logs in each increment of depth should show excellent agreement. Such information can be of great value to the engineer if questions arise later about the quality of a particular drilled shaft.

7.5.2 Influence of Slurry on Axial Resistance of Drilled Shafts

Geotechnical design of drilled shafts for axial loading is covered in Chapter 13 of this manual. Equations are presented for calculating nominal side and base resistances for drilled shafts embedded in various types of soil and rock. A concern that often arises pertains to the possibility that the calculated resistances could be adversely affected (reduced) by the use of slurry in drilled shaft construction. In particular, it is postulated that bentonite filter cake or the presence of polymer in the sidewalls of the borehole could create an interface that is weaker in shear than would be the case in the absence of slurry. Earlier in this chapter, it was pointed out that many drilled shafts have been successfully installed with slurry, as evidenced by the results of numerous load tests. Also noted was that drilled shafts that were installed with bentonitic slurry have been exhumed and the interface between the concrete and the parent soil examined. In the vast majority of cases, no evidence was found of a thick, weak layer of bentonite. Furthermore, no evidence was found in the drilled shafts described of any loss of bond between the rebar and the concrete. Similar statements can be made about drilled shafts installed with polymer slurries. Nevertheless, concerns about the effects of slurry are valid because drilled shaft performance depends upon quality of construction, and proper use of slurry is an important aspect of quality.

The following paragraphs summarize research on the effects of slurry on drilled shaft behavior, with an emphasis on side resistance. The overall conclusion, supported by the available evidence, is that the design equations presented in Chapter 13 are valid for all construction methods, including slurry, *provided that the practices recommended in this manual are followed*. Most importantly, with regard to bentonite slurry, practices that limit the thickness of the filter cake to the value suggested earlier (1/8 inch), adherence to the project specifications (*e.g.*, TABLE 7-1 and TABLE 7-2), and prompt placement of concrete will result in drilled shafts with side resistances that can be predicted with confidence. Research on this topic is reviewed in the following order: (1) bentonite slurry, (2) polymer slurry, and (3) studies involving comparisons between bentonite and polymer slurries.

7.5.2.1 Mineral Slurry

As discussed and illustrated in Figure 7-1, formation of a filter cake along the sidewalls is one of the mechanisms by which mineral slurry provides borehole stability in permeable materials. A thorough review on the effects of mineral slurry on side resistance was presented by Majano and O'Neill (1993), including a summary of all published load tests and other relevant research conducted up to that time. The conclusion reached by that study was that: "*An excessively thick cake (thicker than the soil asperities) degrades the interface and decreases the available perimeter shear*". In reviewing load tests that involved direct comparison between shafts constructed under mineral slurry and other methods, the authors noted that "*Research in soils regarding the degree to which perimeter load transfer is reduced by slurry is largely contradictory*". This statement regarding contradictions stems from studies showing that the effects of mineral slurry can range from zero or minimal (Fleming and Sliwinski, 1977; Cooke, 1979) to minor decreases on the order of ten percent (Farmer and Goldberger, 1969), to significant reductions (Wates and Knight, 1975; Cernak, 1976). Further consideration of the test conditions, however, makes it possible to identify the factors that control potential degradation of side resistance. Basically, understanding and controlling the factors that determine filter cake thickness and strength are the keys to proper use of mineral slurry. The studies that showed significant decreases in side resistance generally involved long exposure times and/or filter cake thicknesses in excess of the value recommended for current practice. In fact, some of these early studies led to the current recommended practices.

Thickness of the filter cake is a function of several factors, the most important of which are: time of exposure of the slurry to the borehole wall, properties of the slurry (dosage, unit weight), and the head difference between the slurry and the groundwater in the formation. Nash (1974) developed an analytical equation to predict filter cake thickness as a function of these variables (including time) and noted that a thickness of about 0.2 in. would be predicted at 24 hours of exposure for typical slurry and filter cake at a depth of 65 ft. Wates and Knight (1975) investigated the thickness of bentonite filter cake between concrete and sand and its effect on side resistance for diaphragm walls and drilled shafts. Laboratory tests were performed in which the filter cake thickness was found to vary with time and with the hydrostatic head of the slurry column. Small-sized piles were cast against the slurry in the laboratory and their pullout capacities were compared to those of a pile that was cast dry and one that was cast with direct displacement of the slurry by the concrete. The authors concluded that a filter cake of significant thickness (0.3 to 0.4 inches) will develop in 24 hours and that, unless removed, reduced the side resistance to a value significantly less than if the concrete is cast directly against the natural soil. This experimental evidence and the work of Nash (1974) are some of the early studies showing the detrimental effects of allowing bentonite slurry to be left in place for 24 hours. Currently, the recommended practice is to limit to four hours the time during which mineral slurry is left unagitated in the borehole. Under some circumstances, it may not be practical to meet this time limit. In those cases, the contractor's installation plan should address the procedures to be used that will ensure proper displacement of slurry in a manner that is not detrimental to performance of the drilled shaft. Load testing provides a means to verify the suitability of the contractor's methods.

Sliwinski (1977) and Fleming and Sliwinski (1977) argue strongly that the influence of filter cake should be minimal if exposure time is not excessive and slurry properties are controlled. Sliwinski (1977) reports that the rising column of concrete will displace the slurry and much of the cake because of the considerable difference in unit weight and shear strength of the fluid concrete and mineral slurry. Although the portion of the slurry that penetrates the soil cannot be displaced, Sliwinski states that field and laboratory tests seem to indicate that the influence of some mineral slurry in the parent soil has an insignificant influence on load transfer. The conclusion is based on the assumptions that the properties of the slurry are within reasonable limits and that the concrete placement is done within a reasonably short time after the excavation is completed. In support of this opinion, Fleming and Sliwinski (1977) reported on 49 field tests from several different countries. They report that the test results suggest that the development of shaft friction had not been "impaired or inhibited" by the presence of mineral slurry. They point out that the drilled shafts that were tested and analyzed had "in all probability been constructed and tested without any inordinately long delay between boring and concrete placing."

The following case reported by O'Neill and Hassan (1994) demonstrates dramatically that mineral drilling slurry can either produce a devastating loss of side resistance or a completely satisfactory value of side resistance, depending on how the slurry is mixed and controlled, and the importance of good slurry specifications and inspection of the slurry drilling process. Two drilled shafts, 3 ft in diameter, were constructed side by side to a depth of about 35 ft in a medium dense, saturated, silty sand under bentonite drilling slurry. For the first drilled shaft, the Marsh funnel viscosity was 155 sec./quart, the yield point was 30 Pa, the time of exposure of the slurry to the borehole without slurry agitation prior to concrete placement was 72 hours, and the resulting measured filter cake thickness before concreting was 0.4 in. In the second shaft, the Marsh funnel viscosity was 40 sec./quart, the yield point was 9.6 Pa, the time of exposure was 2 hours, and the mudcake thickness was less than 0.04 in. The first drilled shaft developed an ultimate side resistance of 45 kips, or about 136 psf average unit side resistance, while the second drilled shaft developed an ultimate side resistance of about 606 kips, or about 1,800 psf average unit side resistance.

Taken together, the studies summarized above point to the following conclusions:

Potentially adverse effects of mineral slurry on drilled shaft side resistance can be avoided by maintaining the properties of the slurry within tolerable limits and by placement of concrete within a maximum of a few hours after the excavation is completed. The drilling and concreting processes should proceed in a continuous fashion and the soil or rock should not be exposed to the mineral slurry for an excessive period of time. In general, if mineral slurry remains in a borehole unagitated for more than about four hours, its gel or shear strength becomes too high to permit full flushing by the concrete. Furthermore, the filter cake that builds up on the borehole walls can become hard, and a layer of very viscous gel can accumulate over the filter cake, possibly reducing the side resistance that can be developed in the completed drilled shaft. Good practice, therefore, includes specifying that the contractor agitate mineral slurry that will be held in the borehole for more than four hours between the completion of drilling and the commencement of concrete placement. Otherwise, the contractor should re-cut the sides of the borehole, possibly using a side cutter affixed to an auger or drilling bucket, to a diameter of about 2 inches larger than the diameter of the original borehole and then re-clean the base before placing concrete. Considering this potential problem, contractors should not be permitted to place the rebar cage in the slurry until just prior to concreting.

The preceding discussion relates to the production of filter cake in permeable soils and rocks. Since filtration into the formation being drilled is the principal mechanism of filter cake buildup in mineral slurries, filter cake tends not to develop in impermeable geomaterials such as clays, and concern about loss of skin friction due to filter cake buildup is lessened. This hypothesis is supported by load tests, for example, see Cooke (1979).

7.5.2.2 Polymer Slurry

O'Neill and Hassan (1994) report on load tests performed by Caltrans on five drilled shafts in sandy silt to silty sand in the Los Angeles area. These shafts were all 2 ft in diameter and about 33 ft deep. Four were constructed under polymer slurry -- two with emulsified PAM and two with dry vinyl-extended PAM. All of the shafts were loaded in compression. In all four cases the average unit side resistances were consistent with values predicted using the design methods recommended by O'Neill and Reese (1999). While no filter cake builds up with polymer slurry, the slurry itself has a "slimy" texture, and it may appear that such slurry could lubricate the interface between the concrete and soil. However, the polymer breaks down at values of pH greater than about 11.7 when exposed to lime in the concrete, with the resulting chemical products being water and carbon dioxide. Since fluid concrete generally has a pH greater than 12, it has been hypothesized that the exposure of concrete to polymer slurry destroys the polymer and appears to leave the concrete in contact with the soil at the surface of the borehole. The small amount of residual water and carbon dioxide remaining near the interface do not appear to cause any problems, although long-term test data are not available. A fifth drilled shaft, constructed at the same site with only water as a drilling fluid, developed slightly higher unit side resistance than the shafts constructed with polymer drilling slurries. This single test result suggests the slurry itself appeared to affect some reduction in side resistance from the value that would have been achieved had slurry not been used.

Majano et al. (1994) observed that side resistance increased slightly with time of exposure of polymer slurry to the soil prior to concrete placement in model drilled shafts constructed with two polymer slurries, whereas side resistance decreased with time of exposure when mineral slurries were used. Ata and O'Neill (1997) report values of unit side resistance in excess of those that are predicted with the design equations given by O'Neill and Reese (1999) constructed with high-molecular-weight PAM slurry in stiff clay, stiff very silty clay, and medium dense sand.

While development of side resistance does not appear to be a problem with polymer drilling slurries, there is anecdotal evidence that difficulties have been experienced on some transportation projects with polymer slurries that have not maintained borehole stability, particularly for deep, large-diameter boreholes in sand and gravel. Whether these problems were caused by physical properties of the particular polymer slurries used on these projects, or whether they are caused by inadequate construction practices, is unclear. It is clear that the slurry should be mixed and conditioned properly and its viscosity and hardness closely controlled throughout the drilling process (for hardness, indirectly by continually monitoring pH).

It is also clear that contractors must be diligent in introducing the slurry at the time the piezometric surface is reached, not at the time caving problems are experienced. Once caving starts at any level, it is very difficult for any drilling fluid, especially a low-density polymer slurry, to keep the borehole from continuing to ravel or slough, even if ideal practices are followed for the remainder of borehole excavation. The contractor must also be careful to maintain the slurry head well above the piezometric level at all times and use vented drilling tools operated at a relatively slow rate. If sloughing starts under a head of slurry, the contractor may be forced to re-cut the hole back to a cylindrical shape to arrest the sloughing or to backfill and redrill the hole.

7.5.2.3 Comparisons of Bentonite and Polymer Slurries

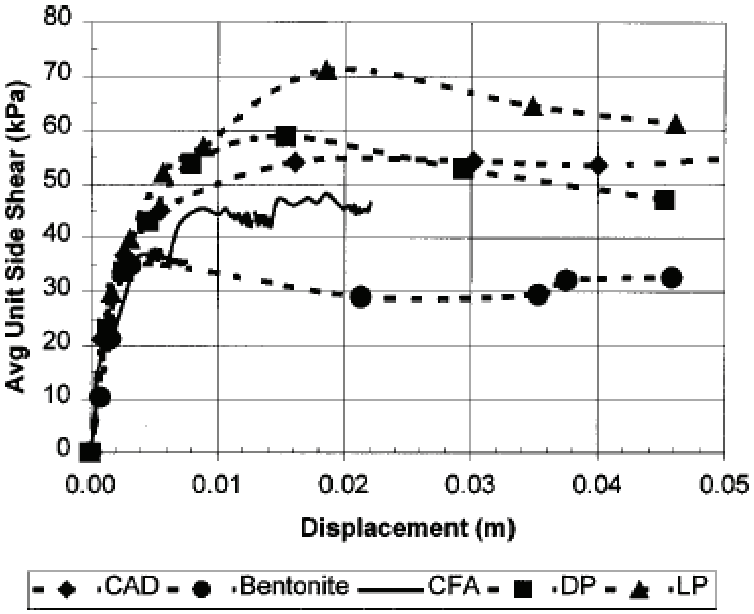
Several comparative studies have been published in which drilled shafts constructed side by side under both bentonite and polymer slurries were load tested. Meyers (1996) describes a case where two drilled shafts, 2.5 ft in diameter and 45 ft deep, were constructed and tested in saturated sand/gravel/cobble alluvium to develop design criteria for a foundation for a bridge project in New Mexico. One shaft was constructed with controlled bentonite slurry, and the other was constructed with a high-molecular-weight proprietary dry polymer. Both boreholes were calipered to verify that they had equivalent diameters. While both drilled shafts developed higher side resistances than would be predicted by the methods given by O’Neill and Reese (1999), the drilled shaft constructed with the polymer slurry developed higher side resistance than the shaft constructed with bentonite slurry.

Camp et al. (2002) describe load tests on twelve instrumented drilled shafts in Cooper marl, a stiff calcareous clay, in the Charleston, S.C. area. Test shafts were either 6 ft or 8 ft diameter and either 100 ft or 150 ft deep and were constructed in the dry, with bentonite slurry, with polymer slurry, and using fresh water as a drilling fluid. The authors report that measured average unit side resistances were all within 10% of each other and conclude that no discernible differences could be attributed to the construction method. The authors also note that the Cooper marl is a low-permeability material, and that bentonite filter cake would not be expected to form under these conditions.

Brown (2002) describes a load testing program involving ten drilled shafts installed in Piedmont residual soils in Spring Villa, AL. The soil profile is described as micaceous sandy clayey silt, classified as ML-SM, with sand seams. All test shafts were 3-ft diameter, 35-ft deep. Two shafts were constructed under bentonite slurry; four under polymer slurry (2 dry, 2 liquid), and four with full-depth casing advanced ahead of the excavation. Figure 7-14 shows average unit side resistance versus displacement curves (averaged for each construction method). [Also shown is the result for a single continuous flight auger, or CFA, pile]. The most noteworthy result shown in Figure 7-14 is that the bentonite shafts exhibited significantly lower side resistance than shafts constructed by the other techniques. Subsequent excavation of the test shafts revealed an easily identifiable seam of bentonite along the sidewalls of the shafts constructed under bentonite slurry. No visible film was observed along the walls of the shafts constructed under polymer slurries. Brown concludes that the lower observed side resistances in the fine-grained silty soils at this site are a result of filter cake formation, even though exposure times were limited. Marsh funnel values for bentonite were 52 seconds/quart, slightly above the range recommended in TABLE **7-1**.

Frizzi et al. (2004) report the results of load tests on three 6-ft diameter, 120-ft long drilled shafts installed in alternating layers of soft rock (sandstone and limestone) and sand in Miami, FL. Two of the test shafts were installed using polymer slurry and one shaft was constructed using bentonite slurry. Load testing was by Osterberg load cells embedded near the bottom of the test shafts and load transfer was inferred from strain gage readings on sister bars (see Chapter 17 for a full description of this test method). Figure

7-15 shows the mobilized unit side resistance versus depth for all three shafts, over the depth interval 70 to 120 ft, which corresponds to rock sockets in the Fort Thompson Formation. For the polymer shafts (PS1 and PS2), unit side resistance varies between 5 and 20 ksf, while for the bentonite shaft unit side resistance varies between 4 and 23 ksf. The authors state that unit side resistance along the upper one-half of the bentonite shaft is approximately 25% to 50% lower than in the polymer shafts, but approximately similar in the lower one-half of the socket. However, as can be observed in the figure, mobilized unit side resistance varied significantly between the two polymer slurry shafts (PS1 and PS2) and, over the depth interval from approximately 103 – 106 ft, the bentonite shaft exhibits much higher side resistance than the slurry shafts, making it difficult to draw a strong conclusion regarding the influence of the various polymer slurries. The authors report that sampling of the sidewalls during excavation identified a 0.3-inch thick layer of soft bentonite on the perimeter of the borehole plus a 0.04-inch thick filter cake penetrating the soft rock in the upper rock strata, but that no well-defined bentonite accumulation or filter cake could be discerned in the lower rock strata. It is not stated at what depths these sidewall samples were obtained, but reduced side resistance in the upper portion of the socket would be consistent with higher filter cake thickness. It is also possible that side resistance of the test shafts was influenced by factors other than slurry type, for example, variable ground conditions. As a footnote, it is interesting that the bentonite shaft exhibited an overall higher capacity, derived mainly from a much higher base resistance than either of the polymer slurry shafts.



CAD: cased-ahead method; CFA: auger-cast pile; DP: dry polymer; LP: liquid polymer

Figure 7-14 Average Load Transfer in Side Shear for Different Construction Methods (Brown, 2002)

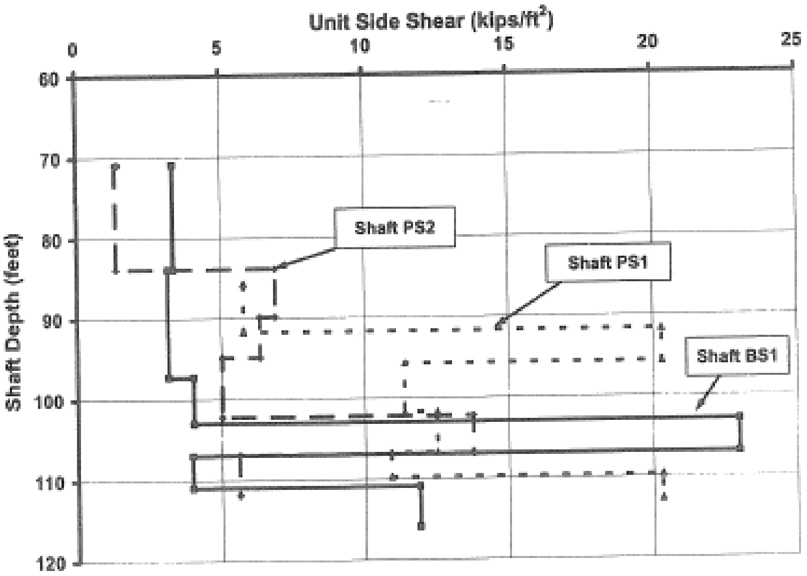


Figure 7-15 Mobilized Unit Side Resistance in Lower Fort Thompson Formation Rock Sockets (Frizzi et al., 2004)

Laboratory and field evidence suggest that polymer slurries may improve the side resistance of drilled shafts in rock that may otherwise degrade in the presence of water. Brown (2008) reports the results of slake durability tests on shale as part of a load testing program for the Paseo River Bridge in Kansas City. Slake Durability Index (I_D) is a measure of a material's resistance to degradation when subjected to a series of wet-dry cycles with mechanical agitation by tumbling in a drum. A higher value of I_D indicates greater resistance to degradation in the presence of water (slaking). The index was measured on identical samples, but one using Missouri River water and the other using a polymer slurry. For the sample tested in water, $I_D = 72$, while for polymer slurry $I_D = 98$. Both of these results exceed the value that would suggest significant degradation ($I_D \leq 60$) but these data suggest that the polymer has a beneficial effect on the shale slake durability. Based on the laboratory tests, polymer slurry was recommended as the drilling fluid for construction of rock sockets in the shale.

Conditions at the base of a drilled shaft constructed under slurry must also be considered carefully. If excessive soil or rock cuttings or flocculated or agglomerated slurry accumulate on the base of a drilled shaft constructed by the wet method, some of this loose material may be pushed to the side by the introduction of concrete, rather than being lifted up by the concrete. This action will result in a "bullet-shaped" base that is bearing against the soil or rock only over part of the cross-section of the drilled shaft, adversely affecting base resistance. Cleaning of the base of the drilled shaft just prior to placing the cage and concrete and verification that the base is clean just before concreting, are therefore very important parts of the construction and inspection processes.

7.5.3 Bond with Reinforcing Steel

Fleming and Sliwinski (1977) report that the general opinion is that there is no significant reduction of bond between concrete and the reinforcing steel in drilled shafts constructed under bentonitic slurry. They report that the Federation of Piling Specialists (1975) recommends the use of the maximum allowable bond stress values for round, nondeformed bars in bentonitic slurry. For deformed bars the FPS recommend an increase in bond of not more than 10 per cent of the value specified for plain bars.

Butler (1973) exhumed full-sized drilled shafts constructed under light bentonitic drilling slurry and conducted pullout tests on the rebar. He concluded that the bond between the concrete and No. 8 deformed longitudinal rebars was not degraded.

Most information on bond between concrete and rebar when the drilled shaft is concreted under a polymer slurry has been developed by research commissioned by the polymer suppliers, and documentation can be obtained from them. One laboratory study was made of the simulated placement of a standard mix of concrete (Type II Portland cement and maximum coarse aggregate size of ½ inch) around No. 5 deformed bars under a slurry made from an anionic, high-molecular-weight PAM mixed to the manufacturer's specifications. Test results suggested that the bond strength develops more slowly than when drilled shafts are concreted under light bentonite slurry. At 28 days, however, the bond strength obtained when the rebar had been exposed to the polymer slurry at a dosage of 2.5 g (solid powder) / L (mixing water) was slightly greater than the bond strength obtained by similar simulated concreting under a light bentonite slurry [50 g (solid powder) / L (mixing water)] (Maxim Technologies, Inc. 1996).

The current state of knowledge on this topic suggests that the use of mineral and polymer slurries for drilled shaft construction does not reduce the bond resistance between concrete and reinforcing bars. There is currently no reason to account for the use of drilling fluids when considering development length of rebar in drilled shafts.

7.5.4 Summary of Major Handling Considerations

This chapter includes a large amount of information on various types of drilling fluids currently used for drilled shaft construction. Some of the most important construction-related issues to keep in mind for the two major categories of drilling fluids (mineral slurry and polymer slurries) are summarized in the following. All of these issues are discussed in more detail in preceding sections of this chapter and are merely listed here for convenience.

For mineral slurries the major areas of risk are associated with (1) improper mixing and handling that can lead to instability of the borehole, (2) excessive filter cake thickness that reduces side resistance, (3) inadequate cleanout at the base of the shaft, and (4) improper concrete placement techniques that fail to completely displace the slurry. The following measures are therefore critical:

- <u>Mixing and handling</u> Trial mix designs should be established on the basis of testing as described in Sections 7.3.1 and 7.4.3.2. The mixing water must be screened for salt content, pH, hardness, and chloride content to avoid flocculation. Provide high-shear mixing and adequate time for hydration of bentonite, preferably 24 hours prior to its introduction into the borehole. Properties of mineral slurries during construction should be monitored and maintained within the limits specified in TABLE 7-1 or in accordance with owner-defined specifications.
- <u>Control of Filter Cake Thickness</u> A filter cake thickness greater than approximately 1/8 inch on the sidewalls of the borehole prevents complete displacement of bentonite by the fluid concrete and adversely affects side resistance. To avoid excessive filter cake thickness place concrete as promptly as possible, preferably within four hours after completion of the excavation. Where this is not possible, the measures outlined in Section 7.5.2.1 are recommended, such as re-cutting the sidewalls of the borehole, additional cleaning of the slurry, etc. For very large shafts requiring massive volumes of concrete, it may not be possible to avoid formation of excessive filter cake and side resistance may have to be reduced. Load testing provides a means to quantify the reduced side resistance.

- Adequate Cleaning and Processing The amount of sediment suspended by a mineral slurry determines its ability to be displaced by fluid concrete. Procedures and equipment used to circulate and clean the slurry must be adequate to maintain the viscosity and sand content within the limits specified in TABLE 7-1. Cleaning of slurry at the base of the drilled shaft is critical to avoid trapping of slurry and sediment beneath the tip of the shaft, a condition that may prevent mobilization of base resistance without excessive settlement. This issue is addressed further in Section 9.3.3.3.
- Proper Concrete Placement Proper procedures for placement of concrete under slurry are covered in Section 9.3.3. The most important considerations are that that the concrete have good workability for the duration of the placement operations and that the bottom of the concrete delivery tube be maintained below the rising surface of fresh concrete. A minimum depth of embedment of 10 ft is recommended.

For drilling fluids made from polymers the primary risks are associated with (1) incompatibility with the ground conditions, (2) damage to the polymer chains by improper mixing equipment, (3) hole instability due to insufficient pressure head, and (4) inadequate time for sedimentation and cleaning. The following measures are most important.

- Consultation with the Supplier Polymers used for drilling fluids encompass a wide range of products having different chemical compositions and additives. It is important to match the product with the ground conditions and this requires the expertise of the polymer supplier in order to select appropriate product and additives based on soil type and water chemistry.
- Mixing and Handling Any type of mechanical action that disrupts the chain structure of polymers diminishes the effectiveness of the slurry. Use of in-line mixers, diaphragm pumps, and splash plates are effective measures to avoid damage. High-shear mixing, mechanical mixing with blades, and cyclones should be avoided. Equipment for mixing and cleaning mineral slurries is not appropriate for polymer slurries. Polymer slurry would not be considered suitable with full-circulation drilling in most cases.
- Adequate Pressure Head Good practice includes introduction of the slurry before excavating into unstable strata and maintenance of sufficient head of slurry. The elevation head difference between slurry and piezometric elevation should be a minimum of 6 ft and preferably 10 ft. This measure is important when using bentonite slurry also, but it is especially critical with polymer slurries because of their lower densities.
- Adequate Time for Sedimentation Polymer slurries do not suspend soil particles. It is important to allow sufficient time for sediment to settle to the bottom of the slurry column, then to clean the slurry of sediment using a cleanout bucket or airlift just prior to placement of concrete. The time required for sedimentation can range from 30 minutes to 2 hours, depending on the size of the shaft, amount of sediment, and type of polymer. For polymer slurry with excess silt, complete replacement with clean slurry should be considered.

In addition, the concrete placement methods described above for bentonite slurry are applicable to polymer slurries.

7.6 SELECTION OF DRILLING FLUIDS

Selecting the type of drilling fluid to use on a particular project is often a major consideration for a contractor in the bid preparation. Some of the most significant factors taken into account are discussed as follows.

- Ground conditions Both bentonite and polymer slurries are applicable to a wide range of soil conditions. Regardless of the product, the contractor must be confident that the drilling fluid will provide a stable borehole without caving and will allow for proper placement of concrete, *for the particular subsurface conditions associated with each job*. This must be achieved while also meeting the specifications provided by the owner. In Chapter 2 it is emphasized that a thorough site characterization program and report are needed not just for drilled shaft design, but also for construction. Selection and mix design of a suitable drilling fluid are prime examples of construction-related issues that requires accurate subsurface information, especially on soil classification, grain size distribution (for example, fines content), and groundwater conditions.
- Equipment availability The equipment required for mixing, storage, circulation, cleaning, and testing of drilling fluid can represent a major investment and/or rental cost to drilled shaft contractors. As described in Section 7.4, much of the equipment used to handle bentonite slurry is different than the equipment used to handle polymer slurry. Some contractors have invested in one or the other and therefore will plan to use the type of drilling fluid governed by their equipment capabilities.
- Experience The experience of a contractor will always affect the means and methods they select to apply on a particular job. Some contractors have broad experience with the use of different slurry types while others have more narrow experience and will prefer to use the type of slurry with which they are experienced. Local experience may also suggest that particular drilling fluid products be used. For example, some regions of the U.S. have a long history of successful use of bentonite slurry for drilled shaft construction and the local market has evolved such that contractors in that area are experienced primarily with bentonite slurry construction.
- Specifications Specifications imposed by the owner will be taken into account by a contractor when considering the costs of meeting the requirements for material properties, costs of testing, the need for additives or special equipment, or any other costs associated with meeting specifications. Also, some transportation agencies have specifications that impose strict limitations on the types of drilling fluid products allowed. Some states prohibit the use of mineral slurries and allow only polymer products which have been screened and included on a list of approved products. Other states have specifications that prohibit the use of polymer slurry.
- Environmental factors The possibility of contamination to the environment is a consideration by contractors and owners in evaluating the use and disposal of drilling fluids.
- Level and quality of technical support provided by the material supplier On some projects, especially large projects, very close cooperation is required between the contractor and the material provider in order to select the appropriate product, evaluate mix designs, install and monitor technique shafts, and work through problems and issues as they arise during construction. The availability of the supplier's representatives and the quality of service they provide to the contractor are important considerations in selecting a particular product. In effect, the contractor is not simply purchasing a material; rather they are investing in the supplier's expertise and experience.
- Disposal The issue of disposal affects the cost and the operations of the contractor. It is noted several times in this chapter that disposal of mineral slurries can be challenging and costly,

depending upon local environmental regulations, distance from the project site to disposal facilities, and the amount of slurry to be disposed. Less cumbersome (and less costly) disposal measures are often possible with polymer slurries, however, disposal is project-specific and must be evaluated on a case-by-case basis.

- Cost In addition to the basic costs of the mineral or polymer materials and their transportation, all of the items listed above will affect the total cost to the contractor for construction with the use of drilling fluids. The total cost is the deciding factor in competitive bidding for drilled shaft construction.

7.7 EXAMPLES OF PROBLEMS AND SOLUTIONS WITH CONSTRUCTION UNDER DRILLING FLUIDS

Several scenarios are discussed in this section in which problems can develop with construction under drilling fluids. They demonstrate that, when installing a drilled shaft with drilling fluids, both the contractor and the inspector need to be continually trying to visualize what is happening in the ground.

- **Problem 1:** Figure 7-16 illustrates one of the most common cases where difficulties arise in slurry construction. The drilling fluid can be either a mineral slurry or a polymer slurry. An excavation is made through overburden soil into disintegrated rock using fluid. Figure 7-16a shows the completed excavation with the fluid in place. The slurry is carrying more sand than it can hold in suspension. However, it is not sampled properly and consequently is not cleaned prior to starting the concrete placement with a tremie. Sand settles to the top of the concrete column as the pour progresses, as shown in Figure 7-16b. Frictional resistance between the borehole wall and granular material is such that the flowing concrete breaks through and folds the layer of granular material into the concrete, creating a defect, as shown in Figure 7-16c. A cubic yard or more of granular material can settle to the top of the concrete column in a large-sized drilled shaft if the slurry is poorly cleaned.

Solution: Measure the depth of the excavation two or more times after drilling ceases to verify that sediment is not settling out and that the hole is as deep as indicated by the penetration of the drilling tools. Furthermore, the drilling fluid should be sampled carefully from the bottom of the hole and tested to ensure that specifications are met. A comparison of the actual volume of concrete that is placed with the expected volume, as pre-determined from the use of calipers or from the planned shaft dimensions, can readily reveal if a considerable amount of sediment has been left in the concrete, and the plotting of a concreting curve (Chapter 9) can reveal the general location of the trapped sediment.

- **Problem 2:** Figure 7-17a shows that an excavation has been made to a certain depth by use of mineral slurry and that a casing has been placed in the slurry with its bottom being sealed in an impermeable formation. The slurry has been pumped from the casing, and the excavation has been carried to its full depth. Some slurry is left in the overbreak (void) zone between the casing and the side of the borehole. Figure 7-17b shows that the concrete has been placed and that a layer of liquid slurry has been left at the interface of the concrete and the natural soil. The slurry is so thick that a considerable mound of thickened slurry and solids has piled up on the ground surface where it was displaced by the concrete, which in turn has impeded the complete flushing of all of the liquid slurry that was initially in the overbreak zone. The problem was caused because the slurry was not sampled and tested before the casing was placed. The mineral slurry was much too thick (too viscous), contained inclusions of clay and granular material (had too high a density value), and it could not be displaced completely by the concrete.

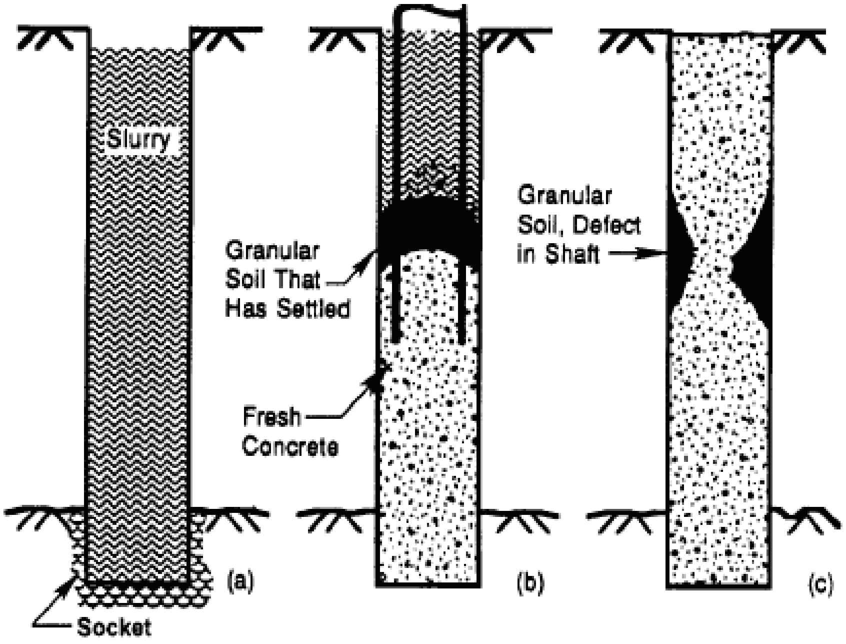


Figure 7-16 Placing Concrete through Heavily-Contaminated Slurry

Solution: Be sure that the slurry meets the proper specifications before the casing is placed, and complete the concrete pour within a reasonable time after the casing is placed. Coordinate concrete placement and extraction of the temporary casing to more effectively flush the slurry from the sidewalls of the borehole.

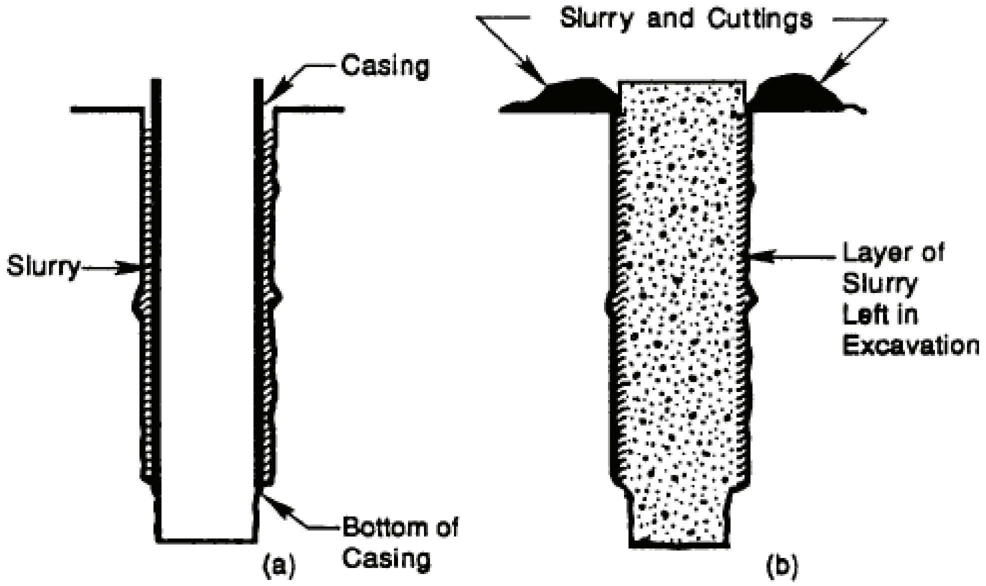


Figure 7-17 Placing Casing into Mineral Slurry with Excessive Solids Content

- **Problem 3:** Figure 7-18a shows the case where construction has been carried out properly with the casing method, with the casing being sealed at its base in an impermeable formation. Figure 7-18b shows that the casing has been pulled with an insufficient amount of concrete in the casing so that the hydrostatic pressure in the drilling fluid was greater than that in the concrete, with the result that the drilling fluid invaded the concrete and produced a "neck" in the drilled shaft.

Solution: Pull the casing only after it is filled with concrete with good flow characteristics. Then, the hydrostatic pressure in the concrete will always be greater than that in the drilling fluid in the overbreak zone because the unit weight of the concrete is greater than that of the drilling fluid.

- **Problem 4:** Figure 7-19 illustrates a casing that is driven by a vibratory driver into a sand stratum, and it is intended that the casing penetrate through the stratum of caving soil into an impermeable material. However, the casing is stopped short of the impermeable material into which it could seal. Drilling fluid is used to extend the borehole below the casing. As the drilling progresses, the sand collapses behind the casing for a considerable distance, as shown in Figure 7-19a. When the concrete is placed, even though the casing is filled with concrete with good flow characteristics, some of the drilling fluid outside and above the bottom of the casing becomes trapped and is not ejected. The result is shown in Figure 7-19b; some of the drilling fluid has fallen into the concrete, and a weak zone is created in the completed drilled shaft.

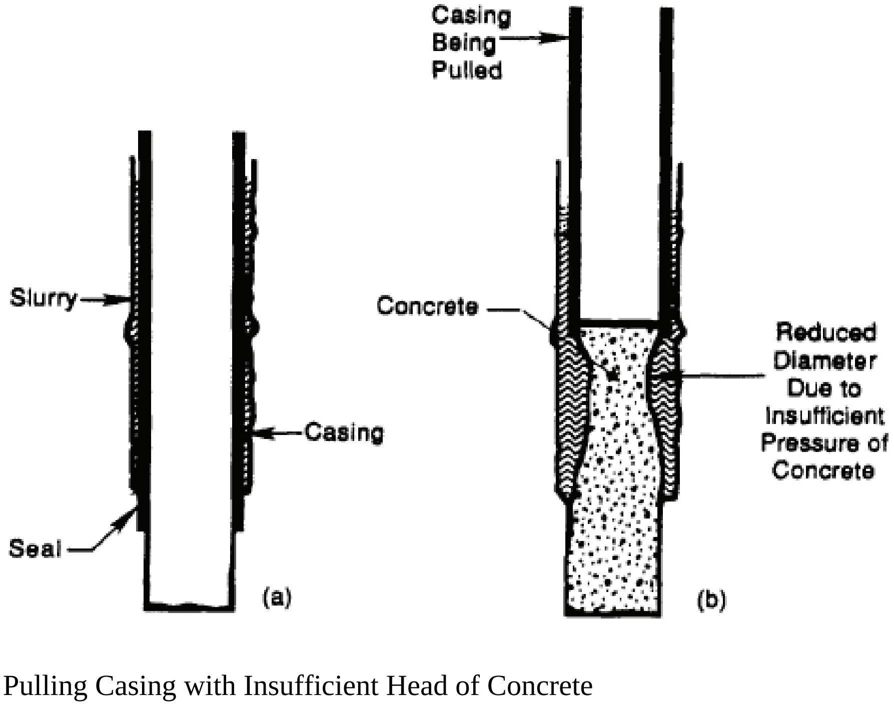


Figure 7-18 Pulling Casing with Insufficient Head of Concrete

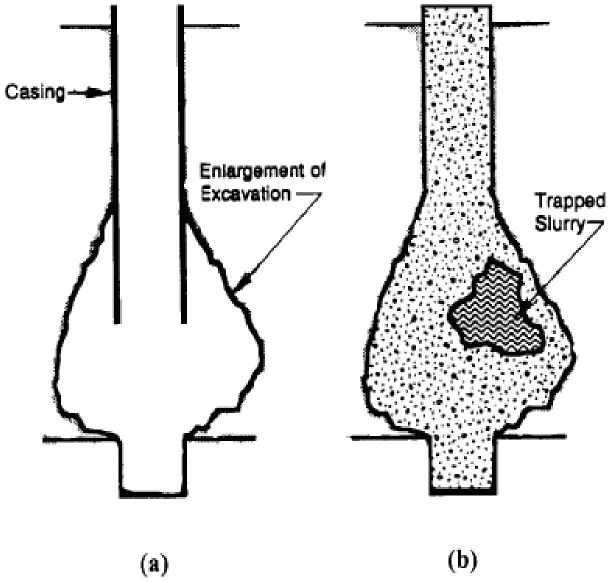


Figure 7-19 Placing Concrete where Casing was Improperly Sealed

Solution: Be sure that the casing penetrates the caving layer fully, if at all possible. The fluid pressure in the slurry column in any case should be kept at an appropriate value so that no caving occurs. It is of utmost importance that the level of the drilling fluid be kept well above that of the natural water table (piezometric level) in order to prevent any inward flow and a consequent loosening of the supporting soil. Additionally, the hole below the casing can be calipered and, if the enlarged excavation is discovered, appropriate measures taken.

- **Problem 5:** A large-diameter drilled shaft is being advanced into a stratum of sand and gravel under a polymer slurry and, despite using an effective tool and bringing up considerable cuttings on each pass, the borehole is not being deepened. This condition is likely being caused by sloughing from the walls of the borehole, indicating that the slurry is not acting effectively in maintaining stability.

Solution: Verify that the slurry properties, particularly the viscosity and the pH, are as specified. If not, modify the properties of the polymer slurry before proceeding. Make sure that the head of slurry is kept above the piezometric surface at all times and is not even momentarily allowed to drop below that level. This may require placing a surface casing to use as a standpipe to bring the slurry surface above ground level if the piezometric surface is near the ground surface. It may be necessary to enlarge the diameter of the borehole to the full depth of the present excavation to arrest the sloughing process even though the slurry properties and construction procedures are now correct. Once overhang zones start to appear due to borehole sloughing, sloughing may continue even with correct techniques until the hole is made cylindrical once again. Alternatively, the excavation can be backfilled to above the zone of caving and the hole redrilled. Casing could be used instead of slurry, if the contractor is prepared for this option.

The descriptions of potential problems given above may give the incorrect impression that construction with drilling fluids is inherently problematic. While occasional difficulties have occurred, the collective experience of the drilled shaft industry suggests that the overall performance of slurry-constructed drilled shafts has generally been excellent. For those shafts that are not satisfactory, steps in the construction process can almost always be identified that were not in accordance with good practice, either due to contractor errors or to factors that were beyond the contractor's immediate control, such as a delay in the delivery of concrete from a ready mix plant while a concrete pour was underway. If care is taken in the construction process, a finished product of high quality can, and should, be expected.

7.8 SUMMARY

Drilling fluids play a critical role in the construction of drilled shaft foundations. Their primary functions are to maintain the stability of the borehole and to facilitate the placement of concrete by displacement of the drilling fluid. This chapter describes the issues that must be addressed in order for drilling fluids to be used successfully. Drilling fluids for drilled shafts are made from two types of materials: bentonite or related clay minerals, and synthetic polymers. Each has different material properties and they must be handled differently in order to perform properly in drilled shaft construction. Engineers and contractors involved in drilled shaft construction with drilling fluids must recognize and understand the unique characteristics of each. One of the primary differences is that bentonite slurries will suspend silt and sand particles while polymer slurries generally do not.

Experience and research have demonstrated that drilling fluids made from both types of materials, bentonite and polymers, can provide a highly effective means for constructing quality drilled shafts when handled properly. Factors that lead to successful performance, and those that may lead to unsatisfactory performance, are identified in this chapter.