Techniques and Materials for Sealing Large Diameter Pipe in Salt Stock

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ABSTRACT

In salt mining operations, it is often necessary to seal large diameter pipe in the salt stock as an access shaft. Sealing material for this purpose must provide an acceptable hydraulic and shear bond, and positively exclude all fluids from the bottom of the shaft. Pipe large enough to serve as a mine shaft is extremely difficult to seal by conventional methods due to the great amount of expansion and contraction produced by temperature and pressure changes.

A new process using conventional cementing equipment, but making use of special materials and techniques, has proved successful in obtaining an effective seal economically. This paper will discuss the problems associated with sealing large diameter pipe in salt stock and the techniques and materials developed to solve these problems. A description of successful jobs using the new process is included.

INTRODUCTION

Special sealing materials and techniques can successfully and economically seal casing in a water-soluble formation in a shaft drilled through overlying aquifers. This is one of the most difficult underground sealing problems and one that is often encountered in sealing casing in salt stock. It is a problem common to small-diameter pipe used in storage wells and large-diameter pipe which serves as an access shaft for mining operations. It becomes more and more pronounced as pipe diameter increases. This paper, therefore, will discuss mainly the sealing of large-diameter casing, although the materials and procedures discussed will readily apply to the smaller sizes as well.

SUCCESS FACTORS

Successful sealing of large-diameter pipe in a drilled hole, or shaft, will depend on several factors, many of which are not directly related to the cementation process itself. The first of these is the drilling, or shaft-sinking, practice used. It must be such that the shaft will be relatively straight and large enough to accept the desired size casing. The shaft must be bottomed in clean, competent salt stock, and the drilling fluids in the shaft during cementation must be compatible with the sealant being used.

Next, the casing and auxiliary hardware must be specifically designed to facilitate proper placement of the sealant.

Finally, the techniques and materials used in the cementation process itself must be designed to meet the particular conditions existing in the individual shaft or wellbore.

DRILLING TECHNIQUES

Big-hole drilling techniques and capabilities have been widely publicized during the past year or two, and will not be discussed here. Primary concern will be with the shaft after it has reached target depth. One of the tools available to determine the condition of the shaft is the Sonar Caliper. Figure 1 is a Sonar Caliper survey model of a shaft drilled with a 72-inch bit to 2,605 feet (1 in. = 100 ft. vertically and 1 in. = 40 in. horizontally). This model is the reverse of the familiar Sonar Caliper model of a washed-out storage cavern in salt stock. Here, the contour of the hole is removed from the plastic plates. Since the problem of lowering from 2,000 to 5,000 feet of large-diameter casing, weighing several million pounds, into a drilled hole can be acute, such models are very useful in determining ahead of time whether or not the casing can be safely lowered into the shaft.

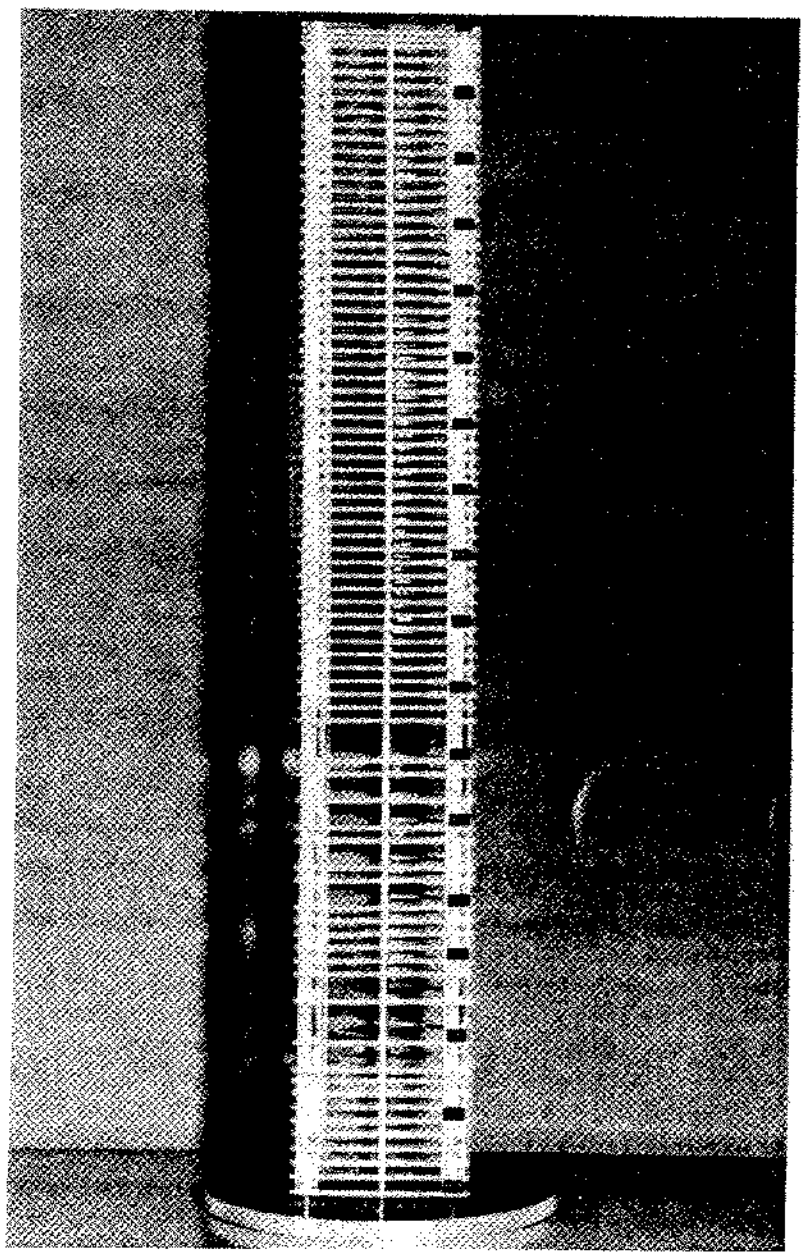

Figure 1. Sonar Caliper model of 72-inch drilled shaft. Such models are useful in determining whether or not casing may be safely lowered into shaft.

CASING AND AUXILIARY HARDWARE

The casing and auxiliary hardware also are a separate subject and detailed discussion here will be omitted. They must, however, meet certain basic requirements if successful sealing is to be accomplished. Briefly, these are:

1. The casing must be designed to withstand the forces and stresses imposed on it during both cementation and during mining operations. Normally, these forces are more severe during cementation.
2. The casing must be centered in the shaft so that it is encircled by the sealant. Properly designed centralizers serve this purpose.
3. Some means must be provided to isolate the casing from the annulus during cementation. Otherwise, the heavier sealant will fill the casing as it fills the annulus. Several means of isolation are available. These include specially designed cementing shoes, steel caps welded onto the casing or spotting a small first-stage cement plug in the casing and annulus.
4. Grout lines must be easily run and withdrawn in the annulus. The depth of the grout lines must be known so that all lines can be lowered to the same depth. Severe contamination will occur during cementation when the lines are at different depths.
5. Grout line guides are required to permit proper grout line usage. The most commonly used guides are slotted tubes welded to the casing. The grout lines are run inside these tubular guides.

SEALANT REQUIREMENTS

There are several reasons for sealing pipe in a wellbore or shaft. These are:

1. To support the pipe.
2. To protect the formations penetrated.
3. To exclude unwanted fluids from the hole.
4. To prevent communication of fluid between formations behind the pipe.

To accomplish these objectives, a sealant material obviously must completely fill the annulus between the casing and shaft walls in such a manner that there are no drilling fluid or water-filled channels existing in the annulus following cementation, and the material must hydraulically bond to both the casing and formation. Actually, an ideal sealant material should meet the following requirements:

1. It should be field applicable. An ideal material would be one that could be mixed and pumped easily with existing equipment. Use of special equipment would greatly increase cost. The material also should be applicable under normal atmospheric conditions.
2. The thickening time should be controllable. Thickening time requirements vary widely, depending on use and down-hole conditions. An ideal sealant would be one whose thickening time could be shortened or lengthened to meet existing conditions. In all cases, thickening time should be long enough to allow safe placement, but short enough to prevent costly delays while waiting for the sealant to set.
3. The density should be compatible with that of the drilling fluids. If the density of the sealant is not enough greater than that of the drilling fluid, it will tend either to float on top of the drilling fluid or disperse through it. In either case, the sealant would not completely fill the annulus and failure would result. The differential density should be great enough that the sealant will completely and positively displace the drilling fluid from the bottom upwards.
4. The sealant must tolerate minor contamination. Since a sealant will be in contact with drilling fluids, formation fluids, and formations themselves during placement, it must be of such a chemical composition that there will not be a "flash set" or complete lack of set

due to contamination from these sources. There will be some slight mixing, at least at the interface, of the sealant and other fluids regardless of the placement technique.

5. The sealant must not dissolve or leach the formation. This is a primary consideration when cementing in salt stock. Here, any sealant slurry containing water obviously must be mixed with salt-saturated water.

6. A low heat of reaction is desirable. High temperatures cause excessive expansion of the pipe. Subsequent contraction can cause bond failure between the pipe and sealant. This is a critical factor with large-diameter pipe and will be discussed more fully with placement techniques.

7. The sealant should be nonshrinking. A sealant which shrinks as it sets may pull away from either the pipe or formation, or both. This would result in bond breakage and provide channels for fluid flow. Actually, an ideal sealant should exhibit a slight degree of expansion.

8. The sealant should be inert. If a sealant is chemically reactive with drilling fluids, formation fluid, or the formations themselves, prolonged contact will cause deterioration of the sealant and failure after a period of time.

9. The sealant should be impermeable. If there were any flow of fluid through the sealant material itself, the sealing process would be as much a failure as it would with channeling or poor bonding.

10. The sealant should be resilient. In many areas, overburden subsidence and earth movements are a problem. A good sealant must be flexible enough to withstand the additional stresses imposed by such movements.

11. The set sealant must possess sufficient strength. The set sealant must be strong enough to withstand all stresses likely to be imposed on it -- regardless of whether these are compressive, tensile, or shear stresses.

12. The sealant must be reasonable in cost. Providing a low-cost sealant which meets all the previous requirements is extremely difficult. It is, however, a very important factor in "big-hole cementing" where large amounts of sealant material are required.

The universal material for sealing pipe in a wellbore or shaft at the present time is Portland Cement. This is chiefly due to the cost factor. While neat cement does not meet many of the requirements above, low-cost additives are readily available which permit alteration of cement slurries to meet existing conditions without adversely affecting the desired properties of the set cement. Cement slurries can be "tailor-made" to provide desired thickening time, density, compatibility, shrinkage, and strength for almost any condition and still be easily mixed and pumped in the field.

As previously mentioned, such problems as expansion and contraction of the pipe and contamination increase greatly as shaft and pipe size increase, and the chances of failure are correspondingly greater. When dealing with large-diameter pipe, then, a second line of defense should be provided to offset any possibility of the cement failing to meet one or more of its requirements. Two special sealing materials have been developed for this purpose. These are a Chemical Seal Ring material and Expanding Cement. These are so designed that they may be used in small amounts in conjunction with more conventional cement slurries to provide an ideal sealing process at reasonable cost.

CHEMICAL SEAL RING

Chemical Seal Ring is a unique chemical slurry with a controlled working time. It is mixed and handled as a liquid, but sets to form a tough, rubberlike material with the following properties:

1. It is impermeable and inert. The set Chemical Seal Ring material is impermeable and inert to all fluids and materials likely to be encountered in the shaft sealing process.

2. <u>It has high bonding strength.</u> The material adheres strongly to both metal and rock. In Fig. 2, two bricks were spaced two inches apart and cemented with Seal Ring material. They were then subjected to a pull of ten pounds per square inch and remained firmly bonded to the material. In other tests, short sections of pipe were sealed in salt stock with this material. Differential pressures of nearly 2,000 psi did not produce extrusion or failure of the material.

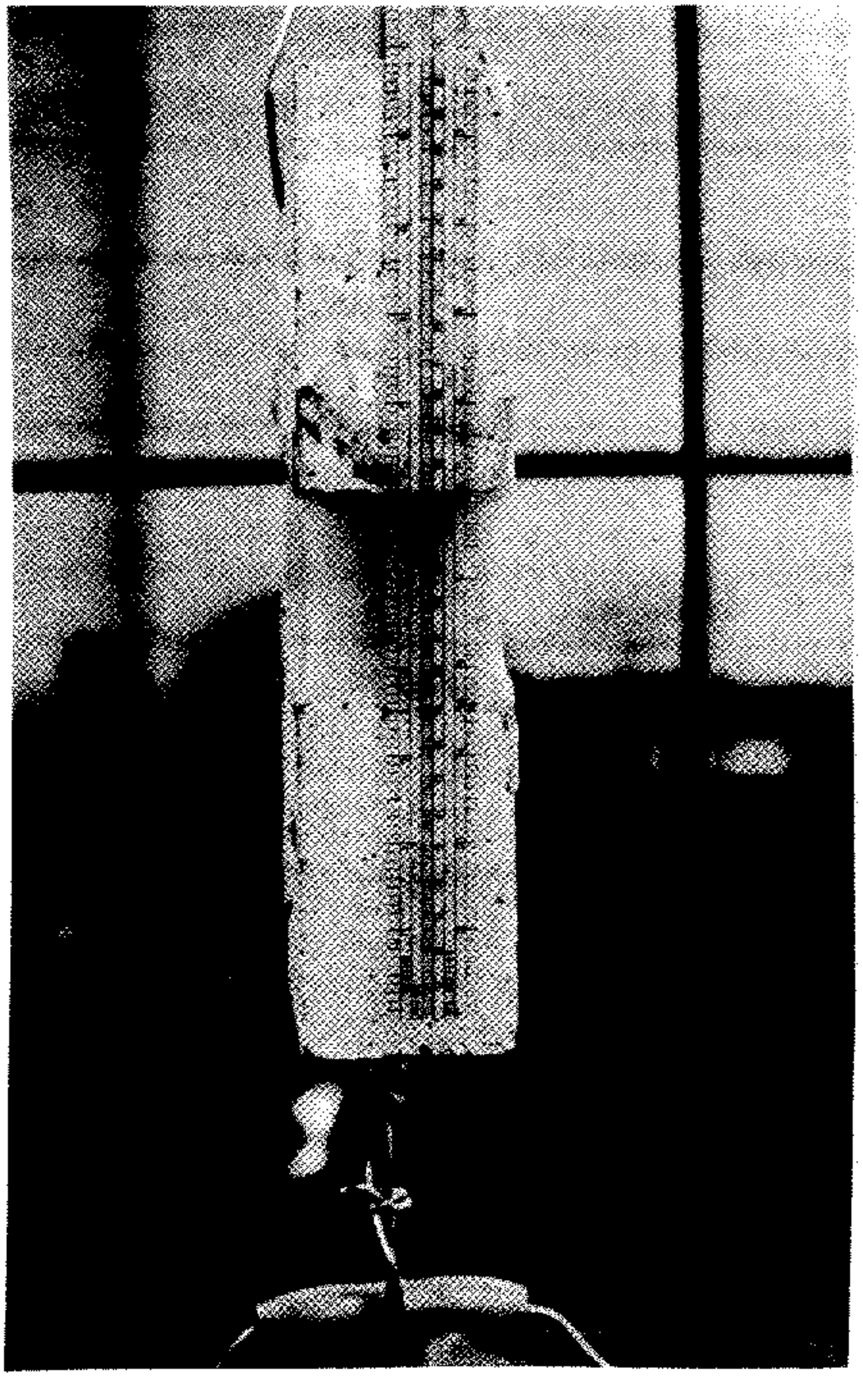

Figure 2. Bricks spaced two inches apart and cemented together with Chemical Seal Ring. Bonding strength of material is apparent in this photo where bricks are subjected to pull of ten pounds per square inch.

3. It imbibes water or brine and swells. This is the only currently known sealant which functions in this manner. Osmotic pressure tests indicate that pressure actually builds up within the material as water is imbibed. Figure 3 shows two plugs of Seal Ring material. Both were poured in the same size molds and allowed to set. The plug on the right was then immersed in water. The degree of expansion was 151 percent in five days.

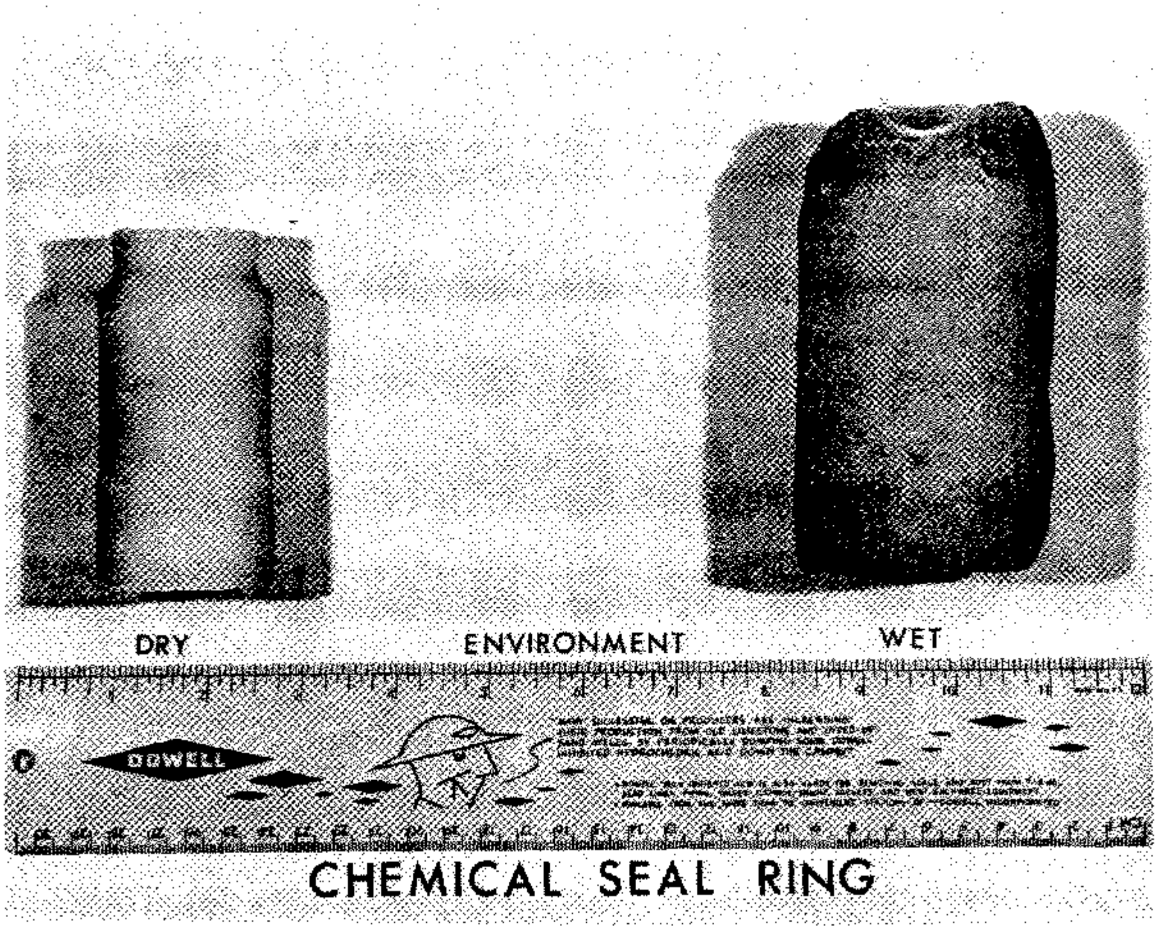

Figure 3. These plugs of Chemical Seal Ring material were originally the same size. Plug on right was immersed and imbibed in water. After five days volumetric expansion was 151 percent.

4. It seals against liquids and gases. Extensive testing indicates the material will withstand extremely high differential pressures from either liquid or gas without rupture and without leaks.

5. The set material is resilient and flexible. Actually, the physical properties of the set sealant can be varied to meet a wide range of conditions.

Chemical Seal Ring is expensive, but only small quantities are required. In practice, a relatively narrow ring is placed at a point, or points, in the cement column to provide a positive seal against fluid from overlying formations.

EXPANDING CEMENT

Expanding Cement is a true expanding cement since the expansion occurs after the cement has taken its set. It is a cement containing an expansive component and not cement to which aluminum powder is added. (In the latter case, gas is generated causing expansion before the cement takes its set.) The cement, as it sets, is restrained by the formation and by the casing. Thus, with Expanding Cement, a self-stress is produced in the set cement. As the restraint is removed, the self-stress is relieved. The cement maintains a shrink fit around the casing as the casing diameter is reduced by temperature and pressure reductions.

A wide range of expansion can be obtained by altering the amount of expansive component in the cement. Figure 4 illustrates a part of this range. The cubes in the photograph were all cured in two-inch × two-inch × two-inch molds for seven days under simulated bottom-hole conditions of 120°F and 1,000 psi. The cube on the left is Class A cement with no expansive component. The effect of varying the amount of expansive component is readily noticeable. (The degree of expansion is much greater when the cement is cured under no restraint. Volumetric expansion as high as 35 percent has been attained where there was no restraint.)

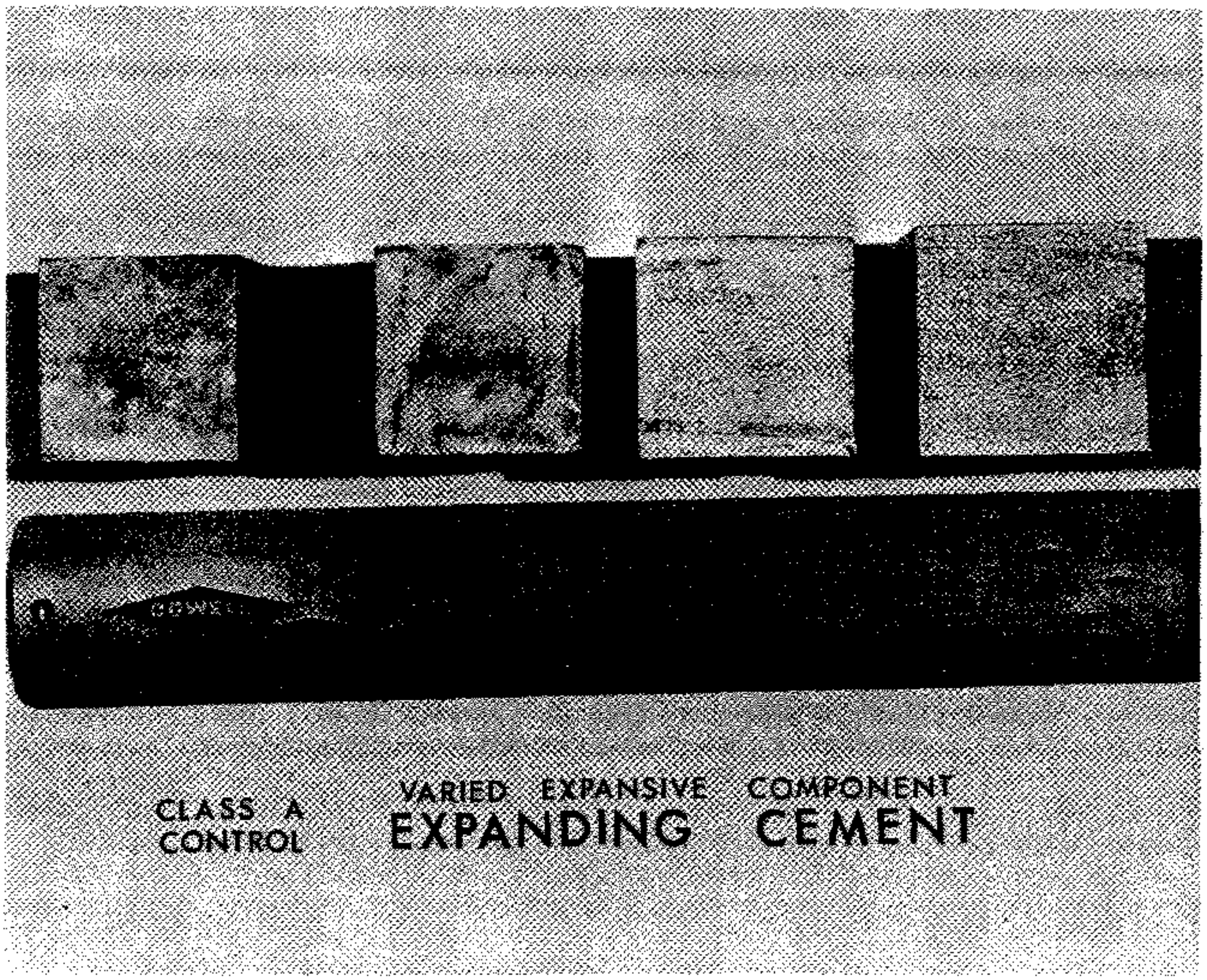

Figure 4. Expanding Cement cubes cured for seven days at 120° F and 1,000 psi. Cube on left is Class A cement only, while remaining cubes contain varying amounts of expansive component.

Tests were conducted to determine the force required to shear the bond between small pipes and cement. Tests were made with both mud-coated and sandblasted pipe. The results, shown in Fig. 5, clearly indicate the higher bonding strength of Expanding Cement.

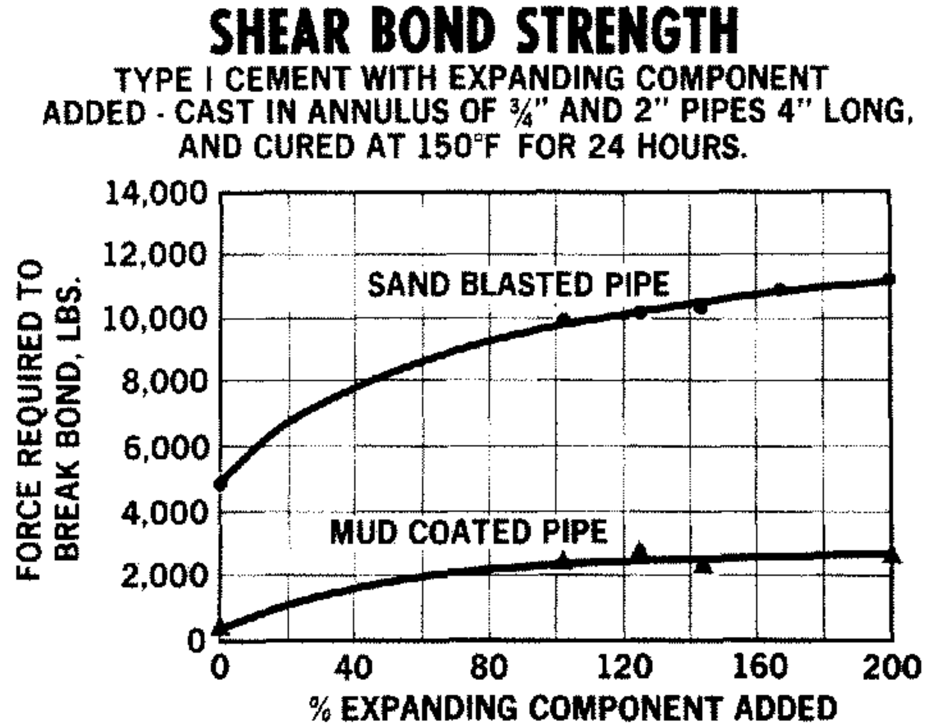

Figure 5. Superior shear bond strength of Expanding Cement may be seen in this graph of tests run on both mud-coated and sandblasted pipe.

PLACEMENT TECHNIQUES

Even ideal sealant materials and the most carefully engineered sealing systems can fail if they are not properly placed. Placement technique, then, becomes as important a part of the job planning as the materials to be used.

The first consideration is the drilling fluid itself. This must be dispersed and well conditioned prior to starting any cementing operation.

The type of flow and annular velocities must next be selected. Materials such as cement slurries exhibit three types of flow depending on velocity, annular volume and physical properties of the fluids. These are plug flow, laminar flow and turbulent flow. Laminar flow is undesirable in all cementing operations since it produces channeling and poor bonding. Turbulent flow generally is desirable in smaller diameter holes such as storage wells. Plug flow generally prevails in the large-diameter shafts, however, due to the large annular volumes. In small-diameter holes, the sealant generally is pumped down the casing and displaces the drilling fluid in the annulus upwards from the bottom. With large-diameter pipe, only the initial or shoe stage can be placed by pumping through drill-pipe latched into a shoe at the bottom of the casing. If too long a column of sealant is placed in the annulus in a single stage, differential hydrostatic pressures can easily become high enough to collapse the pipe. Subsequent stages of sealant must then be placed through small grout lines, equally spaced, and run into the annulus between the shaft wall and the casing. The grouting procedure would make the cost of turbulent flow prohibitive.

The maximum annular velocity for plug flow will depend on the properties of the drilling fluid and sealant used. Extensive studies and experience with plug flow techniques for liner cementing in the Louisiana Gulf Coast Area indicate that the velocity should not exceed 30 to 45 feet per minute.

During the cementing operation, the sealant should rise upward in the annulus in order to displace the drilling fluid. As previously mentioned, its density should be enough greater than that of the drilling fluid so that there is no tendency for it to float on top or intermix with the drilling fluid. Less drilling fluid will remain in the annulus as the volume of sealant passing through an interval is increased. The time period that the sealant is passing through a critical interval is referred to as contact time. The contact time is a maximum only when all sealant rises upward from the bottom. The lower velocities of plug flow also increase contact time.

In grouting procedures, the grout lines during each stage should be placed as close as possible to the top of the set cement from the preceding stage so that drilling fluid removal is as complete as possible. The plane of contact between the sealant columns from two separate stages is known as a pour joint. At best, the sealant at the pour joint is probably of inferior quality and each joint is a possible source of leaks. Each job, therefore, should be designed with the minimum number of pour joints consistent with safe hydrostatic loads.

One problem that becomes critical with the larger diameter casings is the adverse effects of temperature and pressure differentials. This is particularly true with Portland Cement systems. As the cement in a shaft takes its initial set, the casing temperature is greatly increased and the casing expands, increasing the diameter. Further expansion takes place due to the internal pressure exerted by fluid in the casing.

After cement has set and mining operations start, the casing is evacuated, thus eliminating the internal pressure. The casing temperature also is reduced to that of the formation or less. Both these differentials cause a reduction in the casing diameter. If the sealant is not self-stressed, bond breakage between the casing and sealant could occur and a channel, or slot, would exist through which water could flow.

To illustrate this problem, calculations were made using temperature and pressure differentials observed in a typical shaft sealing operation. Using the Roark formula, $\Delta D = \frac{2\,PR^2}{Et}\,(1 - \frac{\mu}{2})$, and Brownell and Young formula, $\Delta D = \alpha\,(\Delta T)\,D$, a temperature differential of 60°F and a pressure differential of 500 psi could produce a slot surrounding 75 1/2-inch casing with a width of 0.035 inches. This appears small; but according to Lamb's Slot Flow Formula, the flow capacity of such a channel would approach 22,500 bbl of water per day with a 1,000-foot column of cement in the annulus and a waterhead of 500 psi. This analysis is oversimplified since there are too many unknowns to permit accurate calculations. It does, however, emphasize the seriousness of the problem.

Techniques to counteract the effects of temperature and pressure differentials include circulating lightweight fluids in the casing while the cement takes its initial set. The fluid can be cooled by heat exchangers at the surface. Another technique uses liquified CO_2 gas to both cool and lighten the circulating fluid. Expanding Cement also helps counteract these effects.

CASE HISTORY

An actual shaft-sealing job will serve to illustrate the use of both materials and techniques previously discussed. Figure 6 shows the placement of materials used to seal 20-inch O.D. casing in a 28-inch shaft drilled into salt stock. This hole penetrated several major aquifers before reaching the salt. The caprock was vertically communicated with the aquifers so that it was necessary to seal the pipe in the salt stock itself.

In this job, Expanding Cement was placed from 2,200 to 1,700 feet. While this first stage of cement was taking its initial set, the casing was circulated with a lightweight, cool fluid as shown in Fig. 7. Water was used as the circulating fluid. Liquid CO_2 was used to lower the density of the circulating water to 4.5 ppg, and also to cool the circulating fluid by about 10°F.

After the first stage of expanding cement had set, Chemical Seal Ring material was placed from 1,700 to 1,600 feet. Another 160-foot column of Expanding Cement was placed above the Seal Ring and the remainder of the annulus to the surface was filled with a conventional cement system.

This hole was successfully dry tested and then air drilled to a depth of 2,800 feet in the salt stock with no water entry. Success of this job was responsible for rejuvenation of a multimillion-dollar project which was near abandonment. Several previous efforts to seal pipe in the salt stock, including extensive remedial attempts by squeezing, had failed and the project appeared hopeless.

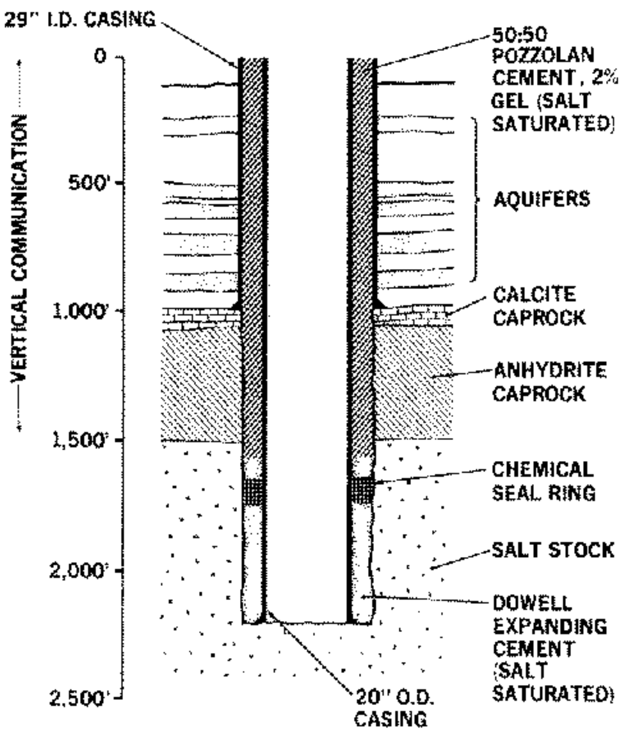

Figure 6. Approximate placement of various sealant materials in unique big-hole operation.

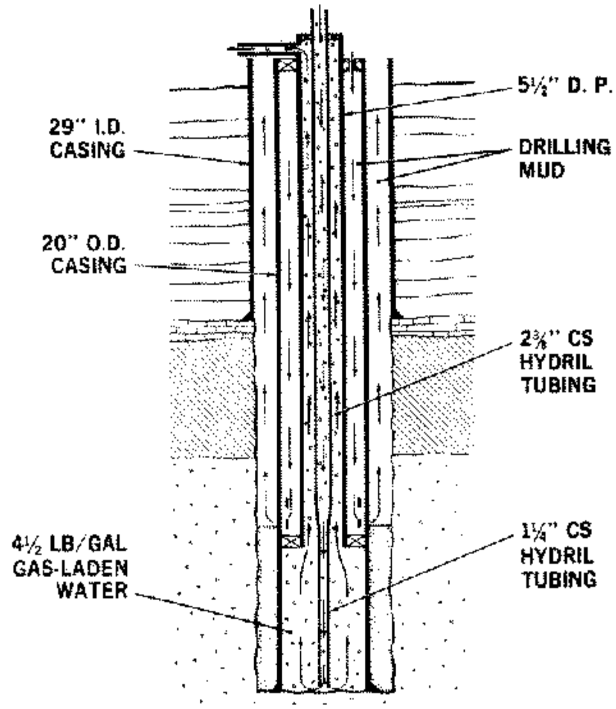

Figure 7. Circulating system used to control internal hydrostatic pressure and pipe temperature. Liquid CO_2 was used to lower density of circulating water to 4.5 ppg and also to cool the circulating fluid by about 10° F.

CONCLUSIONS

Cementation of pipe in salt stock is one of the most difficult sealing problems encountered. The problem becomes even more difficult as pipe diameter increases. However, careful consideration of all factors involved in each individual well or shaft, together with a sound engineering approach in selection of materials, methods and techniques of placement can result in effective and successful sealing.

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