GUIDELINES FOR SELECTING CEMENT THAT WILL BE PERFORATED

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ABSTRACT

Results of work performed to determine the degree of cement sheath shattering that occurs during perforation indicate the application potential of lightweight "lead" cements as "perforating" cements. Four lightweight cement candidate blends were tested and compared to conventional, normal density, tail cement. A 7 in. OD, 23 lb/ft J-55 casing test fixture was used. The formation was simulated by a piece of tubing 10.75 in. OD by 0.188 in. wall. The 10 in. thin wall tubing is not a component of normal well completions; it served to act as a simulated formation to hold cement in place. The cement was perforated with 0.42-in. dia. perforations, 90° phasing, four shots per foot (spf) with 22 gm charges placed in each test fixture. The test procedure was specifically designed to duplicate typical field conditions in the Midland, Texas, area, and to determine the amount of cement shattering that occurred while perforating. Test fixtures were sectioned after perforating, examined for cement sheath damage, and photographed.

INTRODUCTION

Cement compositions normally considered only for special or unusual applications, or as lead cement slurries only, have demonstrated good-to-excellent perforating characteristics in laboratory testing conditions. New lightweight slurry designs that meet local guidelines and regulations for critical zone compressive strength requirements, and which also can be perforated with minimal damage, are now being used for liner cementing.

Many fields in the Permian basin are characterized by extremely weak formations which break down either (1) during cement placement because of circulating pressures, or (2) after cement placement because of hydrostatic pressures. To alleviate this problem, lightweight cements of various types have been employed, with generally good results. However, some areas still experience cement fallback on a fairly routine basis. Because the weak formation is often also the productive interval, or in close proximity to it, enough tail slurry can be lost so that the lightweight lead cement may wind up covering the zone of interest. Experience with this situation in the past has shown that these lightweight cements appear to provide good properties for completing critical zones, especially with respect to perforating properties. Furthermore, use of these lightweight cements as critical zone cements in place of conventional density tail cements should also help eliminate cement fallback altogether. A description of a series of tests conducted on different lightweight cement compositions shows their suitability for perforating and completing critical zones.

Background

For most well completions a production casing is set through the oil or gas producing zone, cemented in place and perforated. The perforation penetrates the casing, cement, and formation to allow a flow conduit for the producing fluids. Ideally, the perforation process would leave a round, burr-less hole with a perforation tunnel extended well into the hydrocarbon zone with minimal damage to the casing, cement sheath, and formation. Most of the research conducted on perforating has been focused on the well productivity perforation density and perforating techniques.

Previous investigations have studied casing damage and cement bond strength damage when perforating. Bell and Shore[1] concluded that less casing deformation would be expected under a confining pressure such as under downhole conditions vs perforating tests at atmospheric pressure. Godfrey[2] performed his tests under 3000 or 5000 psi confining pressure with targets fired in single shot tests. Due to time and logistics, these tests were fired four spf through casing and cement at the surface, which might be considered a "worst case." Higher strength cements (on the order of 3500 psi) are recommended in these early studies. However, in the case of critical zone lightweight cements a minimum compressive strength of 500 psi would be expected at the time of perforating.

Jet perforation uses a shaped charge to generate a high velocity "plasma" of particles and gasses. Pressures at the tip of the jet are on the order of 2 to 4 million psi. Once the tip pressure exceeds the yield strength of the target, the jet of particles and gasses displace material as the perforation and tunnel are being made. This leaves a "crushed zone" of cement approximately 0.5 in. thick around the perforation tunnel. Target interaction time is approximately 500 micro seconds. According to Smith, "Only 5 to 10% of the explosive force creates the perforation, while 90 to 95% of the force creates very short term, ultrahigh pressures and large shock forces on the inside walls of the shaped-charge container."[3]

Bullets propelled by an explosive charge are another commonly used perforating device. Bullets, like jet perforation, also displace material as the perforation tunnel is being made. Thompson[4] compares the relative penetration of bullets vs jets in hard and soft formations. Hydraulic jetting and mechanical cutters are also used to establish communication with the formation but are not as common.

With bullets, penetration is generally limited in hard formations or cements when the strength exceeds 2,500 psi, whereas jets perform better above 3000 psi.[3] The tests referenced here were conducted for lower compressive strength cement more typical of what would be seen in cements commonly used in the Midland area at the time of perforation. Although a lower strength cement provides less backup to the casing, it is less likely to shatter from the shock forces of perforation. For a cement composition to allow the best perforation possible, it must avoid shattering from the perforating process and, once perforated, maintain a tight seal to the casing and formation so that communication of fluids from one perforation to another will not occur.

Most previous investigations have focused on compressive strength of cement as the most important phenomenon in selecting cement for perforating characteristics. The consensus of opinion has been that, for good perforating properties, compressive strengths between 1000 and 2000 psi are desirable.[2] Cements rated below 1000 psi exhibited poor bond characteristics and sealability, whereas cements with strengths above 2000 psi were too hard and exhibited shattering when perforated.[4] Other authors concluded that bond strength by itself was the most important parameter, and that the bond strength was only slightly dependent on compressive strength with pipe conditions and curing environment acting as the major factor influencing cement bonding. Recent papers have shown that the environment under which the cement sets is the controlling factor on the cement bonding to the pipe.[5] Cement set across low restraint environments produces poor bonding as evidenced by bond logs and shear bond data even though annular fill is high.

Limited work has been conducted on additives in cements that are claimed to promote better perforating. Two examples are fibers and latex polymers.[6,7] Fibers are credited with improving shattering resistance with high strength cements and latex for improving bonding of cement to pipe.

Current Completion Techniques

Normal completion techniques in the Yates and Clearfork formations in west Texas are to cement the production string with a lead and tail cement. Wells are typically 5000 ft deep with ± 85 to 110°F bottom hole static temperature. Lead cement compositions are typically lightweight, extended water ratio cements mixed at 12 to 14 lb/gal densities. Several other types of special lightweight cements have also been used including foam cement and microfine silica. The lightweight cements are used for two reasons: first, these cement compositions generally have a high volumetric yield per sack of cement which helps in an economic analysis; second, the low density is required to prevent breakdown of fragile producing zones and subsequent fallback. Even utilizing a lead and tail cement system, however, an unacceptable number of wells still experienced cement fallback, creating the concern that the lightweight lead cement left across the zone after fallback would not have good perforating qualities. There was a need for a lightweight cement that would limit fallback and provide adequate bonding characteristics, and that could also be perforated if needed. Field testing was begun in early 1987.

MODEL STUDIES

Apparatus

Materials and testing procedures were chosen to simulate current field practices in the Midland area in west Texas. Figure 1 is a schematic of the testing apparatus. The tubular material chosen was 7 in., 23 lb/ft, J-55 casing with a flat mild steel plate welded on one end. A joint of 10.75-in. OD by 0.188-in. thin wall tubing was centered around the 7-in. casing and welded to the bottom plate, forming a 1.69 in. annular space for the cement slurries. The 10.75-in., thin wall tubing served only to hold the cement in place and is not a component of normal completions.

Cement Compositions

The following is a summary (see Table 1 and Table 2) of each of the cement compositions tested for specific application.

Slurry A: This slurry is a cementing composition incorporating microfine silica (MFS) to a standard cement slurry. This slurry will meet Texas Railroad Commission strength requirements for surface pipe and critical zone applications.[9] Cement compositions are typically mixed at densities of 11.6 to 12.2 lb/gal and can develop in excess of the required 250 psi compressive strength in 24 hours for a surface pipe, and a composition mixed at 12.4 lb/gal can develop 1200 psi in less than 72 hours.

Extensive surface area (150,000 cm^2/kg) of the MFS provides for a wide range of water extension at a fixed concentration while maintaining little or no free water. MFS generally is more efficient in slurries of high water-to-cement ratio. In slurries of normal density, compensation for viscosity increases caused by addition of MFS can be made by adding dispersants or extra water.

Slurry B: This slurry is a standard pozzolan:cement (50% pozzolan by volume) slurry mixed at 13.8 lb/gal. Pozzolan or (fly ash), which has been used in cementing compositions for many years, hydrates with lime and water to produce a cementitious material. At temperatures below 140°F the reactions are slower than portland cements. The advantages of pozzolan cements are lower cost, lighter weight and strength stability at higher temperatures. This slurry is commonly used as both a lead and tail cement in west Texas.

Slurry C: This composition is also a pozzolan-cement system but with only 25% by volume pozzolan. This slurry was mixed at a density of 12.5 lb/gal to provide a contrast with Slurry B. Both Slurries B and C are typical filler type cements used in cementing surface casing where high strength cements are not required. Compressive strength, if need be, can be adjusted by changing the water-to-cement ratio.

Slurry D: This is a conventional slurry design for a tail cement (Class H-neat). Typically this slurry composition is used across most production intervals in shallow applications where high strength is generally considered to be an advantage. The small amount of bentonite was included to eliminate any free water breakout of the cement slurry while static and before set. This composition was used as a control to compare with the results of the other slurries. Class C neat cement, which is also used as a tail cement, would be presumed to have physical properties similar to Class H.

Slurry E: In some well conditions it is desirable to produce extremely lightweight cement slurries while providing relatively good strength. This cement composition is a foamed cement at a density of 9.9 lb/gal. Applications of foamed cement systems have been increasing over the last few years.[9] Particularly in west Texas, application of foam cement have been very successful in areas that exhibit lost circulation over extremely long intervals, formation of gaps in annular fill, water aquifers, inadequate bonding to shale and salt formations, persistent annular gas flow from pressured gas zones, and cement fall back due to excessive hydrostatic pressure exerted by the cement column. Foam cement has been effectively used as a solution for these problems in field operations.

Slurry Mixing

All slurries tested were batch mixed in a 20 gal tank equipped with a bulk agitator and a high shear dispersator. Slurries A, B, C, and D were mixed by adding the dry material with the mixers operating at about 50% power. After all materials were added the slurries were mixed at 100% power for 2 minutes. Slurry E was mixed as outlined above except a recirculating pump was used to circulate slurry from the bottom to the top of the batch mixer. Surfactants were added and nitrogen was injected into the circulation system until the volume increased to a predetermined level. This produced a uniform foam within the density guidelines desired. The cementing compositions were blended and poured into the annular space around the test fixtures. The cemented test fixtures were then cured under water for three days at 100 psi curing pressure. Samples of the slurries were poured into standard cube molds and crush tests were performed after six days. Core samples of the cement specimens were also taken for strength measurement after perforating.

Perforating Specifics

Test fixtures were perforated after curing for six days. Table 2 gives the compressive strengths at the time of perforation for each of the slurry blends. These compressive strengths are the average of the lab stored samples and the core sample taken from the specimens.

The perforating gun was a 4 in. casing gun, centralized with 90 degree phasing. Four shots/ft (spf) were fired simultaneously with 22 gm charges designed to generate a 0.42 in. diameter perforation in 7 in. casing.

It should be noted that the procedure was specifically designed to duplicate typical field conditions and to determine the amount of cement sheath shattering and hole enlargement that occurred while perforating.

DISCUSSION OF RESULTS

The test fixture schematic is shown in Fig. 1. Perforations are referred to as No. 1 (top) through No. 4 (bottom). The cement sheath thickness was 1.69 in. The five cement blends are referred to as "A" through "E" as noted in Tables 1 and 2. The test fixtures were perforated 4 spf, leaving a 3 in. vertical height between perforations. A horizontal band saw cut was made 2 in. above the top perforation, and 2 in. below the bottom perforation (Fig. 2). Cuts between perforations were 1.5 in. above or below the respective perforations.

A visual examination found no cracks or shattering of the cement 2 in. above the top perforation or 2 in. below the bottom perforation on <u>any</u> test cement blend. Note the band saw cut above perforation "D1" in Fig. 2. In addition, no cracks were found between perforations Nos. 1 and 2, between 2 and 3, or between 3 and 4 on four of the five cement blends. An example photo is shown in Fig. 2. The exception was cement blend "D," with 6 day compressive strength = 2076 psi. The vertical distance from the centerline of the perforation tunnel to the horizontal band saw cut was approximately 1.5 in. Small cracks in the cement along the band saw cut were noted directly above and below the perforation tunnels on the inside band saw cuts (between perfs 1-2, 2-3, 3-4). Note the hairline fractures in Fig. 3 above and below perforation D-2. On the top and bottom band saw cut 2 in. away from the top and bottom perforation, no cracks were found even on the cement Slurry D.

The photos in Fig. 4 illustrate metal castings of the perforation through the cement sheath. The metal castings were poured directly in the perforation tunnels to obtain a permanent mold of the perforation. The mushroom shaped head shown in Fig. 4 was caused by "splash back" from the jet charge hitting the 10.75 in. OD tubing. Theoretically, the mushroom would not be indicative of the actual perforation tunnel diameter, unless the formation is highly resistant to penetration by the perforation charge.

Table 3 shows the perforation tunnel diameter measured 1 in. outside from the surface the 7-in. casing. It is interesting to compare Table 3 with Fig. 4. The diameter of the perforation tunnel serves to indicate the relative hardness of the cement or the shock absorbing ability. The harder slurry "D" has a relatively small tunnel, but an examination of the mushroom head on casting "D" leads to the conclusion that the harder cement "blunted" the plasma of the jet charge. This conclusion is supported by Fig. 3, in which the 10.75-in. OD tubing is split around the perforation exit. The jet appears to have been blunted enough that pressures built up to the point that the outside tubing split immediately around the perforation exit. The phenomenon of the outside tubing splitting is not evident in Fig. 2 (Slurry "E," foam cement). Referring to Fig. 4, the foam cement perforation tunnel is much larger and the mushroom head is relatively small showing that less resistance to perforating was encountered as the jet penetrated the cement.

RECOMMENDATIONS AND GUIDELINES

Lightweight cements investigated in this study can be used not only to minimize fallback and lost circulation, but can also allow adequate sealing after perforating. These slurries could be used to cement liners from top to bottom which would reduce logistics and possible costs. Some operators in the Midland area have placed foam cement across a zone that was later considered for production and perforated with good results. The foam and microfine silica cements tested can be designed to meet Texas Railroad Commission requirements.

A uniformly cemented annulus is even more critical in lightweight slurries. A good bond to the formation provides substantial backup for the casing and reduces damage when perforating. Cementing practices that improve cement displacement of the drilling fluid should be employed to help provide maximum backup for perforating and no communication problems after cementing.

CONCLUSIONS

Based on these tests the following conclusions are made:

1. The lightweight cements tested performed well even when perforated by large diameter, high density perforators, i.e., 4 spf, with 22 gm charges.

2. Lightweight cements can be used across production intervals and perforated with minimum damage to the cement sheath or formation.

3. Lightweight cements tested did not produce perforation tunnels large enough to be a problem in field operations.

4. Job logistics can be simplified and costs reduced by cutting the number of lightweight cement and tail cement blends on critical jobs, i.e., cement entire job with lightweight cements such as microsilica, foam cement, or any lightweight pozzolan cements used in this study.

5. Foam cement, which traditionally has not been used for perforating, should be considered. Foam cement appears to absorb the shock of perforation without losing structural integrity.

6. No shattering occurred when the compressive strength was below 2000 psi. Only minor shattering occurred on normal density cement with a compressive strength of 2076 psi.

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Table 1
Cement Slurry Compositions

A. Slurry A - Class H cement + 39% Microfine silica + 7% Gilsonite + 1% $CaCl_2$ + 0.4% CFR-2 + 12 lb/sk salt mixed at 12.1 lb/gal.

B. Slurry B - 50:50 Pozzolan:Class H cement mixed at 13.8 lb/gal.

C. Slurry C - 75:25 Pozzolan:Class H cement + 6% gel mixed at 12.5 lb/gal.

D. Slurry D - Class H cement + 0.5% gel mixed at 16.1 lb/gal.

E. Slurry E - Class H cement mixed at 14.9 lb/gal foamed to 9.9 lb/gal.

Table 2
Compressive Strength Data

Slurry	Slurry Density (lb/gal)	Day 6 Compressive Strength Crush	Day 6 Compressive Strength (UCA)
A	12.1	745	1180
B	13.8	454	1020
C	12.5	444	650
D	16.1	2076	3430
E	9.9	795	ND

NOTE: UCA (Ultrasonic Cement Analyzer) tests were at room temperature (70-78°F), perforating models were cured at 60-70°F.

Table 3
Compressive Strength Tunnel Diameter Comparison

Slurry	Compressive Strength (psi)	Tunnel Diameter (in)
A	745	1.47
B	454	1.56
C	444	1.67
D	2076	0.96
E	795	1.53

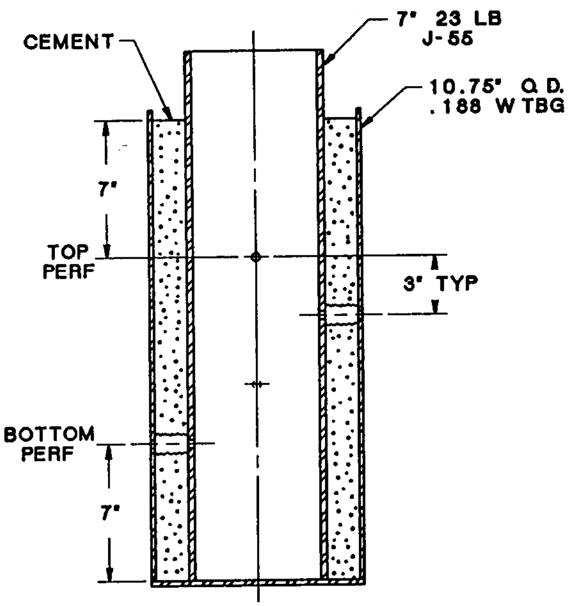

Figure 1 — Test fixture cross section

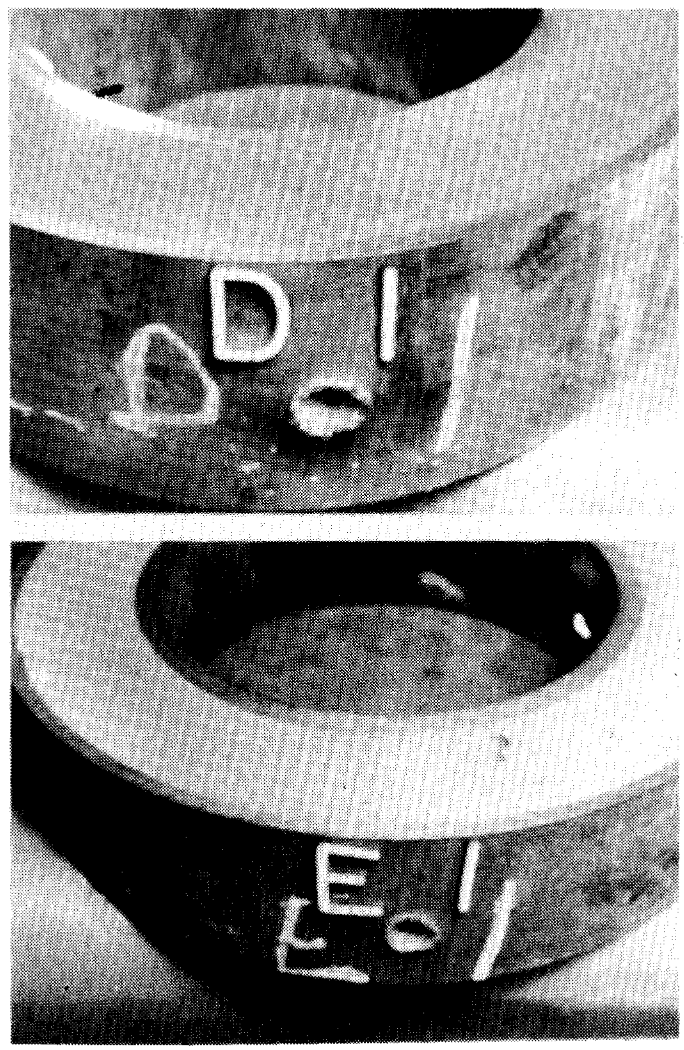

Figure 2 — Perforated samples

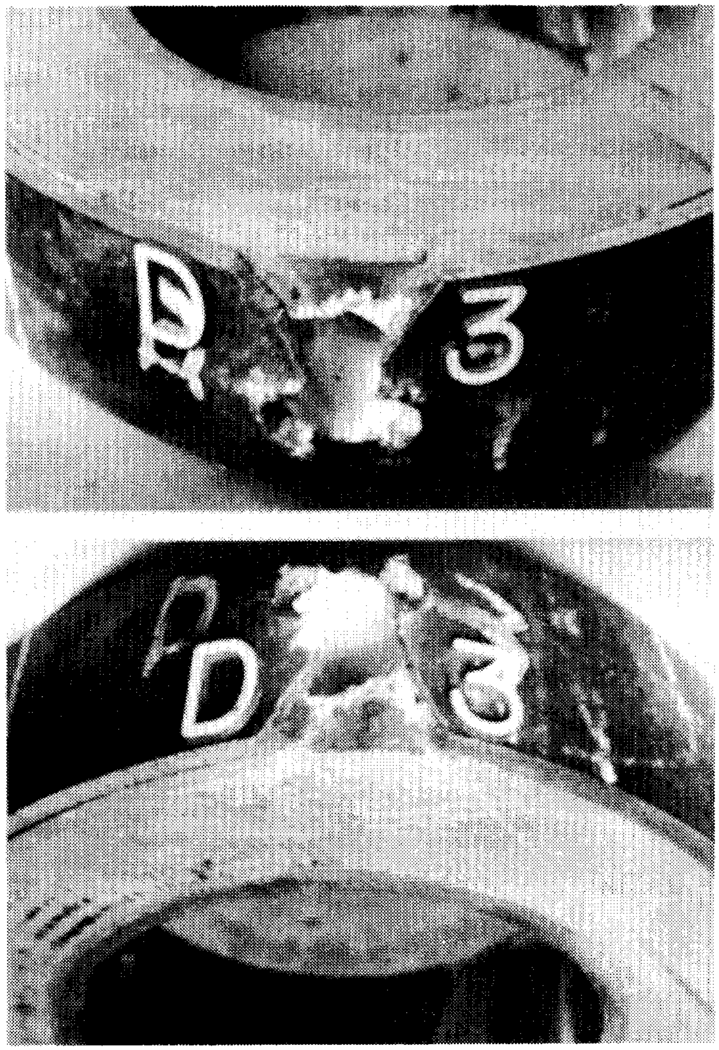

Figure 3 — Perforated samples

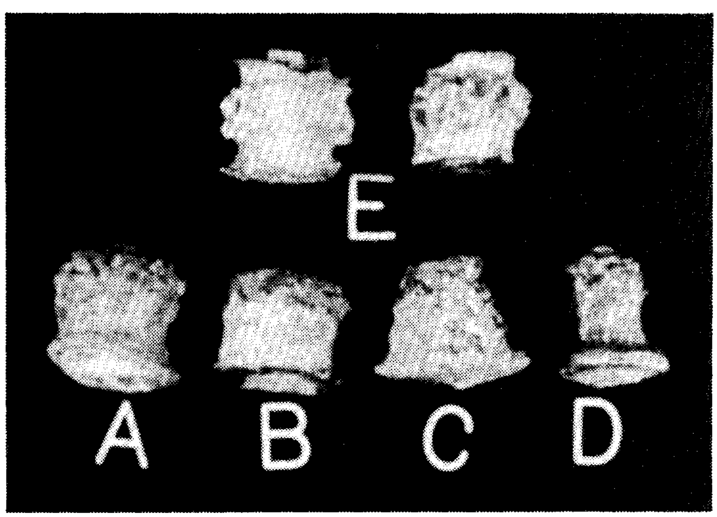

Figure 4 — Metal castings of
perforation tunnels