SLURRY DESIGN FOR SHALLOW WELL CEMENTING

G. W. HAWKINS and W. C. JONES
Dowell Division of Dow Chemical U.S.A.

ABSTRACT

Fluid-loss control additives for cement slurries have historically tended to undesirably retard compressive strength development at temperatures below approximately 130°F. In order to counteract this retardation, calcium chloride set accelerator has often been added to the slurry. Unfortunately, calcium chloride adversely affects the performance of commonly used fluid-loss additives. Frequently, fluid-loss control can only be obtained by adding significantly higher concentrations of the additive. This often results in an unacceptably high slurry viscosity and cost.

An ideal cement slurry for low-temperature applications should provide excellent fluid-loss control, adequate pumping time and rapid strength development. In addition, it is often desirable to use calcium chloride to economically accelerate the set of the cement, reducing the WOC (wait on cement) time.

Recent studies of cementing applications at temperatures below 130°F have resulted in the development of cement slurries that provide excellent fluid-loss control, rapid strength development and are not adversely affected by the addition of calcium chloride. Excellent performance can be obtained using API Class A and C cements, as well as fly ash and bentonite containing lightweight slurries. Laboratory data comparing currently used fluid-loss additives with these newly developed slurries are presented. Case histories of wells cemented using these new slurries are also discussed.

INTRODUCTION

Fluid-loss additives for cement slurries are used to prevent fluid (water) loss from the slurry to permeable formations encountered downhole. Fluid-loss additives can reduce the rate of water loss from the cement slurry by as much as three orders of magnitude.[1,2] Excessive fluid loss can occur whenever the total pressure exerted by the slurry exceeds the pore pressure in a permeable rock formation. The total pressure exerted by the slurry is the result of two components: hydrostatic pressure due to the slurry density and frictional pressure due to the slurry viscosity (resistance to flow) while it is being pumped.

The rate of fluid-loss from the slurry can also be determined by the relative permeability of the formation or the permeability of a mud filter cake, if any, desposited on the formation face.[3] In some cases, a low-permeability mud filter cake will decrease the fluid-loss rate to the point that no additional fluid-loss control in the cement slurry is necessary. However, if there is no mud filter cake, the filter cake is relatively permeable or the filter cake has been removed, a large amount of fluid from the cement slurry will be rapidly lost and a thick cement filter cake will be formed.

This thick cement filter cake forms a restriction in the wellbore that may significantly increase pumping pressures. If pumping is continued, formation breakdown may occur. In some cases, the cement filter cake will fully bridge the annular gap between formation and pipe preventing any further movement of the slurry, and the job must be terminated prematurely. When this occurs, slurry remains inside the pipe, hardens before it can be removed, and must be drilled out. In both cases, the required annular fill up has not been achieved and further remedial (squeeze) cementing may be necessary.

During primary cementing, fluid-loss additives are commonly used in wells where:

1. the annular gap is small;

2. air, water or native mud has been used as the drilling fluid;

3. water-sensitive formations, such as shales that expand and slough, are present; and

4. portions of a (low-permeability) mud filter cake have been disturbed or removed by scratchers or pipe movement.

Fluid-loss additives are also used in remedial (squeeze) cementing where the precise placement of a cement slurry is desired.[4] In this operation, the fluid-loss rate is controlled to promote penetration of the cement slurry into a void before a filter-cake plug is formed. The sealing of perforations or a channel in a cemented annulus are two examples of this application. In these cases, the function of the fluid-loss control additive is similar to that of a diverting agent. Initially, slurry will flow into the more permeable areas but further flow is then diverted to less-permeable areas.

Generally, fluid-loss additives consist of a combination of a water-soluble polymer and a cement slurry dispersant (fluidizer).[5] Most commonly, a blend of cellulosic-base polymer with a sulfonated aromatic polymer is used. Fluid-loss control additives are designed to function by allowing a predetermined portion of the slurry water to be lost to the formation leaving a thin cement filter cake behind. Fluid-loss additives dramatically decrease the permeability of this filter cake relative to an unmodified slurry and any further loss of water is minimized.

CEMENT STRENGTH DEVELOPMENT LOW AT TEMPERATURES

A compressive strength of at least 500 psi is generally regarded as the minimum compressive stength that must be achieved by the cement before further operations in the hole are recommended.[6a, 6b] Neat cement slurries (cement and water) often required an undesirable amount of time to achieve this 500-psi value at temperatures below roughly 130°F. Inorganic salts such as calcium chloride, calcium sulfate, sodium chloride and sodium metasilicates can be used to accelerate the compressive strength development.[7] In oil-field cementing applications, calcium chloride in its dihydrate form is preferably used due to its cost-effective performance and generally favorable secondary properties it imparts to the slurry.† Below 130°F, the most commonly used concentration of calcium chloride is 2% BWOC (by weight of cement).[7c]

EXPERIMENTAL

The following laboratory procedures were used during recent investigations of cement slurries designed for shallow, low-temperature wells.

Testing was performed using API Class A or C cement. Slurry density was maintained at recommended API values of 15.6 and 14.8 lb/gal for Class A and C, respectively. Thickening time, compressive strength and fluid-loss tests were performed according to API procedures (API Spec. 10, Jan. 1982) except as noted below. Fluid-loss tests were performed using 1,000 psi differential pressure. Thickening time and compressive strength tests were run using casing schedules 1, 3 and 4 assuming a geothermal temperature gradient of 1.5°F/100 ft of depth. In order to span the desired range of temperatures from 80° to 130°F, increases in the final temperatures of schedules 3 and 4 were made. All compressive strength samples were cured under (recommended) pressure.

To ensure that any reduction of compressive strength due to Additive S (vide infra) could be readily observed, a more severe test was devised. Instead of placing these cement slurries directly into the compressive strength curing mold immediately after mixing, the slurry was first stirred in an atmospheric pressure consistometer for 20 min at test temperature. This assured that the Additive S would be thoroughly mixed throughout the slurry and that any detrimental effects would be more readily apparent. This modified procedure was believed to be reasonable since it more closely resembles the conditions the slurry would actually encounter during placement in the field.

NOTE: Throughout this discussion fluid loss, thickening time and eight-hour compressive strength laboratory data are compared at the same temperature. This is common practice for remedial (squeeze) cementing. However, for primary cementing, fluid-loss and thickening time data are generally obtained at the bottom-hole circulating temperature (BHCT), while the compressive strength tests are conducted at the bottom-hole static temperature (BHST), which is generally higher. For relatively long curing times, such as 1, 3 or 7 days, this is valid. However, at the short curing times and low temperatures discussed here, the BHCT, rather than the BHST, is believed to be more representative of the temperature the slurry experiences in its first eight hours in the hole.

†When discussed in this paper, calcium chloride will be in the dihydrate form.

PERFORMANCE OF CELLULOSIC-BASE FLUID-LOSS ADDITIVES AT TEMPERATURES FROM 80° to 130°F

Historically, problems have been encountered when using cellulosic or cellulosic plus dispersant-base fluid-loss additives at temperatures roughly 130°F and below.[2,5] An example of the difficulties experienced appears in Table 1. Good fluid-loss control (<100 mL) is obtained when using 1% BWOC of Additive R, a cellulose plus dispersant-base additive. Unfortunately, the corresponding eight-hour compressive strength is quite low. This slow strength development results in excessive rig time waiting on the cement slurry to gain sufficient compressive strength (WOC time) to support further well operations. As is common practice, calcium chloride was added to the slurry to accelerate the compressive strength development. Sufficient early strength was attained; however, a dramatic reduction in fluid-loss control occurred (Table 1). In order to regain the original fluid-loss control, the concentration of Additive R was increased by 0.3% BWOC (a 30% increase). While both good strength development and fluid-loss control were obtained, the slurry viscosity became undesirably high and was difficult to mix (Table 2). Unfortunately, the mixability of slurries, while easily observed qualitatively, is different to measure quantitatively. Therefore, the significance of the rheological model parameters listed in Table 2 is open to various interpretations, a discussion of which is outside the scope of this paper. For data gathered using a Fann Model 35 Rheometer (R1, B1, 1X) the following rule of thumb is often used: as the 300 RPM reading increases above 160, slurries become progressively more difficult to mix using field equipment. Slurries with 300 RPM readings above 220 are very difficult to mix.

During recent investigations of low-temperature cementing operations the performance of cellulosic-base additives was studied. Additive R, the cellulosic plus dispersant-base additive, was chosen for detailed study due to its superior overall performance in comparison to other cellulosic-base additives and the wide use of similar additives throughout the cementing service industry. General performance data were obtained using API Class A cement mixed with recommended API water content.[8] Supplementary data were obtained using API Class C cement. The test temperatures were varied from 80° to 130°F.

Initially, the performance of Additive R in normal, unaccelerated cement slurries was studied. Fluid-loss control, eight-hour compressive strength and thickening time data appear in Figures 1a through 1d. While generally acceptable, fluid-loss control and thickening time values are obtained, the early compressive strength developed is found to be lower than desired, even at 130°F. Generally speaking, when the fluid-loss control became significant (<200 mL), the early compressive strength was relatively poor.

As is common practice, calcium chloride accelerator (2% BWOC) was then added and these slurries were tested under the same conditions as before (Figures 2a through 2d). While calcium chloride did significantly accelerate compressive strength development, a dramatic deterioration in fluid-loss control occurred. For example at 100°F with an Additive R concentration of 1.0% BWOC, the fluid loss increased from 75 to 150 mL

(Figures 1b through 2b); at 130°F and the same concentration of Additive R, the fluid loss increased from 135 to 250 mL (Figures 1c and 2c). To regain equivalent fluid-loss control performance in the accelerated slurries, the Additive R concentration had to be increased by one-fourth when compared to the unaccelerated slurries.

An increase in Additive R concentration is very undesirable since the slurries became difficult to mix and significantly more viscous as the Additive R concentration was increased (cf. Table 2). In addition, the compressive strength of accelerated slurries, even though acceptable, decreased as the concentration of Additive R increased.

In slurries prepared using API Class C (High Early Strength) cement, substantially higher concentrations of Additive R were required for fluid-loss performance values equivalent to those in Class A cement slurries (compare Figures 1 and 4; 2a, 2b and 5a, 5b). This was true for both in normal and accelerated slurries. However, the early compressive strength values and trends were found to be comparable. The Class C, like the Class A, slurries also became difficult to mix and exhibited undesirably high viscosity at Additive R concentrations required to obtain acceptable fluid-loss control (<200 mL/30 min).

The decrease in the early compressive strength of accelerated cement slurries as the concentration of Additive R is increased and the decrease in fluid-loss control when calcium chloride is added to the slurries indicate that the calcium chloride and Additive R counteract each other. In actual practice, it has often come to a choice: good fluid-loss control with poor strength development or good strength development with poor fluid-loss control.

DEVELOPMENT OF FLUID-LOSS-CONTROLLED CEMENT SLURRIES FOR USE AT LOW TEMPERATURES

An ideal fluid-loss-controlled cement slurry should not only provide excellent fluid-loss control, but also mix easily, have low viscosity, provide adequate thickening time and rapidly develop compressive strength. For use at lower well temperatures (< 130°F), it is desirable to use calcium chloride in the slurry to economically accelerate the set of the cement. Since the overall performance of cellulosic-base fluid-loss additives (Additive R) was found to be undesirable, a project was undertaken to develop slurries with better performance. Since the strength development of "neat" cement slurries is slow at these low temperatures, it is apparent that any fluid-loss additive must perform well in the presence of an accelerator. Calcium chloride was selected as the accelerator of choice.

Since it is highly desirable that fluid-loss-controlled slurries provide many different properties (fluid-loss control, low viscosity, etc.), the development of a new additive system whose performance would be optimized at low temperatures was emphasized. Improved overall performance in API Class A and C cement and pozzolan (fly ash) - cement slurries was also sought.

As the result of these investigations, a new low-temperature fluid-loss additive that is designed to be compatible with a calcium chloride accelerator has been developed. Through use of this new additive, Additive S, both excellent fluid-loss control and eight-hour compressive strength development (>1,500 psi) can now be obtained (Figures 3a through 3d).

In comparison with the cellulose-base additive, Additive R, much less Additive S is required to obtain significant fluid-loss control, and significantly more compressive strength is developed. For example, in a Class A cement slurry at 100°F, to obtain a fluid-loss value of 50 mL, 1.3% BWOC Additive R must be used. Only 0.6% BWOC Additive S is needed and less than 50 mL fluid loss is obtained (Figure 2b vs. 3b). The corresponding eight-hour compressive strength is also significantly better in slurries with Additive S and R: 1,700 vs. 1,300 psi for slurries with Additives S and R, respectively. In general, Additive S provided dramatically better fluid-loss control and improved early compressive strength development at low temperatures when compared with Additive R.

Additive S was also found to be significantly less retarding than Additive R. For example, at 130°F slurries with Additive R still require 2% BWOC accelerator to obtain both acceptable early compressive strength and fluid-loss control (Figures 1c and 2c). By contrast, in slurries containing Additive S at 130°F, the accelerator was removed and a lignosulfonate retarder added (Figures 3c and 3d). Again, both excellent fluid-loss control and high early strength development are obtained even in these retarded slurries. (Generally, a retarder must be added to slurries containing Additive S at the same temperature as would be the case for the same slurry without Additive S, again indicating the less retarding nature of the additive.)

The slurries containing Additive S were also found to be dramatically easier to mix and significantly less viscous (Table 2). The viscosity for the Class A cement slurries with Additive S was approximately one-third less than similar slurries with Additive R at additive concentrations which gave equivalent fluid-loss values (Table 2).

In slurries prepared using API Class C cement, similar results were obtained (Figures 6 and 7). Approximately two-thirds less Additive S was needed to obtain good fluid-loss control when compared to Additive R (Figures 5b and 6). Substantially better early compressive strength was also found in these slurries.

Additive S also performed well in pozzolan (fly ash):cement systems (Table 3). Due to the high water content of these slurries, compressive strength develops more slowly than in "neat" normal weight slurries. Therefore, any tendency of the fluid-loss additive to retard is readily apparent. However, even in these lightweight slurries, Additive S provided both efficient fluid-loss control and good compressive strength.

After this general investigation, further laboratory work was performed for specific low-temperature well applications. In accelerated API Class G and H cement slurries with Additive S, analogous improved fluid-loss control, mixing and early compressive strength were also obtained. Additive S also has been applied successfully in cement jobs at temperatures lower and higher than the 80° to 130°F range discussed here.

CASE HISTORIES

Fluid-loss-controlled cement sluries are used both in primary and remedial (squeeze) cementing. In primary cementing, successful fluid-loss control is commonly indicated by the absence of any unusual pressure increase during the job. An unusual pressure increase could indicate that, due to rapid slurry water loss, a thick cement filter cake had formed and was restricting slurry flow. In remedial (squeeze) cementing, the objective is to penetrate all selected voids, form a durable, permanent seal and to do so in one operation. An effective fluid-loss-controlled cement slurry regulates filter cake growth and helps assure that pressure, and therefore the slurry, will be transmitted to all voids rather than to just the more permeable voids. In this case, success is measured by the degree to which fluid flow or pressure communication has been stopped. In practice, a "squeeze" is successful if a further "squeeze" is not required.

Case History No. 1

In Moore County, Texas, a well was air-drilled with "mist" from 1,200 to 2,550 ft through a water-sensitive, sloughing shale zone. A 4-1/2-in. casing string was set in eight-inch open hole. Bottom-hole temperature was 80°F. Twenty barrels of water-base surfactant were pumped ahead of the cement slurry to condition the hole and water-wet the casing. The cement system consisted of 50:50 Fly Ash:API Class H cement slurry containing a granular lost-circulation material, accelerator and Additive S. Slurry density was 14.2 lb/gal. API fluid-loss volume for the system was 18 mL/30 min, a very low value. The slurry thickening time was three hours.

On location, the slurry mixed easily and was displaced at an average rate of three barrels per minute. No unusual pressure increases were observed during the job. This cement system is currently being used in a 125-well program.

Case History No. 2

Previous attempts to complete wells through this water-sensitive shale formation had only very limited success. Swelling and sloughing were such a problem that the operator at first considered using an expensive nonaqueous cement. However, for the well in Routt County, Colorado, a normal portland cement system (with exceptional fluid-loss control provided by Additive S) was designed.

The 15.8-lb/gal API Class G cement slurry also contained retarder, potassium chloride and antifoam additive. The API fluid-loss value for this system was only 7 mL/30 min. Slurry thickening time was 4 hr and 15 min, free water was zero and 24-hr compressive strength was 2,990 psi.

The well had been drilled to a depth of 6,500 ft using an oil-base drilling fluid, and 5-1/2-in. casing was set in 8-3/4-in. open hole. Bottom-hole circulating temperature was 125°F. Twenty-nine barrels of a 13.0-lb/gal oil-base spacer were first pumped into the well followed by 51 barrels of the batch-mixed cement slurry for 1,100 ft of fillup. The spacer and slurry were displaced at an average rate of four barrels per minute using diesel oil. In order to maximize hole stability, the casing was not moved during the job.

On location, the slurry mixed easily. Full returns were maintained during the job and no unusual pressure increases were observed. A cement bond log was subsequently run and showed 100% bond over the entire cemented interval.

Case History No. 3

In Howard County, Texas, a problem well had zonal communication through a narrow channel between two sets of perforations. Several previous attempts to shut off the flow were unsuccessful. Some failures were attributed to insufficient penetration of the cement slurry due to insufficient fluid-loss control and subsequent rapid water loss. Other failures were attributed to slow strength development allowing displacement of the slurry by formation fluids.

A cement slurry that had good fluid-loss control to remain pumpable and fill the channel, yet quickly develop strength, was required. A 15.0-lb/gal system using API Class C cement with calcium chloride and Additive S was recommended. This slurry had an API fluid-loss volume of 64 mL/30 min, a 3 hr and 5 min thickening time and a compressive strength of 1,200 psi in 12 hr at 135°F.

Utilizing this system containing Additive S, the fluid migration was successfully shut off in one treatment.

Case History No. 4

This well in Crane County, Texas, was drilled to 5,286 ft total depth. A 5-1/2-in. casing string was set in. a 7-7/8-in. open hole with a bottom-hole circulating temperature of 98°F. The operator desired a fluid-loss-controlled cement slurry to prevent damage to the producing formation. A 14.8-lb/gal calcium chloride accelerated Class C cement system utilizing Additive S for fluid-loss control was recommended. Laboratory data showed an API fluid loss of 60 mL/30 min with a 12-hr compressive strength of 1,020 psi at the 118°F bottom-hole static temperature. Thickening time was 3 hr and 10 min.

On location, 15 barrels of fresh water were first pumped followed by 47 barrels of the cement slurry for approximately 1,000 ft of fillup. The slurry was mixed at five barrels per minute and displaced with fresh water at a rate of six barrels per minute. The pipe was reciprocated during displacement. Full returns were maintained during the job and no unuusual treatment pressures were observed.

CONCLUSIONS

1. Commonly used cellulosic + dispersant-base cement fluid-loss additives, such as Additive R, significantly retard compressive strength development at temperatures below 130°F.

2. While the early compressive strength of slurries with Additive R is increased by the addition of calcium chloride accelerator, the fluid-loss control is significantly decreased. Increasing the concentration of Additive R to regain the original control results in mixing problems, high slurry viscosity and lower early compressive strength.

3. In order to avoid these problems, new additive systems utilizing accelerators and Additive S have been developed. Dramatically less Additive S compared to Additive R is required to achieve low fluid-loss values in accelerated cement slurries. In addition, higher early compressive strength and lower slurry viscosities are obtained. Additive S performs well in API Class A and C and in pozzolan (fly ash):cement slurries.

4. Successful primary and remedial (squeeze) cementing jobs using slurries with Additive S confirm laboratory data. In wells where fluid-loss control was essential, the slurries with Additive S were readily mixed, pumped and displaced.

REFERENCES

1. Smith, D. K.: "Cementing," SPE Monograph (1976) 4, 24, 41.

2. Suman, G.O. Jr. and Ellis, R. C.: "World Oil's Cementing Handbook," (1977) 26.

3. Bannister, C. E.: "Evaluation of Cement Fluid Loss Behavior under Dynamic Conditions," SPE Paper 7592 (1978).

4. Beach, H. J., O'Brien, T. B., and Goins, W. C., Jr.: "The Role of Filtration in Cement Squeezing," API Drilling and Production Practice (1961) 27-35.

6a. Bearden, W. G. and Lane, R. D.: "Engineered Cementing Operations to Eliminate WOC Time," API Drilling and Production Practice (1961) 17.

6b. Ref. 2, 6.

7a. Lea, F. M.: "The Chemistry of Cement and Concrete," 3rd Ed., Chemical Publishing Co., Inc. (1970) 301, 605.

7b. Montgomery P. C.: "Cement Accelerators cut Rig Downtime," Drilling (June 1965) 26, 76.

7c. Ref. 1, 16.

8. API Specification for Well Cements and Cement Additives, API Spec. 10, 1st Ed., American Petroleum Institute (Jan. 1982).

Table 1
Performance of Additive R in Cement Slurries at 100°F

Fluid-Loss Additive Concentration (% BWOC)	Calcium Chloride Concentration (% BWOC)	API Fluid Loss (mL/30 min)	8-hr Compressive Strength (psi)
1.0	--	75	290
1.0	2.0	150	1,310
1.3	2.0	50	1,300
--	2.0	--	1,520

Slurry: API Class A Cement + 46% Water; 15.6 lb/gal.

Table 2
Rheological Data
Slurry: Class A Cement + 46% Water; 15.6 lb/gal, 75° F

Line	Fluid-Loss Additive Type	Fluid-Loss Additive Conc. (% BWOC)	Acc.[a] Conc. (% BWOC)	Retarder[b] Conc. (% BWOC)	Rheological Model: Bingham Plastic up (cp)	Bingham Plastic Ty $\frac{lb}{100\ ft^2}$	Power Law n'	Power Law K' $\frac{lb\text{-}ft^2}{sec}$	0 300[c]
1	-	-	-	-	39	24.4	0.414	0.053	64
2	-	-	2.0	-	42	37.0	0.320	0.117	80
3	R	1.3	-	-	207	15.9	0.827	0.013	240
4	R	1.3	2.0	-	171	9.8	0.873	0.008	199
5	S	0.4	2.0	-	78	39.1	0.284	0.176	109
6	S	0.6	2.0	-	80	35.0	0.460	0.076	112
7	S	0.8	-	0.4	133	42.2	0.338	0.179	167

Procedure: API Spec. 10 (1-82), Fann 35/SR 12 Rheometer, R1, B1, 1X

[a]Calcium Chloride Dihydrate

[b]Lignosulfonate Retarder

[c]Fann Rheometer Reading at 300 RPM

Table 3
Performance of Additive S in Pozzolan:Cement Systems at 100°F

FLY ASH: CEMENT (% by vol)	SLURRY DENSITY (lb/gal)	ADDITIVE S (% BWOS*)	API FLUID LOSS (mL/30 min)	COMPRESSIVE STRENGTH at 24-hr (psi)
35:65	14.4	0.6	22	1,156
50:50	14.1	0.6	28	724
50:50	14.1	--	>500	508

Pozzolan: Fly ash, 74 lb/sk

All slurries contain 2% BWOS* calcium chloride accelerator
and 2% BWOS* bentonite extender

*By weight of solids (cement + fly ash)

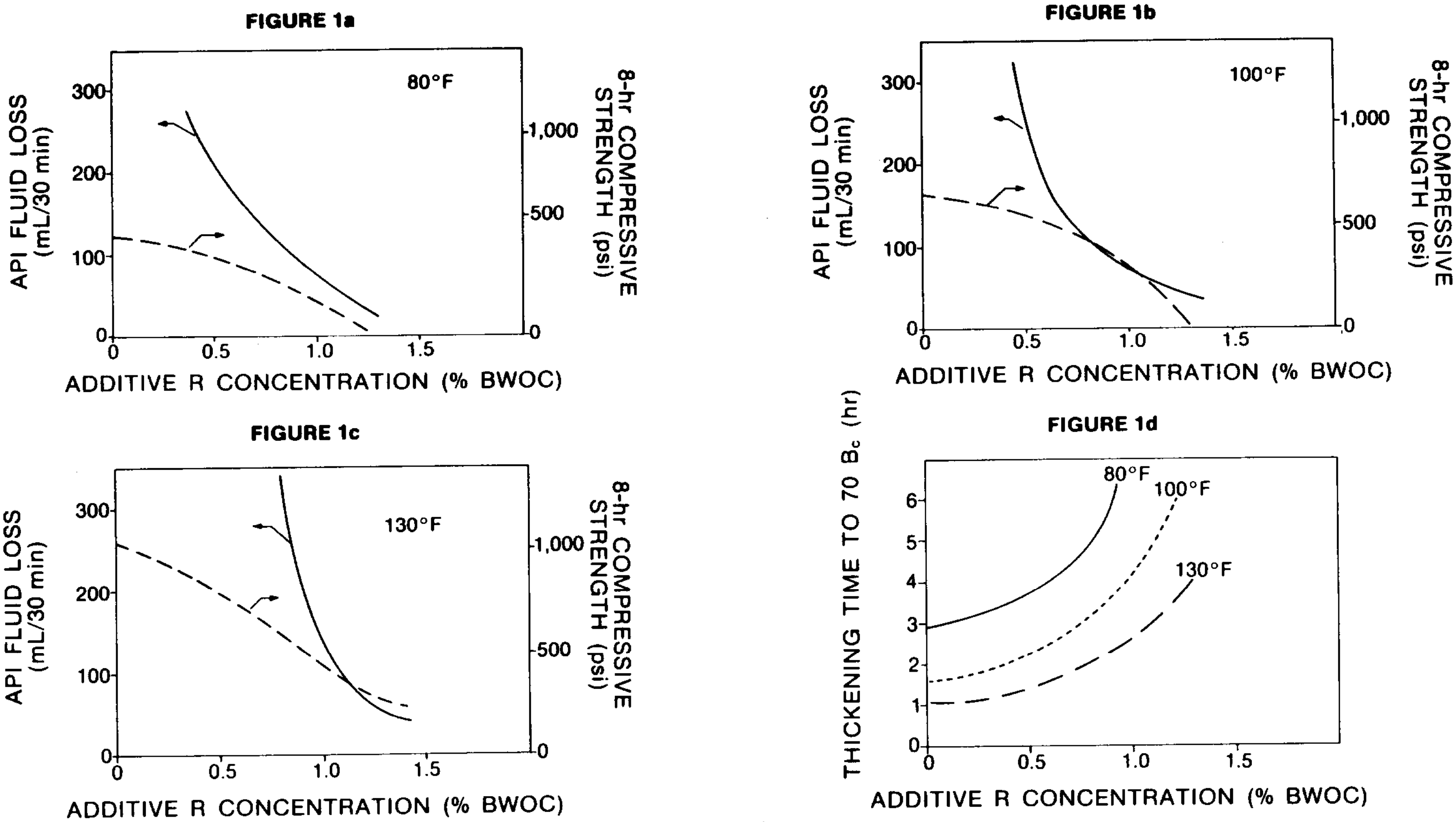

Figure 1 - Performance of Additive R in Class A cement slurries

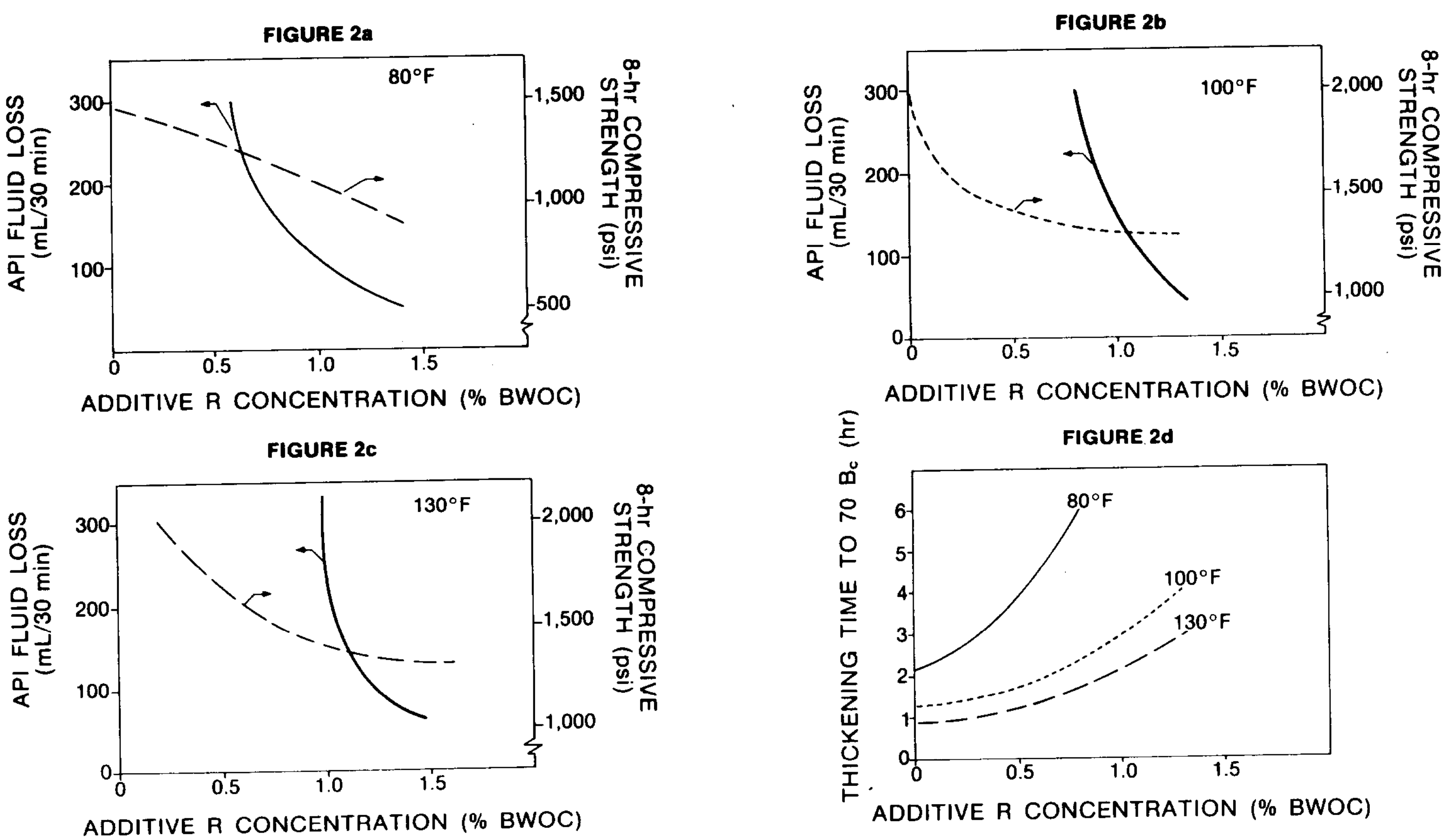

Figure 2 - Performance of Additive R in calcium chloride accelerated Class A slurries (all slurries contain 2% BWOC calcium chloride)

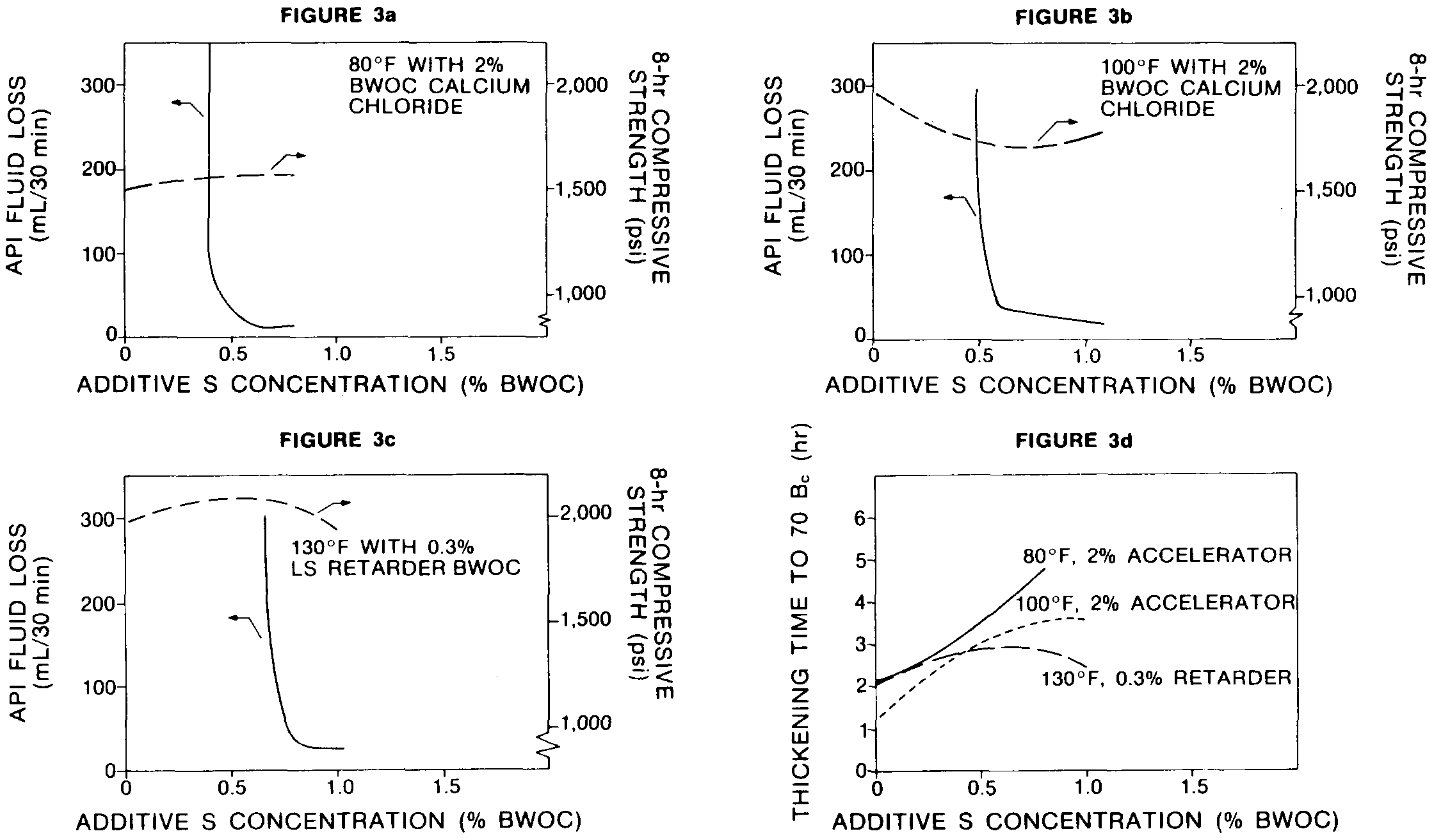

Figure 3 - Performance of Additive S in Class A cement slurries

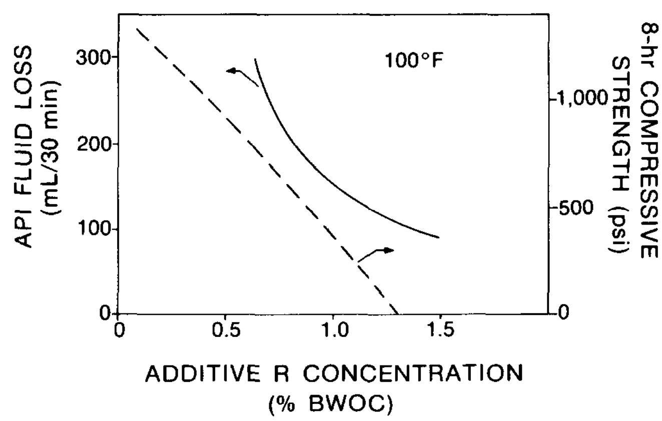

Figure 4 - Performance of Additive R in Class C cement slurries

FIGURE 5a FIGURE 5b

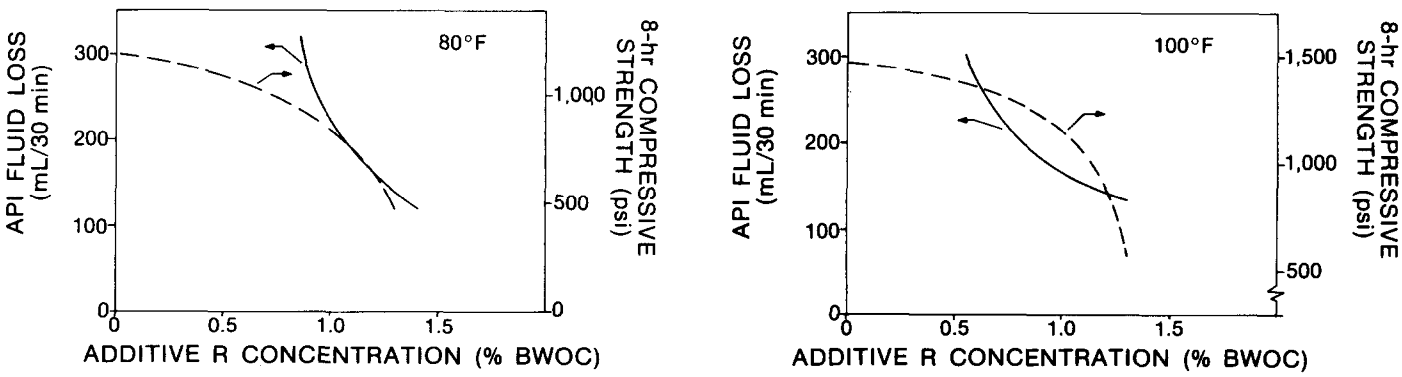

Figure 5 - Performance of Additive R in calcium chloride accelerated Class C cement slurries (all slurries contain 2% BWOC calcium chloride)

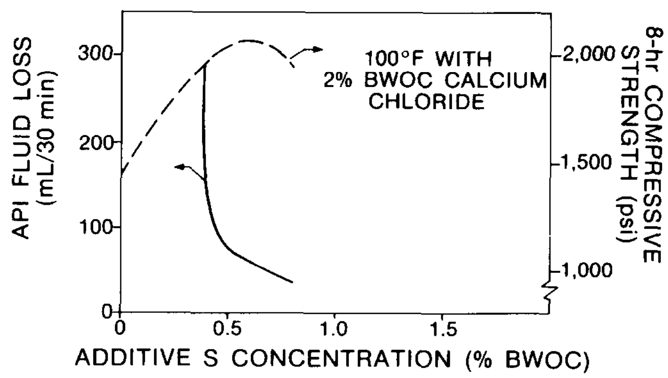

Figure 6 - Performance of Additive S in calcium chloride accelerated Class C cement slurries

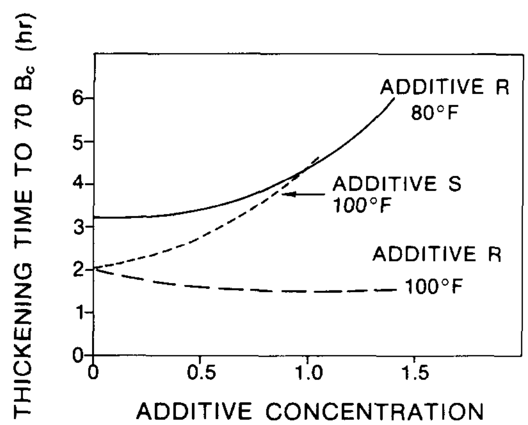

Figure 7 - Thickening times of Class C cement slurries (all slurries contain 2% BWOC calcium chloride)