Sealing Characteristics of Selected Grouts for Water Wells

by Tuncer B. Edil[a], Michael M. K. Chang[b], L. T. Lan[c], and Thomas V. Riewe[d]

Abstract

Sealing characteristics of commonly used water well annular space grouts were investigated using a large-scale laboratory model. The investigation was carried out in two phases. In the first phase, a bentonite drilling mud, often used as a well sealant, was investigated both in the laboratory well model and in the field. For this purpose, Quik-Gel® mud with different amounts of formation material (in this case sand) entrained in it was used as a sealant. In the second phase, an evaluation of four grouts: neat cement, bentonite-cement, powder bentonite (Volclay®), and granular bentonite (Benseal® and bentonite slurry mixed according to the "Ohio" recipe) was undertaken with respect to their effectiveness in sealing the annular space. A well model consisting of a sand-filled plexiglass container was constructed in this investigation. Four metal well casings were installed in boreholes formed in the sand. The annular space between the well casings and the boreholes formed in the sand were filled with various grouts. The effectiveness of these materials in sealing the annular space was evaluated by observation of their structural stability, infiltration of water placed on top of the sealants, and inspection of the sealants dissected during disassembling of the models. A finite-element computer program modeling the seepage in these well experiments was used to assist in the interpretation of the experimental results. The results indicate that the final success of a sealant depends on its structural stability as much as its permeability. Benseal®-bentonite slurry grout behaved best; neat cement and bentonite-cement grouts also provided good seals. Volclay® and various Quik-Gel® slurries formed poorer seals compared to these. Among the Quik-Gel® slurries, best results were obtained in the laboratory when a Marsh Funnel Viscosity of about 70 sec/qt was achieved and a mud weight of about 10 to 11 lb/gal resulted from mixing of formation soils. However, field observations of drilling mud slurries with entrained cuttings exhibited problems of excessive settling even when the slurries had heavy mud weight, greater than 11 lb/gal. The extent of settling appears to be positively correlated with the relative permeability of the native formation. This limits the types of well construction where these slurries may be used as annular space seal.

Introduction

Ground water needs to be protected from comingling and contamination. Water-supply and ground-water monitoring wells and quite often geotechnical borings and mine exploration holes penetrate from the surface into the ground-water table. These holes provide potential channels for contaminated surface and ground waters to migrate to the aquifer. To provide the necessary protection the annular space between the well casings and the adjacent formation and the geotechnical boreholes have to be sealed properly. A variety of sealants are used such as cement, cement-bentonite, and bentonite slurries. There is increased scrutiny in recent years regarding the effectiveness of various sealing techniques and materials. There has been a tendency towards the use of only neat cement grout as an annular space seal. Some states, including Minnesota, Colorado, New Jersey, New Mexico, and Wisconsin, allow bentonite seals. There is also a move to force geotechnical organizations to change their drilling and sealing operations of boreholes to conform to water well drilling.

In the State of Wisconsin, the well sealing requirements have been in review in recent years to provide better requirements for annular space seals for wells that are not required to be cement-grouted, that is, those wells that are not high capacity, school or waste-water treatment plant wells; or those low-capacity bedrock wells when the upper enlarged drillhole does not extend more than 2 ft into the top of the bedrock. Recent field inspections indicated that the current requirements were not always providing good seals when drilling mud (bentonite slurry) is used as the annular-space grout. A survey of manufacturing representatives, drillers, regulatory agencies from other states, and

[a]Professor of Civil and Environmental Engineering, University of Wisconsin-Madison, 53706.
[b]Engineer, Fewell Geotechnical Engineering Ltd., 96-1416 Waihona Place, Pearl City, Hawaii 96782.
[c]Graduate Student in Civil and Environmental Engineering, University of Wisconsin-Madison, 53706.
[d]Hydrogeologist, Bureau of Water Supply, Wisconsin Department of Natural Resources, Madison, Wisconsin 53707.
Received March 1990, revised May and September 1991, accepted September 1991.
Discussion open until November 1, 1992.

research people has not provided conclusive evidence for or against bentonite seals. To help the state regulators decide either to keep or modify the sealing requirements, a twofold research project was proposed involving a laboratory investigation to be followed by a field verification program. The laboratory investigation, carried out in two successive phases in a simulated well environment, is described and the results obtained along with analytical interpretations are presented herein. Of course, these findings are valid within the context of the well model experiments. Such experiments provide an assessment of the sealing behavior of the grouts on a comparative basis; as such they assist in screening unsuitable grouts. However, the overall effectiveness of a grout can be observed only in the field. Field investigation of only drilling mud grouting was carried out since such grouts are somewhat borderline in their performance. There was no field testing for the other grouts within the constraints of the project.

Well Model Experiment

A well model was constructed using a sand-filled plexiglass container, 1.5 ft × 6 ft × 6 ft deep. The container is reinforced at its edges and sides by aluminum angle sections and it has a hollow tank at its base. The tank has a series of 1/4-inch holes atop to allow water flow to and from the soil container. A porous stone covers the top of the water tank.

In setting up the model, four 8-inch ID PVC pipes (1/3-inch wall thickness) were placed vertically on the bottom porous stone in the container at equal center-to-center spacings of 1.5 ft. The sand representing the aquifer material (Portage Sand-Granusil 2040) was then poured into the container. Granusil 2040 is a coarse sand with a uniform grain size between 0.43 to 0.85 mm. After filling the container with sand, water was applied to moisten and compact the sand. The excess water drained from the bottom.

Metal well casings (ASTM A120 4-inch diameter steel well casing pipes with 1/4-inch wall thickness) were placed concentrically within the 8-inch diameter PVC temporary outer casing pipes. The casings were not steam-cleaned but simply washed with water. Completely mixed batches of drilling mud sealant materials were placed in the annular space of each of the four simulated wells using a tremie tube extending to the bottom of the annulus. The neat cement and Volclay® grouts were placed in the annular space by use of a tremie hose attached to a 5-gallon mixing tank pressurized to 5 psi. This driving pressure was necessitated because of the high viscosity of these grouts. In the case of the bentonite-cement and Benseal®-bentonite slurry grouts, it was not possible to use the tremie method because of the continuous plugging of the tremie hose and the fittings within 5 to 20 minutes after the tremieing started. Therefore, these grouts were placed in the annular space by simply pouring them from the mixing tank. Recently, a mixing technique in the field has been proposed to mix and pump the Benseal®-bentonite slurry grout more easily into the annular space. Each of the four wells in the container was sealed using a separate grout.

Following the emplacement of the sealant into the annular space between the well casing and the temporary outer casing pipes, the outer casings were removed by slow lifting using a hoist. This allowed direct contact of the slurry with the sand aquifer material. Subsequently, each well was fitted with a short section of 8-inch PVC casing pipe at the surface. These infiltrometer casings were pushed in 1 ft below the surface of the sand at the sand-sealant contact surface. They were fitted with a graduated water-level burette to indicate the level of the water placed in the annular space during infiltration experiments. The sketch of the well model along with the fitted infiltrometer casings is shown in Figure 1.

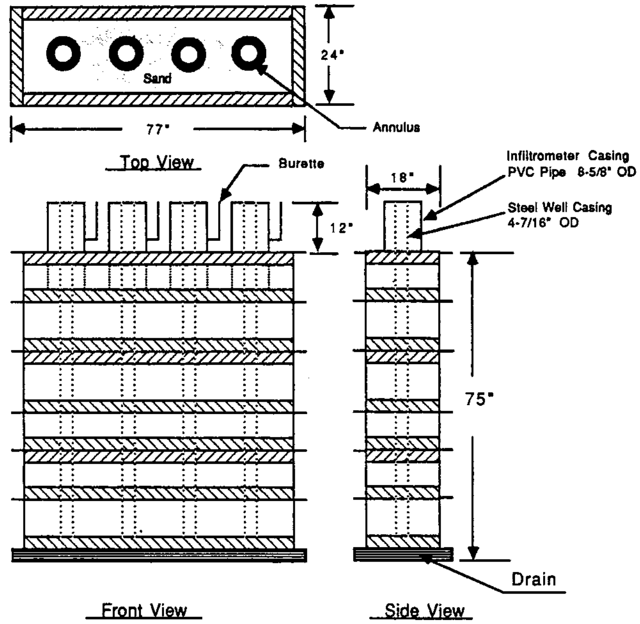

Fig. 1. Sketch of well model.

Sealants Tested

The well model experiments were conducted in two phases each using different sealants. In the first phase, sodium bentonite slurries (drilling mud type) were used in sealing the annular space of the model wells. A commercially available sodium bentonite slurry, known as Quik-Gel® and marketed for use primarily as a drilling mud, was emplaced in the annular spaces as a sealant. The mud was prepared at varying viscosities and with different amounts of entrained sand representing the drill cuttings ordinarily found in such slurries at the end of drilling operations. In the second phase, the sealing characteristics of certain selected well sealants, i.e., neat cement grout, bentonite-cement grout, and two commercially available bentonitic grouts, powder Volclay® and granular Benseal® (mixed with a bentonite slurry), were investigated. Table 1 summarizes the sealants used in the experiments.

In current practice, the materials described above are commonly used at the discretion of the drillers within the governmental regulations. Sodium bentonite slurries (drilling mud) is one of the most popular sealing materials for low-capacity wells not requiring special approval. One of the objectives of the study was to identify better requirements for the use of drilling mud-type sealants that are used in

Table 1. Sealants Tested

Test phase	Well 1	Well 2	Well 3	Well 4
I	Quik-Gel® MFV = 50 SC = 10%	Quik-Gel® MFV = 50 SC = 20%	Quik-Gel® MFV = 70 SC = 10%	Quik-Gel® MFV = 70 SC = 20%
II	Benseal®/Bentonite Slurry	Neat Cement	Bentonite-Cement	Volclay®

Note: MFV = Marsh funnel viscosity in sec/qt; SC = Volumetric sand content.

wells not required to be cement-grouted. Therefore, the first phase was devoted to: (1) evaluating the overall sealing capabilities of drilling mud type materials, and (2) identifying a practical basis for specifying them in field applications. The overall objective of the second phase was to determine the relative effectiveness of commonly used sealants and to provide a basis to compare the sealing effectiveness of the drilling mud slurries that were tested in the first phase.

Properties of Sand Entrained Bentonite Slurries

Sodium bentonite slurries, like Quik-Gel®, are primarily used in well drilling as well as in geotechnical or mining drilling for removal of the cuttings during drilling and for borehole stabilization. However, they are left in the annular space after drilling as a sealant and, therefore, would contain some of the formation cuttings that have not settled out of the suspension in the mud pit. It is argued that the entrained cuttings would increase the stability of the drilling mud and make it more effective in sealing the annular space than a pure bentonite slurry. Based on this premise, the overall objective of Phase I of the study was directed to determine the effectiveness of sodium bentonite slurries with varying amounts of entrained formation material, in this case, sand.

The cuttings that are carried by the drilling fluid during well drilling would partly settle after the drilling operation ceases and partly be entrained in the drilling fluid left in the annular space. One of the first questions faced in the investigation was to determine the amount of cuttings that would normally be entrained in the drilling fluid.

In order to obtain a measure of the typical range of cuttings that would be suspended in the drilling fluid, two approaches were taken. In the first approach, samples of drilling fluid were obtained in the field as it was being circulated during well drilling. Two such samples coming from two different wells in different types of formations were analyzed in the laboratory for the amount of cuttings, in particular, the coarse cuttings they contained. The results of these tests indicated a volumetric sand content of 6% and 20%, respectively.

The second approach involved preparing mixtures of varying quantities of sand with Quik-Gel® slurries of varying viscosities. In order to develop a feel for how much sand could be entrained into a Quik-Gel® slurry, increasing quantities of the sand used in the well model experiment (Granusil 2040) was added to Quik-Gel® slurries. About 50% sand, by weight, could be mixed into a Quik-Gel® slurry; however, the question is how much of the sand would be suspended in the slurry after part of it settles out. In order to investigate this point, the sand was mixed up to 50% by weight with Quik-Gel® slurries of 50, 70, and 90 sec/qt initial Marsh funnel viscosities (MFV) and allowed to settle for a period of six days. After six days, samples of the slurry were retreived from the top, middle, and bottom part of the 1-liter jar in which the slurries were prepared. Table 2 gives the mud weights (MW) and volumetric sand contents (VSC) of these samples along with the mud weight that was obtained immediately after mixing sand into the slurry. Table 2 shows that the amount of sand entrained in the drilling mud increases with increasing initial viscosity of the slurry and the initial sand content. It also shows that the sand mixed with the slurry settles resulting in increasing sand content with depth. While mud weight clearly shows these variations, it is not a sensitive measure of the differ-

Table 2. Volumetric Sand Content (VSC) and Mud Weight (MW) after 6 Days of Settling

Position in settling jar	50 sec/qt MFV$ 25% Sand*		50 sec/qt MFV 50% Sand		70 sec/qt MFV 50% Sand		90 sec/qt MFV 50% Sand	
	VSC$^{\delta}$ (%)	MW@ (lb/gal)	VSC (%)	MW (lb/gal)	VSC (%)	MW (lb/gal)	VSC (%)	MW (lb/gal)
After mixing		9.92		10.92		11.05		11.25
Top third	15.0	10.10	28.5	—	23.5	11.0	26	—
Middle third	18.0	10.30	30.5	11.55	27.0	11.0	28	—
Bottom third	18.5	10.60	34.5	11.80	30.5	11.5	32	—

Note: Missing values are due to insufficient amount of sample for the test.
* Weight basis.
δ Volumetric sand content measured in accordance with ASTM Standard D 4381 (1984).
@ Mud weight measured in accordance with ASTM Standard D 4380 (1984).
$ Marsh funnel viscosity measured in accordance with API Standard RP13-B-1 (1990).

ences in sand content because it varies within such a narrow range. Slurries with varying viscosities mixed with 50% sand initially resulted in a volumetric sand content between 25 to 30%. This may represent an upper bound for the amount of sand likely to be entrained in the slurry.

In another effort to define the range of variables to be tested in the well modeled experiment, filtration and gel strength of Quik-Gel® slurries with initial MFVs of 50, 70 and 90 sec/qt were measured at 0, 25, and 50% sand contents (Muhanna, 1987; Edil and Muhanna, 1992). The procedures used in testing for these properties were in accordance with API Standard RP 13-B-1 (1990). The results showed that the addition of sand up to 50% by weight yields a volumetric sand content of about 25%. The slurries without any addition of sand ordinarily have a volumetric sand content of 1 to 1.5%. This is the coarse material normally contained in Quik-Gel®. This small quantity of coarse material exerts a measurable influence on the viscosity of Quik-Gel® and on its other physical properties (Muhanna, 1987). These tests further indicated that the addition of sand increases the thickness of the filter cake; however, its influence on rate of filtration (filtrate volume obtained in 30 minutes) is not as clearly delineated. Gel strength increases markedly with increasing sand content, implying better stability for cuttings-entrained slurries than pure slurries. Similarly, there was a noticeable decrease in permeability with the addition of sand. However, this effect was not observed for the 90 sec/qt slurry.

Based on these observations, it was decided to test two Quik-Gel® slurries with the initial MFVs of 50 and 70 sec/qt mixed with the coarse-sand (Granusil 2040) to have volumetric sand contents of nominally 10 and 20% each in Phase I of the well model experiment.

Properties of Selected Grouts

The four commercial grouts that were tested in Phase II were:

Neat Cement: Type I C-150 Portland Cement was used in preparing the neat cement grout. Neat cement grout is considered to be the most reliable sealant in current practice.

Bentonite-Cement: Bentonite-Cement mixture is one of the popular well sealing materials used in the field. With the addition of a small amount of bentonite, more water will be taken up by the mixture, resulting in a low unit weight, lower strength and lower cost cement-based slurry product.

Volclay®: Volclay® is a commercial high solid bentonite-based clay grout especially formulated for use as a borehole and well casing seal.

Benseal®-Bentonite Slurry: Benseal® is a commercial, specially processed, coarse ground, nondrilling mud grade bentonite for use in sealing and grouting well casings and earthen structures. It is a granulated material and in this study, a specific application of Benseal® used in the State of Ohio was adopted. In this application, Benseal® is entrained into a Natural Gel® slurry using a venturi pump. Natural Gel® is a finely ground, naturally occurring, chemically unaltered bentonite for drilling applications.

After a series of preliminary evaluations of a number of trial mixes and based on the recommendations of the manufacturers, the following recipes were adopted in the preparation of the sealants used in the Phase II study.

Neat Cement: One bag (94 lbs) of C-150 T Type I cement was mixed with 5.5 gallons of water.

Bentonite-Cement: Five pounds of Quik-Gel® was mixed with 6.5 gallons of water and to this slurry, one bag (94 lbs) of Type I portland cement was added.

Volclay®: 2.1 lbs of Volclay® was mixed with each gallon of water. Two pounds of magnesium oxide (MgO_2) powder was added to each 50 pounds of Volclay® slurry as setting initiator.

Benseal®-Bentonite Slurry: First a slurry of 30 lbs of Natural Gel® with 100 gallons of water was prepared. 125 lbs of Benseal® was mixed to the slurry through the use of a venturi pump.

The mud weights of the grouts were measured by taking samples while they were being mixed for use in the well experiments. The mud weights measured were as follows: neat cement: 15.1 lbs/gal; bentonite-cement: 13.8 lbs/gal; Volclay®: 9.3 lbs/gal; and Benseal®-bentonite slurry: 9.6 lbs/gal. These results indicate markedly higher mud weights for the neat cement and bentonite-cement grouts. The mud weights of Benseal®-bentonite slurry and Volclay® are higher than the mud weights of pure Quik-Gel® slurries, i.e., 8.6 to 8.7 lbs/gal; however, the Quik-Gel® slurries with entrained sand in them provided mud weights up to about 11 lbs/gal.

Three different mixers were used in preparing the grout materials in Phase II. The bentonite-cement and the Volclay® grouts were prepared using a force-feed large rotary mixer (Reco Model F422). This mixer was also used in the preparation of Quik-Gel® slurries for the well model experiments of Phase I. A regular concrete mixer was used to prepare the neat cement grout. In the field, sealing materials are often prepared by use of venturi pumps rather than the rotary mixers used in the laboratory study. Although the fine-grained bentonite slurries could easily be prepared by the rotary mixer, coarse-grained Benseal® grout could not be prepared in a rotary mixer because of the quick hydration and lumping of the granular Benseal®. It was reported that in the State of Ohio, well drillers were successful in entraining granular Benseal® into a slurry of bentonite (Natural Gel®) using a venturi pump attached to their drilling equipment. Therefore, in order to successfully prepare the Benseal® grout, a venturi pump was built in the laboratory. A slurry pump was used to circulate the Natural Gel® slurry placed in a 5-gallon mixing tank. During the circulation of this slurry, granular Benseal® was added through an opening over a T-section containing the smaller diameter venturi nozzle. After many trials, a system was perfected so that Benseal® could be entrained into a bentonite slurry without causing excessive lumping.

Experimental Program

Phase I

Following the emplacement of the Quik-Gel® slurries with 10% or 20% volumetric sand contents in the annular space, it was noted that the surface of the slurry sealant began to settle. This subsidence was made up from the top by adding more sealant. The subsidence was 79 to 103 in. during the first two weeks after emplacement, with the higher values associated with the slurries having 10% volumetric sand content. The subsidence of the sealants in all four wells practically stopped at the end of two weeks, with a settlement of only 1 to 2 inches during the next 8 weeks, until the termination of the experiment. A comparison of the amount of subsidence of these sealants, with that of the Quik-Gel® sealants without entrained sand used in another investigation (Edil, 1987) shows that they are about the same order of magnitude during the first two weeks. However, the sealants containing sand nearly stabilized at the end of two weeks, whereas the pure Quik-Gel® sealants continued subsiding beyond the first two weeks. The sealant surface was reasonably even without cracks in all wells at all times. This also contrasts with the pure Quik-Gel® sealants of the same MFV used in the experiment reported by Edil (1987). The slurries containing sand appeared decidedly more stable than the pure Quik-Gel® slurries.

The infiltration tests were initiated two weeks after the emplacement of the model wells and were continued through the 10th week to establish the long-term infiltration characteristics. Approximately 5 liters (1.3 gallons) of water adjusted to a temperature of 21° C (70° F) were placed in the annular space above the sealant between the well casing and the infiltrometer casing. Six weeks after the emplacement of the sealants, a dye (Intracid Rhodamine) was added into the infiltrating water. At the termination of the infiltration test, the model was disassembled and the sealants were examined slice by slice for clues regarding where the infiltrating dye was going and consequently the condition of the sealants.

Phase II

While there was no appreciable subsidence of the selected grouts used in Phase II, there were cracks developed that were observed on the surface of Benseal®, bentonite-cement, and Volclay® grouts during the initial two-week waiting period. There were hairline fissures observed in the neat cement grout. These discontinuities developed, apparently, due to the shrinkage caused by surface drying.

After approximately two weeks of gelling/setting time, 5 liters of water at room temperature were added to each infiltration casing. The infiltration tests continued for 117 days (17 weeks) in Phase II, after the 10th week of the infiltration testing, a red dye (Intracid Rhodamine) was added into the infiltrating water in order to trace the seepage path of the water in the sealants.

Hydraulic Conductivity

The hydraulic conductivities of the sealant materials used in the experiments were determined by performing permeability tests on samples of the sealants (Chang, 1988). Falling-head permeability tests were conducted on Quik-Gel® bentonite slurries, Volclay®, and Benseal® in a permeameter with 2-inch diameter. These tests were supplemented with falling-head permeability tests on Quik-Gel® sealant samples retrieved from the annular space with a thin-wall tubing 3/8-inch in diameter. The same sampling and testing procedure was followed for the filter cake material. In Phase II, the hydraulic conductivity tests were performed only on fresh samples of the rigid grouts, neat cement, and bentonite-cement, retrieved during emplacement in the annulus. These samples were put in cylindrical molds and allowed to harden and cure for two weeks prior to testing in a flexible-wall permeameter.

Seepage Analysis

In order to gain a sense of the infiltration conditions, a finite-element analysis of the seepage in the well model was undertaken (Lan, 1987). This analysis provided a theoretical basis for the interpretation of the experimental results. The program used is known as ANSYS® (1985) and its solution of the heat transfer problem was adopted to analyze the seepage in the well model. In the preprocessing phase of the program, choosing the finite element, mesh generation, setting of the boundary conditions, and defining the material properties are easily performed. An isoparametric element was used in this analysis. The element has four nodal points with a single degree of freedom, i.e. hydraulic head, at each node. Two different boundary conditions could be used at the top of the sealant in the infiltrometer casing: constant head or constant flow rate. At the bottom of the well model, there is a porous base with no pressure head. The porous base was taken as the datum. The lateral boundary of the sand in the container was assumed as a cylindrical impervious boundary with a diameter of 1 ft, the longest distance to the walls of the container from the center of the wells. This renders the problem to be an axisymmetric flow problem which could be treated as a two-dimensional problem. A sensitivity analysis indicated that the seepage rate is not sensitive to the distance of the lateral boundary.

Experimental Results and Analyses

Phase I

Infiltration Tests

The results of the infiltration tests conducted in the well model using Quik-Gel® slurries with entrained sand as sealant indicated linear trends similar to the ones shown in Figure 2 for one of the wells. The infiltrating water was replenished as its elevation dropped; thus the sudden jump in the relationship given in Figure 2. The average slopes of

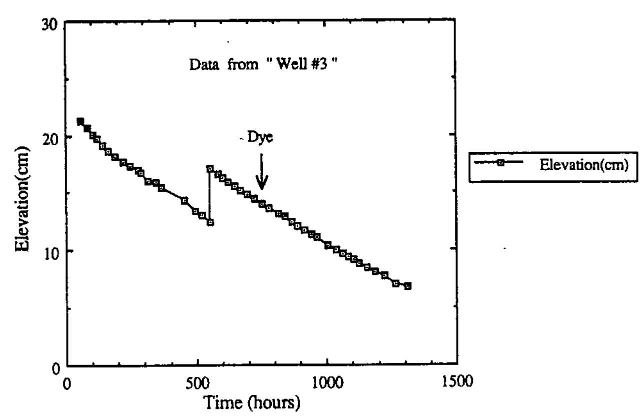

Fig. 2. Infiltration in well model experiment (Sealant MFV = 70 sec/qt, VSC = 10%).

Table 3. Measured and Computed Infiltration Rates in Well Model Experiment—Phase I

Well designation *Sealant viscosity* *Sand content*	*#1* *50 sec/qt* *10%*		*#2* *50 sec/qt* *20%*		*#3* *70 sec/qt* *10%*		*#4* *70 sec/qt* *20%*	
	Δh/Δt*	q**	Δh/Δt	q	Δh/Δt	q	Δh/Δt	q
2-5 weeks	0.60	1.34	0.42	0.94	0.44	0.99	0.26	1.57
5-10 weeks (Dye added at 6th week)	0.46	1.02	0.39	0.86	0.38	0.83	0.24	0.54
Last 4 days	0.75	1.66	0.42	0.93	0.30	0.66	0.30	0.66
Finite element program		0.38		0.42		0.21		0.17

* In cm/sec $\times 10^{-5}$.
** In cm^3/sec $\times 10^{-3}$.

the water surface elevation-time curves (Δh/Δt) are summarized for Phase I in Table 3 along with the infiltration rates obtained by multiplying these slopes by the annular space cross-sectional area (221.7 cm^2).

The infiltration rates are reasonably steady; however, they drop by a small amount after the fifth week. The infiltration rate is higher for Well #1 (about 1×10^{-3} cm/sec) than the other wells, and it is the lowest for Well #4 (0.5×10^{-3} cm/sec). These rates are markedly lower than the infiltration rates of 1 to 7×10^{-3} cm/sec measured for the pure Quik-Gel® slurries (without entrained sand) used to seal the annular space in a reference study (Edil, 1987; Edil and Muhanna, 1992). There was a notable increase in the infiltration rate during the last four days of the experiment in most of the wells. However, it is not clear whether this is an intrinsic trend or an experimental artifact.

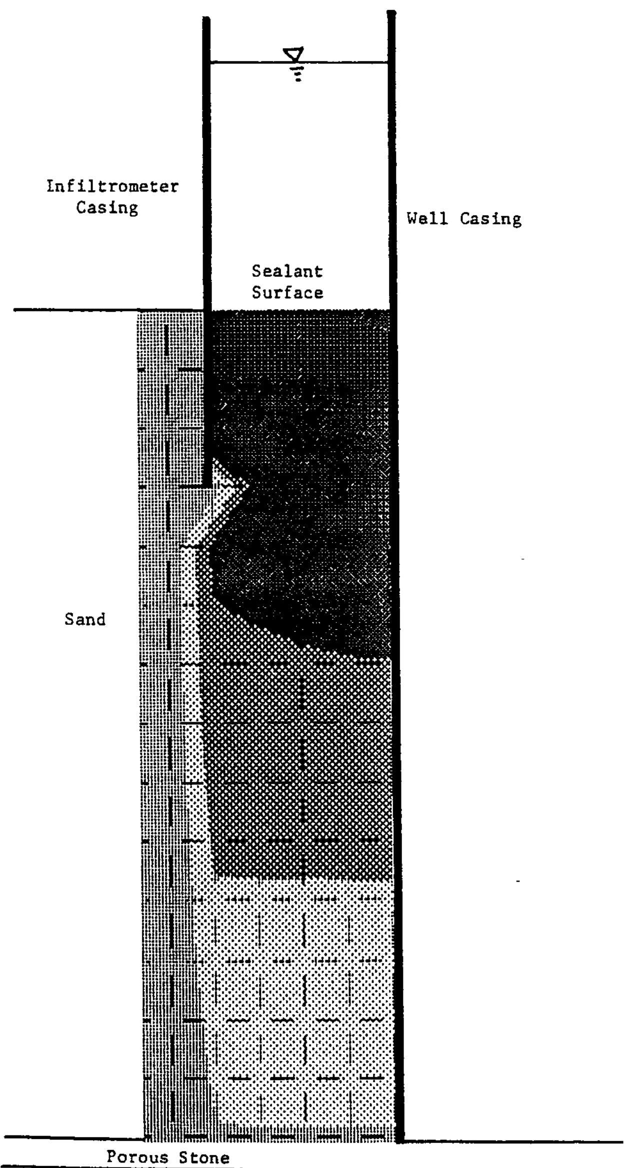

Fig. 3. Zones of equipotentials in well model.

Infiltration Analyses

The finite-element seepage analysis was used in two ways to assist with the interpretation of the experimental results. First, a constant flow rate boundary was employed at the top of the sealant. The measured infiltration rates as given in Table 3 were used for this purpose. This analysis indicated that almost all of the flow is through the sand. In other words, infiltrating water leaves the sealant by laterally exiting into the surrounding sand below the infiltrometer casing. Figure 3 shows the zones of equipotentials in the well model. The second approach used the finite-element seepage analysis to predict the infiltration rates consistent with the estimated hydraulic conductivities of the sealant materials obtained from the permeability tests as given in Table 4 for an assumed constant head at the top of the sealant. An

Table 4. Hydraulic Conductivity, k (cm/sec) of Sealant and Filter Cake Samples

Sealant viscosity sand content	*2 weeks (surface)* ($\times 10^7$)	*5 weeks (surface)* ($\times 10^7$)	*10 weeks (deep)* ($\times 10^7$)	*Filter cake* ($\times 10^3$)	($\times 10^3$)
50 sec/qt 10%	6.3	14.9	1.6	0.2	1.1
50 sec/qt 20%	22.0	16.4	1.7	2.1	3.6
70 sec/qt 10%	8.0	6.7	1.2	0.5	0.1
70 sec/qt 20%	6.1	6.7	1.9	0.1	1.7

k of sand: 2.17×10^{-1} cm/sec.

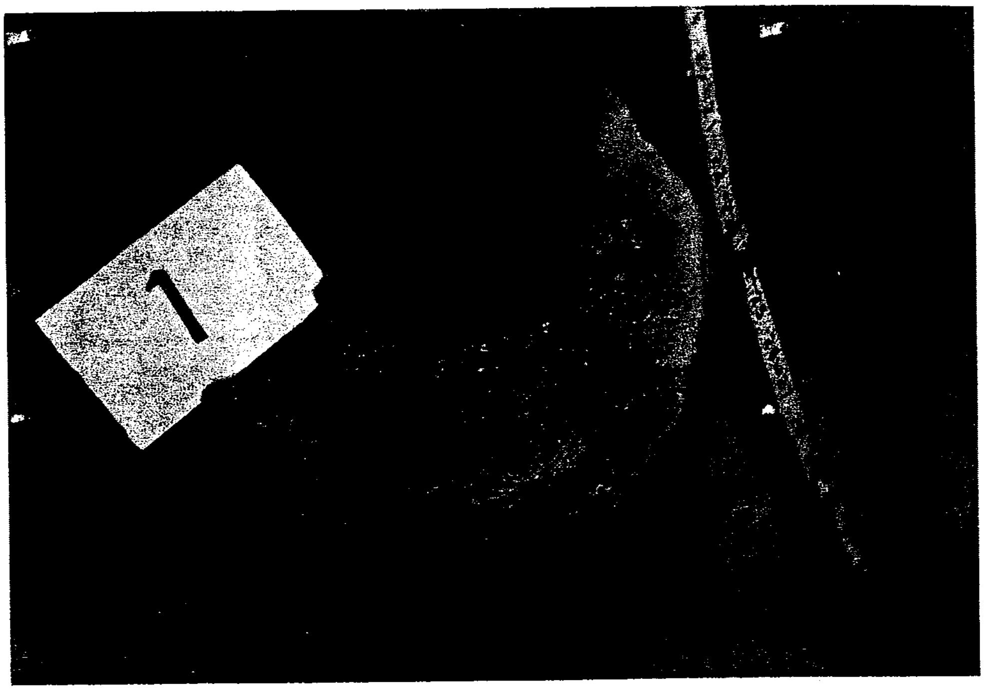

Fig. 4. Section through Quik-Gel® sealant with entrained sand.

average hydraulic head of 1.93 m relative to the bottom porous stone of the well model was used.

While the hydraulic conductivities of the slurries with MFV values of 70 sec/qt appear to be lower than the slurries with 50 sec/qt in the two and five-week surface samples, the 10-week deep samples exhibit nearly the same hydraulic conductivity. No clear-cut influence of the sand content of the initial mixture is seen on hydraulic conductivity. A comparison of the hydraulic conductivities of the surface samples taken in this phase with those reported by Edil (1987) for the pure Quik-Gel® sealants indicates that the sealants with entrained sand have more stable and lower hydraulic conductivities than sealants without any sand with the same Marsh funnel viscosities. However, the hydraulic conductivities of the deep samples taken at the end of the experiments were quite comparable between the two types of sealants at about 10^{-7} cm/sec.

A hydraulic head of 1.93 m at the top of the sealants relative to the bottom porous stone of the well model was used and the infiltration rates were calculated using the finite-element program consistent with the hydraulic conductivities given above for the five-weeks surface samples. The results are presented in Table 3. In the analysis, a filter cake zone of 12.5 mm in thickness was assumed to surround the sealants and have permeabilities corresponding to the second set of filter cake permeabilities given in Table 4. Because of the decidedly higher permeabilities assumed for the zone, it did not exert a significant effect on the computed infiltration rates.

The computed infiltration rates, q, of Table 3 are seen to be less than the corresponding actual infiltration rates measured at different times as given in the same table. In general, the measured infiltration rates during the five to 10-weeks period were two to four times greater than the computed values based on the permeabilities of the five-week (surface) samples. This ratio goes up to 10 to 25 times when the computed infiltration rates corresponding to the deep samples are considered. However, since the infiltration rate is controlled by the characteristics of the upper parts of the sealant, it is reasonable to consider the permeability of the five-week (surface) samples as representative.

When the model was disassembled, the sealants were examined slice by slice. Figure 4 shows an exposed section. There appeared to be very little dye migration down in the sand surrounding the seal. There was not any significant pink hue either in the sealants of the four wells or the surrounding sand. The sealant appeared intact without cracks or fissures through which dyed water could travel. There was no profuse breaking of dye into the sand as was observed in some cases in using pure Quik-Gel® slurries (Edil, 1987).

Phase II

Infiltration Tests

The average slopes of the water surface elevation-time curves of Phase II are given in Table 5 along with the infiltration rates obtained by multiplying these slopes by the annular space cross-sectional area. The data correspond to the first 10 weeks before the addition of the dye and the last nine weeks after adding the dye.

A review of the water level versus time indicated that the infiltration rate tended to slow down after some time. However, the replenishment of water caused an increase in the infiltration rates of the bentonite-cement and Volclay® grouts. This sort of increase in the infiltration rate was also observed after the addition of red dye in all cases except the neat cement grout. Since Intracid Rhodamine is a chemically inactive dye, it is believed that the reason for the

Table 5. Measured and Computed Infiltration Rates in Well Model Experiment—Phase II

Well designation *Sealant*	*#1* *Benseal®*		*#2* *Neat cement*		*#3* *Bentonite-Cement*		*#4* *Volclay®*	
	Δh/Δt*	q**	Δh/Δt	q	Δh/Δt	q	Δh/Δt	q
2-10 weeks	2.2	4.9	4.5	10.0	8.1	17.9	226.9	503.0
10-19 weeks (After adding dye)	3.4	7.5	4.5	10.0	32.3	71.6	403.2	894.0
Finite element program		3.0		3.0		9.0		3.0

* In cm/sec $\times 10^7$.
** In cm^3/sec $\times 10^{-5}$.

increase in the infiltration rate is due to the disturbances caused by the siphoning out of water prior to the addition of dyed water into the infiltrometer casings. Siphoning of the loose seal debris that covers the surface of the sealants in the annular space may have exposed the fissures and cracks resulting in higher rates of infiltration. There is some evidence that the shrinkage-induced volume defects (fissures) cause an increase in the infiltration rate. Benseal® grout appears to heal these fissures upon hydration whereas Volclay® grout tends to retain them.

When the measured infiltration rates of the sealants are compared, irrespective of how the various volume defects were formed, Benseal® provides the lowest infiltration rate, the neat cement and bentonite-cement follow Benseal®, and Volclay® gives a markedly higher infiltration rate. In summary, Benseal®, neat cement, and bentonite-cement form seals with markedly lower infiltration rates than the Quik-Gel® slurries of Phase I and Volclay®.

Infiltration Analyses

The finite-element seepage analysis was used to predict the infiltration rates consistent with the estimated hydraulic conductivities of the sealant materials obtained from the permeability tests. Three of the grouts used in Phase II had comparable hydraulic conductivities slightly above 10^{-7} cm/sec. The bentonite-cement grout had slightly higher value (3.7×10^{-7} cm/sec). The computed infiltration rates corresponding to the measured hydraulic conductivities of the sealants are presented in Table 5. In general, the computed infiltration rates based on the finite-element seepage analysis are lower than the corresponding actual infiltration rates measured at different times as shown in Table 5. The only exception is Benseal®-bentonite slurry grout, for which both the analytical and the measured infiltration rates are nearly equal. In the cases of the neat cement and the bentonite-cement grouts, the analytical infiltration rates are at most one order of magnitude lower than the measured ones. However, in the case of the Volclay® grout, this difference becomes nearly two orders of magnitude. Since the infiltration rate is controlled by the characteristics of the upper part of the sealant and the volume defects contained in this portion, the results confirm the basic observations made during the well model test.

When the well model was disassembled, the sealants were examined slice by slice for clues with regard to where the infiltrating dyed water was going and the condition of the sealants. The following observations were made on the condition of the sealants:

Benseal®-Bentonite Slurry Grout: This grout showed good adhesion with the well casing as well as the infiltrometer casing. There was insignificant degree of dye intrusion at these interfaces or in the seal. It had putty consistency and appeared to be an excellent flexible sealant (Figure 5).

Neat Cement: The dye was found to have penetrated along the interface between the neat cement grout and the steel casing to a depth of approximately 12 inches; however, there was no sign of dye at the interface between the neat cement grout and the PVC infiltrometer casing. A view of the neat cement grout at the well base is shown in Figure 6.

Bentonite-Cement: Approximately 6 inches of dye intrusion were found at the interface of the bentonite-cement grout and the steel well casing. Traces of dye were found at the bottom of the infiltrometer casing, apparently seeped along the interface of the PVC infiltrometer casing and the sealant. The bentonite-cement grout at the well base is shown in Figure 7.

Volclay®: A separation was observed between the Volclay® grout and the steel casing. It appeared as if Volclay® shrank away from the casing. The dye penetrated all the way to the bottom of the well at this interface for more than 6 feet. There was no significant intrusion at the interface of the Volclay® grout and the PVC infiltrometer casing. Figure 8 shows a section through the Volclay® grout and its interface with the well casing.

Field Observations of Drilling Mud Sealants

Observations were made in the field of 14 wells constructed using rotary-mud circulation methods (Riewe, 1991). The rotary drilling muds (bentonite slurries with drill cuttings) were observed and tested in the field at the time of well construction. Subsequent observations of these muds were made to determine how they behaved in field applications as annular space sealants. Mud weights were measured during and following completion of the wells. The slurries were checked for subsidence shortly after well completion, and for some of the wells, at the time of installation of the pitless adapter. However, there were no direct measurements of the continuity and sealing characteristics of the

Fig. 5. Section through Benseal®-bentonite slurry grout.

Fig. 6. Neat cement grout (base of the well casing).

Fig. 7. Bentonite-cement grout (base of the well casing).

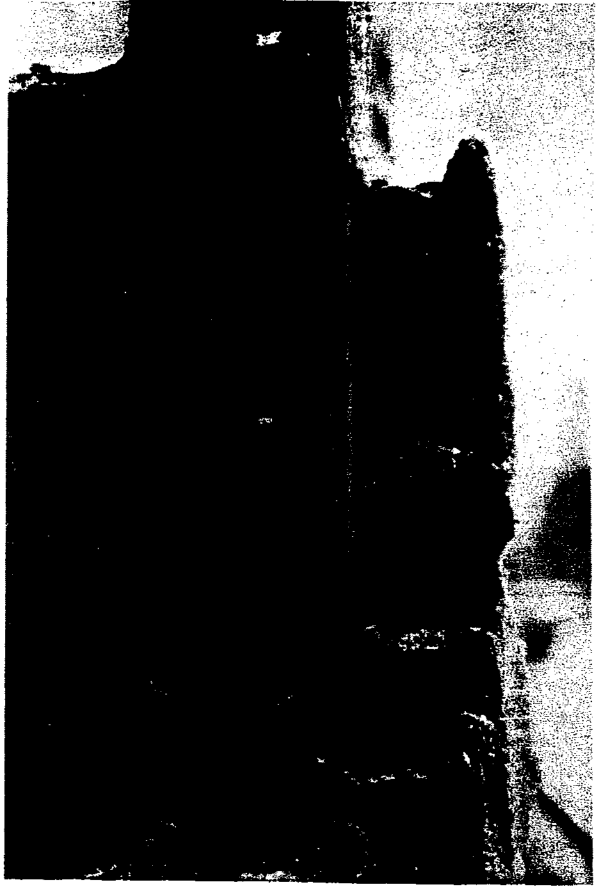

Fig. 8. Volclay® grout (dye intrusion at the interface).

slurries because of the unavailability of such procedures.

The objective of the field observations was to determine if the bentonite slurries with drill cuttings could be confirmed as a well sealant if their Marsh funnel viscosity and mud weight are adjusted to a minimum of 70 sec/qt and 11 lb/gal, respectively, as suggested by Phase I experiments.

The upper enlarged drillholes of all the wells were constructed with the mud-circulation drilling method through glacial till containing sand, gravel, and clay. The upper enlarged drillhole depths ranged from 55 to 231 ft deep, but most were in the range of 55 to 150 ft deep. The mud weights ranged from a low of 9.8 lbs/gal to a high of about 14 lbs/gal, but most were in the range of 10-12 lbs/gal. Difficulty in maintaining mud circulation occurred in only one of these wells. The static water levels in these wells ranged from 8 to 170 ft, with most levels falling in the range of 25 to 80 ft.

The results of the field tests did not show a positive correlation between heavier mud weight drilling muds and the degree of sealant subsidence. The mud settled more than 15 ft from the surface in 6 of the 15 wells (40%) even though the mud weight was heavier than 11 lb/gal in four of these six wells. Conversely, in one well having a mud weight of 9.8 and 10 lb/gal, there was no subsidence of the mud. Thus, it appears that the criterion of mud weight alone is not a good measure to use in the field to determine the stability of a rotary drilling mud as an annular space seal without significant subsidence.

Mud circulation problems encountered during drilling in some of the wells also did not correlate with significant subsidence problems. However, there appeared to be a consistent correlation between the amount of subsidence and the type of formation. Five of the six wells having a subsidence depth of 15 ft or more either had sand and gravel as the predominant formation in the depths of the upper enlarged drillhole or had sand and gravel in that portion of the drillhole where the settling occurred. There did not appear to be a positive correlation between the depth to the static water level and subsidence of the seals.

Conclusions

Based on the results of this investigation, the following observations and conclusions are made:

1. While hydraulic conductivity of a sealant is an important consideration, the final success of the sealant depends on its structural stability under environmental conditions.

2. Model experiments indicate consistently higher rates of surface-water infiltration into the annular space than analytical predictions based on measured sealant hydraulic conductivities.

3. Benseal®-bentonite slurry grout adheres to steel and PVC pipes and with its low permeability and good swelling characteristics and flexibility provides an excellent seal.

4. Neat cement and bentonite-cement grouts form a rigid seal which has low permeability and high durability; however, they allow some infiltration at the seal-casing interface. This is only for a limited distance; overall both sealants provide a good seal even if not as effective as Benseal®-bentonite slurry grout.

5. Volclay® grout has low permeability but it has a stiff gel structure which does not adhere to the well casing. Primarily due to infiltration at this interface, its performance is not comparable to the other three sealants.

6. Quik-Gel® slurries of various viscosities and sand contents (solids), like Volclay® grout, form poorer seals compared to Benseal®-bentonite slurry, neat cement, and cement-bentonite grouts.

7. Among the Quik-Gel® slurries, a slurry adjusted to a Marsh Funnel viscosity of 70 sec/qt forms the best sealant, especially when some formation solids are mixed with it, resulting in a mud weight of 10 to 11 lb/gal. Therefore, a drilling mud so adjusted can be left in the annulus to provide an adequate sealant for wells that are not high capacity, providing that it does not settle in the annular space and therefore become lost.

8. In the model experiments, the drilling mud slurries with entrained sand (cuttings) settled significantly requiring that almost twice the volume of the original sealant be added to maintain a fully grouted annular space. However, once stabilized, they settled very little. Field observations have shown serious subsidence problems even with mud weights higher than 11 lb/gal for such slurries. This problem puts severe limitations on use of drilling muds as annular space sealant. The extent of subsidence appears to be positively correlated with the apparent relative permeability of the

native formation. Therefore, this sealant may be stable only in certain formations.

9. Benseal®-bentonite slurry, neat cement, bentonite-cement, and Volclay® grouts show negligible subsidence due to loss of water to the formation and the atmosphere.

The model well experiments and the material characterization tests have generated useful information and provided significant insights with regards to the behavior of various sealants used in practice. This kind of information generally has been unavailable to the ground-water community. However, the preparation of the model, its characteristics, and the manner in which the tests were conducted have important limitations and may not have simulated all the salient factors controlling field performance. Furthermore, there were no replicate experiments conducted. Therefore, the findings and conclusions of this investigation should not be extrapolated to the practice without further field verification. Until then, the conclusions of the laboratory study can only be considered tentative.

Acknowledgments

This investigation was carried out with financial support from the Wisconsin Ground Water Coordinating Council through the Wisconsin Department of Natural Resources. Assistance of N. H. Severson and A.S.H. Muhanna during the experiments is appreciated. Swanson Analysis Systems, Inc. is acknowledged for permitting the use of ANSYS®.

References

ANSYS®. 1985. Engineering Analysis System. Swanson Analysis Systems, Inc.

API Standard-RP13B-1. 1990. Recommended practice standard procedure for field testing water-based drilling fluids. First Edition. American Petroleum Institute. 48 pp.

ASTM Standards. 1989. Annual Book of ASTM Standards. Volume 04.08. Soil and Rock, Building Stones; Geotextiles. American Society for Testing and Materials.

Chang, M.M.K. 1988. Investigations on the sealing properties and performance of water well sealing materials. M.S. Independent Study Report. Univ. of Wisconsin-Madison, Dept. of Civil and Environmental Engineering.

Edil, T. B. 1987. Sealing characteristics of sodium bentonite slurries for water wells. A report submitted to the Wisconsin Dept. of Natural Resources, Univ. of Wisconsin-Madison, Dept. of Civil and Environmental Engineering.

Edil, T. B. and A.S.H. Muhanna. 1992. Characteristics of a bentonite slurry as a sealant. Geotechnical Testing Journal, American Society for Testing and Materials (accepted for publication).

Lan, L. T. 1987. Analysis of seepage through well annular space using ANSYS®. M.S. Independent Study Report. Univ. of Wisconsin-Madison, Dept. of Civil and Environmental Engineering.

Muhanna, A.S.H. 1987. Characteristics of Quik-Gel® slurries as a water well sealant. M.S. Independent Study Report. Univ. of Wisconsin-Madison, Dept. of Civil and Environmental Engineering.

Riewe, T. V. 1991. Results of fourth, field phase of annular space seal research. Internal Report. Wisconsin Dept. of Natural Resources, Bureau of Water Supply.

* * * * *

Tuncer B. Edil received his B.S. and M.S. degrees from Robert College and his Ph.D. from Northwestern University, all in Civil Engineering. His research interests in geotechnical engineering include engineering behavior of soils, stability of coastal slopes and waste geotechnics.

Michael M. K. Chang received his B.S. and M.S. degrees from the University of Wisconsin-Madison, both in Civil Engineering. His current practice covers geotechnical problems in Hawaii.

L. T. Lan received his B.S. from the National Taiwan University and his M.S. from the University of Wisconsin-Madison where he is currently working towards a Ph.D. degree, all in Civil Engineering. His current research is concerned with compression of peat.

Thomas V. Riewe received his B.S. degree in Meteorology from the University of Wisconsin-Madison where he also attended graduate school in a combination of physical geography, geology, and cartography. He has been working the last several years on a complete revision of the State Well Construction and Pump Installation Code.