CARBON DIOXIDE CORROSION RESISTANCE IN CEMENTS

Rod Bruckdorfer

Dowell Schlumberger

ABSTRACT

Carbon dioxide corrosion studies of oil-well portland cements were initiated using a new microsample technique to determine the effect of carbonic acid on portland cement slurry formulations and to develop a high carbonic acid corrosion-resistant cement for carbon dioxide Enhanced Oil Recovery applications.

Earlier results from studies using two-inch API cement cubes showed carbonic acid had essentially no effect on cement after relative short test periods at elevated temperatures. Similar results with two-inch API cement cubes also were reported in recent literature. Because carbonic acid corrosion in cements was difficult to observe and measure using two-inch API cement cubes, a new microsample technique was developed. Use of this new technique, which represents an accelerated testing method, showed oil-well cements undergo a rapid deterioration in a wet carbon dioxide environment. Similar tests with two-inch cubes showed essentially no cement deterioration under the same conditions.

Experimental details of this new microsample technique are discussed. Data relating cement strength loss and carbon dioxide penetration depths to cement type and slurry formulation are reviewed. Included in the discussion is a new cementing formulation which shows significant promise as a high carbon-dioxide-resistant, oil-well cement.

INTRODUCTION

Carbon dioxide Enhanced Oil Recovery applications have seen a surge of activity in the last several years. Of the 40 projects that are estimated to be underway, 20 are in Texas and 7 are in the Gulf Coast region, while the remaining are distributed throughout the midwest and western states.

Although the carbon dioxide Enhanced Oil Recovery process and carbon dioxide corrosion in oil and gas production are well documented in the literature,[1] very little published information is available on carbonic acid corrosion in oil-well cements.[2] However, the corrosion of cement structures by the leaching action of the carbon-dioxide-laden waters is well documented in the literature.[3] It is well known that carbon-dioxide-laden water can reduce hydrated portland cement to a soft amorphous silica gel.[4]

The basic chemistry describing this process is as follows.

(1) $CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$

(2) $CaOH_2 + H + HCO_3 \rightarrow CaCO_3$

(3) $C\text{-}S\text{-}H + H + HCO_3 \rightarrow CaCO_3 + \text{amorphous silica}$

In Step (1), approximately 1% of the dissolved carbon dioxide reacts with water to form carbonic acid.[5] As the carbon-dioxide-laden water diffuses into the cement matrix, the dissociated acid is free to react with the calcium hydroxide, which makes up 20% of the cement composition, and the hydrated calcium silicates (Steps (2) and (3), respectively). If the reaction would stop after the initial carbonation of the calcium hydroxide, the cementitious calcium carbonate formed would cause an increase in compressive strength. Although a strength increase is observed, as more carbon-dioxide-laden water invades the matrix, several new equilibria are established.

(4) $CO_2 + H_2O + CaCO_3 \rightleftharpoons Ca(HCO_3)_2$

(5) $Ca(HCO_3)_2 + Ca(OH)_2 \rightleftharpoons 2CaCO_3 + H_2O$

In the presence of excess carbon dioxide (Step 4), the calcium carbonate is converted to water-soluble calcium bicarbonate. As more carbon-dioxide-laden water enters the matrix, the equilibrium is moved to the right. The end result is more water-soluble calcium bicarbonate which can diffuse out of the matrix. As the calcium bicarbonate forms, another equilibrium reaction is established (Step 5). The dissolved calcium bicarbonate reacts with more calcium hydroxide to form calcium carbonate and "fresh water." The importance of (Step 5) is that the fresh water formed in the cement matrix is now available to dissolve more calcium bicarbonate. Providing there is a continuing supply of carbon-dioxide-laden water, the reactions will continue to leach cementitious material from the matrix. As the process continues, an increase in permeability and porosity occurs. The end result is an amorphous silca gel that lacks structural integrity.[5] Downhole, this equates to a loss of casing corrosion protection and zonal isolation.

Because of the potential problems that are inherent in cements in a wet carbon dioxide environment, such as that found around a well in a carbon dioxide Enhanced Oil Recovery WAG project, this study was initiated to investigate the effects of wet carbon dioxide on oil-well cements and to determine if portland cements could be made more resistant to carbonic acid attack.

EXPERIMENTAL

Sample Preparation

To study the effects carbonic acid has on hydraulic portland cements, three sample geometries were investigated over the course of the experiments. In the first phase, two-inch API cubes were used, whereas the second phase utilized one-inch-diameter cylindrical samples. Based on the data gained in the first two phases, sample geometry was changed to microcylindrical. The end result was that carbonation effects were observable over relative short exposure periods compared to cubic and macrocylindrical cement samples. Because the use of cubic cement samples was limited to one data set, only the preparation of the macro- and microcylindrical samples is discussed.

The 1-in. OD x 2-in. macrosamples were cast using a 50-cc disposable plastic syringe as a mold. Before preparing the cement slurry and casting the sample, the plunger was removed and the syringe tip was sealed. All cement slurries tested were prepared according to API Specification 10, Section 5, using distilled water. Before mixing the slurry, a defoaming agent was added to the mix water to reduce air entrainment. The cement samples were cast by slowly pouring the slurry down one side of the syringe barrel, then puddling the cement with a stirring rod (API Specification 10, Section 5) to remove any trapped air. After sealing the syringe with a rubber stopper, the samples were cured for 72 hr at 3,000 psi and 175°F. The samples were demolded by cutting of the syringe's tip end, placing the mold in warm water to expand the plastic and pushing the cured cement cylinder out of the barrel with a syringe plunger.

Microcylindrical cement samples were prepared from 2-in. API cubes which were machined and cored to produce a 0.275-in. OD x 0.5-in. cylinder. To make a set of samples, the cement systems were prepared as described above and cast into 2-in. API cubes. Curing conditions were 72 hr at 3,000 psi and 175°F. After demolding the samples, each cube was machined into a 2-in. x 2-in. x 1/2-in. cement blank by first removing about a 1/2-in. thick section from the top and bottom of each cube to form a rough 2-in. x 2-in. x 1/2-in. blank, then milling the major faces flat and parallel to each other. After sealing the faces with a suitable polymer to eliminate possible end effects, nine 0.275-in. OD x 0.5-in. samples were cored from each blank.

SAMPLE CARBONATION

Cement carbonation was done under static conditions using a modified water-filled autoclave. Although both static and dynamic conditions exist downhole, most of the cement sheath at the formation interface is experiencing an essential static carbon dioxide exposure. The only exception is the immediate area around the perforations which is under a dynamic state during both gas and water injection. The main advantage to dynamic testing is that carbonic acid movement to the surface of the cement sample is not dependent on diffusion through water. Because the rate of carbonation in cement is diffusion controlled, moving the carbon-dioxide-laden water over the sample most probably accelerates the corrosion rate by replenishing the carbon dioxide at the cement surface, but is not necessarily representative of actual downhole conditions. Hence, the simpler approach, i.e., static carbonation, was selected for the cement carbonation experiments.

Cement samples were carbonated by loading them in the autoclave in a sample holder. After filling the chamber with water and sealing, liquid carbon dioxide was injected into the water using a sparge tube connected to a carbon dioxide tank until 900 psi was recorded. The test chamber was recharged ever two to three days over the four- to six-week carbonation period. Temperature and pressure were maintained at 175°F and 3,000 psi. To eliminate any effects temperature and pressure had on the results, a second autoclave was used for a control sample set. This was run under the same conditions as the test set except that the chamber was not charged with carbon dioxide.

CARBONATION MEASUREMENTS

Carbonic acid corrosion effects on the macrosample sets were determined using compressive strength and carbonation penetration depth measurements, whereas only compressive strength measurements were used for the microsample sets. Compressive strengths of the 1-in. OD x 2-in. samples were measured by first cutting off one-half inch of each cylinder end, then milling the end surfaces perpendicular to the cylinder's axis. This was done to remove any deteriorated cement at the sample ends and to ensure that the cylinder was perpendicular to the instrument's platens, both of which cause scattering in the test results. Compressive strengths were determined using a Baldwin instrument. Because the length-to-diameter ratio was less than two, the resultant strengths were multiplied by 0.91 to obtain corrected compressive strengths (ASTM Standard C42 - 68).

The depth the carbonic acid penetrated into the cement was determined by staining the freshly cut end of a cylinder with a 1% phenolphthalein solution. By measuring the unstrained area, which indicates no calcium hydroxide is present in the cement matrix, the depth of carbonic acid invasion into the matrix was determined.

Microsample compressive strengths were determined on an Instron 1123 instrument. Prior to the use of this method, research showed that providing the length-to-diameter ratio of the cement microcylinder was greater than a given value, the compressive strength measured was equal to that obtained from a 2-in. cement cube according to API Specification 10, Section 7, when using the Instron compressive/extension test machine. At least three samples were tested and the average strength reported for each cement formulation per sampling period. Since each cylinder's ends were protected with a polymer coating, creating a cylinder of pseudo-infinite length, effects which cause data scattering were essentially eliminated.

RESULTS AND DISCUSSION

Results from the first two phases of this study indicated that the cement mass of a macrosample, i.e., 2-in. cubes and 1-in. diameter cylinders, was too large for the relative short carbon dioxide exposure period to show significant cement deterioration in the samples. Compressive strengths of the carbonated cements compared to the control samples showed no decrease in strength or observable deterioration on the cement surface. Carbonic acid penetration depth into the cement matrix, although measurable, was in all cases insignificant.

As an example, Figures 1 and 2 show compressive strength of a Class H cement and a 50% fly ash/Class H cement as a function of slurry density. Comparison of the carbonated curves to the control curves shows essentially, within the experimental error of the method, no decrease in strength after a 31-day carbonation period at 175°F and 3,000 psi. Although no change in compressive strength was observed, carbonation depth measurements showed that as cement density increased carbon dioxide penetration decreased (Table 1). It is interesting to note that in all cases, except for the 17-lb/gal systems, that the carbon dioxide penetration depth for the fly ash/Class H systems was three times greater than the straight Class H cements. Similar results were obtained when Class A and C cements were compared to a Class H cement mixed at 15.6-lb/gal (Table 2). There was no significant difference in carbon dioxide penetration rates between the three systems. Comparison of the compressive strength of the carbonated samples to those of the control, in all cases, showed no decrease after an exposure period of 31 days at 175°F and 3,000 psi. Although carbonation was observed in the samples, it was concluded that to get meaningful results the carbon dioxide exposure period would have to be increased or the cement sample mass reduced. The latter of the two choices was chosen because sample turnaround would be relatively fast compared to that projected for the macrosamples. Based on the carbon dioxide penetration rates in the macrosamples, a 0.275-in. x 0.5-in. cylindrical samples geometry was calculated to undergo complete carbon dioxide penetration within a four- to six-week exposure period at 175°F and 3,000 psi.

To determine if the conclusion made from the macrosample data was correct, a set of cement microsamples was prepared and tested (Set No. 1). Results from the initial test set showed that oil-well cements deteriorate in the presence of carbonic acid and the use of microsamples represented a pseudo-accelerated method of testing the corrosion resistance of cement formulations to carbonic acid attack. Test conditions were 175°F and 3,000 psi. Exposure period was six weeks with sampling periods at three and six weeks. All cement slurries were mixed at 15.0-lb/gal density. The results were reported as percent strength loss compared to the compressive strength of the control sample set. As shown in Table 3, hydraulic portland cements deteriorate in the presence of carbonic acid. Both Class H and Class C cements underwent an 80% strength loss after six weeks of exposure time. As was indicated in the macrosample carbon dioxide penetration data, increasing the cement density, i.e., increasing cement-to-water ratio, decreased the rate of carbon dioxide corrosion (Table 4). Changing the cement to water from 1.88 to 2.36 by weight improved the corrosion resistance of the cement by about 25% (Table 4). Because high cement-to-water ratio slurries require a dispersant to improve pumping, the effect a dispersant would have on the corrosion rate was studied. As indicated by the data (Table 5), addition of up to 1% dispersing agent by weight of cement has essentially no effect on the carbon dioxide corrosion rate. Salt containing cement slurries were also investigated in the study. The initial data indicate that addition of up to 37% salt has no effect on the cement's resistance to carbon dioxide attack compared to that of a neat cement slurry of the same density (Table 6). In all cases, about an 80% strength loss resulted from carbonic acid attack. In view of the findings of this study which indicated that carbon dioxide corrosion of the casing cement sheath downhole may be real and pose zonal isolation and casing corrosion problems over the life of the well, a second experiment was initiated using the microsample method.

The objective of the second set of experiments was to determine how various additives affect carbonic acid resistance in cements and to develop a high carbon dioxide resistant oil-well cement for carbon dioxide Enhanced Oil Recovery. Marynell Class H cement, which is common to the Permian Basin area, was used in all cement systems. Except for the density study, all cement slurries were mixed at 16.0-lb/gal density. Carbonation was at 3,000 psi and 175°F for an exposure period of six weeks. Results were reported as percent strength loss as compared to the control samples which were run under the same condition, except in the absence of carbon dioxide. Because of several shutdowns during carbonation, each set of experiments, i.e., Set No. 1 and Set No. 2, should be considered independent of each other and only relative comparisons made between the two data sets to avoid introducing any determinate errors into the study. Sampling periods were at zero, three and six weeks. As was shown in the last study, increasing the cement-to-water ratio increased the carbon dioxide resistance of the cement (Table 7). As cement density was increased from 15.0 to 17 lb/gal, percent strength loss went from 100% to 54%. Although there is a small apparent decreasing difference in carbonic acid resistance between the 16- and 17-lb/gal slurries, within the experimental error of the method, increasing the cement density from 16.0 to 17.0-lb/gal had no real effect on the carbonic acid resistance of the cement based on a six-week exposure period. The opposite was observed in the three-week data. A 3% increase in resistance was observed for the 17.0-lb/gal compared to the 16.0-lb/gal system. The two conflicting trends suggest that a 3% difference in data is most probably due to experimental error. Addition of fly ash to the cement mixture had no effect on reducing the leaching action of carbonic acid. A fly ash/cement admixture containing 35% and 50% fly ash was prepared at 16.0-lb/gal density and compared to a neat 16.0-lb/gal cement system. Although the three-week data showed improved resistance to carbonic acid leaching in the 50% fly ash/cement admixture, at the end of the six-week exposure period the percent strength loss in the fly-ash systems was higher than the neat cement system (Table 8). A 66% and 57% strength loss was recorded for the 35% and 50% fly-ash systems, respectively; whereas, a 51% strength loss was recorded for the neat cement slurry. Even assuming a (+) or (-) 3% error in the measurements, the data indicate that fly ash/cement admixtures are as susceptible to the action of carbonic acid leaching as a neat cement. This finding supports the macrosample data which showed that a 50% fly ash/cement admixture at 14.0-lb/gal and 15.6-lb/gal density had three times as high a carbon dioxide penetration rate as the corresponding neat cement (Table 1). Although the addition of fly ash decreases the permeability of cement, which should decrease carbonic acid diffusion into the matrix, a corresponding decrease in the cement-to-water ratio occurs. As an example, a neat cement mixed at 16.0-lb/gal density has a cement-to-water ratio of 2.37 by weight; whereas, addition of 35% and 50% fly ash (mixed at the same density) decreases the ratio to 1.90 and 1.62, respectively. This suggests that a high cement-to-water ratio is as important as low permeability in controlling the leaching action of carbonic acid in the cement matrix. A third factor controlling carbon dioxide corrosion is the ability to "react-up" the calcium hydroxide in the cement matrix, thus decreasing its availability to react with the carbonic acid. This is shown in Table 9. Because silica sand or flour does not easily react with calcium hydroxide below 230°F, addition of 35% silica lowers the cement-to-water ratio to 1.91 when mixed at 16.0 lb/gal density without reacting with the calcium hydroxide in the cement. Compressive strength loss was on the average 20% to 25% higher than the corresponding neat cement or fly ash/cement admixture (Tables 8 and 9). It is interesting to note that addition of a fluid-loss additive has essentially no effect on the end results. The abnormality in the three-week data in Table 9, i.e., the 6% value, at present is attributed to a sampling error. Based on these data, it was hypothesized that a cement having a high cement-to-water ratio, low permeability and no free lime would give the best resistance to carbonic acid corrosion.

To test this theory, magnesium chloride was used to prepare a chemical cement admixture. As reported by Manmohan and Mehta,[6] magnesium chloride, corresponding to 2% anhydrous salt by weight of cement, reduces the pore volume and permeability of cement pastes. The cement slurries were mixed at 16.0 lb/gal (2.37 cement-to-water ratio). As shown in Table 10, addition of 2.5% and 5.0% anhydrous salt resulted in 24% and 9% strength loss, respectively, compared to 33% for a 0% magnesium chloride system after three carbonic acid exposures. Although an improvement in carbon dioxide resistance was observed after three weeks, the six-week results showed a marked increase in strength loss. The 2.5% system lost 49% of its compressive strength compared to 51% for the 0% system; whereas, the 5% system lost 75% of its strength (Table 10) at the end of the six-week test period. Because of the limited data and the marked increase in strength loss after six weeks, it is difficult to make a definitive conclusion regarding the proposed theory. Certainly, the three-week results tend to support the theory that a high cement-to-water ratio and a low-permeable matrix decrease the leaching action of carbonic acid in cements.

During the course of this work a serendipitous discovery (which supports several of the findings in this study) resulted in the development of a cement formulation that exhibits a high degree of resistance to carbonic acid attack. Compared to the neat Class H slurry, the XP-1 cement admixtures are on the average 45% more resistant to the action of carbonic acid leaching (Table 11). At the end of the six-week test, the Class H system had a 51% strength loss, whereas the XP-1 formulations on the average lost 29% of their compressive strengths. An explanation for the improved resistance is suggested in the three-week data. In all cases, the XP-1 systems showed an increase in compressive strength. This is due to the presence of calcium carbonate in the cement matrix. Because calcium carbonate is cementitious, a resultant increase in compressive strength occurs; most important, however, the presence of the carbonate indicates that the diffusion of carbon-dioxide-laden water into the matrix was decreased. Subsequently, the equilibrium reaction that changes calcium carbonate to water-soluble calcium bicarbonate is occurring at a slower rate compared to the neat Class H formulation. If this were not the case, a decrease in strength would be observed.

CONCLUSIONS

The objectives of this study were to determine the effects a wet carbon dioxide environment had on portland-base, oil-well cements and to develop a more resistant cement to the action of carbonic acid leaching. Based on the data collected using microsamples, cements undergo a steady decrease in compressive strength and show a marked visual deterioration in the presence of wet carbon dioxide. Although a direct correlation between the laboratory data and an actual well, at present, cannot be made, the data suggest that a cement corrosion problem may develop over the service life of the well. As cementitious material is leached from the cement matrix to form an amorphous silica gel, casing corrosion protection and zonal isolation will be lost. Although carbon dioxide corrosion in portland cements is difficult to stop, cementing formulations are now available which resist the leaching action of carbonic acid. Under the conditions of most carbon dioxide flood projects, i.e., low temperature and pressure, the recommended completion material is the XP-1 formulated systems mixed at a cement-to-water ratio of 2.3 or greater. These completion materials are less susceptible to the leaching action of carbonic acid than the equivalent density neat cement or fly ash/cement admixture. Performance data show that XP-1 systems are 45% more resistant to carbon dioxide attack than either neat cement, 35/65 or 50/50 fly ash/cement admixtures of equivalent density.

In addition to the discovery and development of the XP-1 completion material, the study clearly demonstrates the advantages of using microsamples over macrosamples for carbon dioxide corrosion studies. As shown in the data, the use of microsamples provides a pseudo-accelerated method to test cements; whereas, information obtained from 2-in. API cubes and 1-in. diameter cylinders is limited and may lead to erroneous conclusions.

A summary of additional observations made during the course of this work is outlined below.

- Portland cements deteriorate in a wet carbon dioxide environment with loss of compressive strength and structural integrity.
- High cement-to-water ratio slurries improve carbon dioxide resistance.
- Addition of fly ash to cements does not improve carbon dioxide resistance.
- Standard cement additives in low concentration do not affect the cement's resistance to carbonic acid attack.
- Magnesium chloride admixtures improve short-term but do not improve long-term resistance.
- Addition of cement diluents, such as lost-circulation additives and silica (well temperature below 230°F), decreases carbon dioxide resistance.
- Initial data indicate that salt does not affect carbon dioxide resistance in cements.

Extrapolation of the carbon dioxide corrosion rates in cements observed in this study to a cement sheath downhole is difficult, but the findings may be indicative of potential corrosion problems that occur over the life of the well. The end result of such problems is a higher frequency of remedial workovers and lost production. In view of the findings of this study, the recommended cement compositions along with good cementing practices is a logical approach to ensuring a successful completion in an Enhanced Oil Recovery project.

REFERENCES

1. Newton, L. E. Jr., Hausler, R. H., eds.: "Carbon Dioxide Corrosion in Oil and Gas Production," Selected Paper, Abstracts, and References, National Association of Corrosion Engineers, Texas (1984).

2. Onan, D. D.: "Effects of Supercritical Carbon Dioxide on Well Cements," SPE 12593 (March 1984).

3. Biczok, I.: **Concrete Corrosion-Concrete Protection**, Chemical Publishing Co., Inc., New York (1967) 281-300.

4. Lea, F. M.: **The Chemistry of Cement and Concrete**, Chemical Publishing Co., Inc., New York (1971) 287-298.

5. Biczok, I.: op cit, 282.

6. Manmohan, D. and Mehta, P. I.: "Influence of Pozzolanic, Slag, and Chemical Admixture No. 1, Pore Size Distribution and Permeability of Hardened Cement Pastes," **Cement, Concrete, and Aggregates**, CCAGOP (Summer 1981) 3 (1),63-67.

Table 1
Carbonation Depth Measurements[†]
(One-Inch Diameter Cylinders)

	Slurry Density		
Cement Admixture	14.0 lb/gal	15.5 lb/gal	17.0 lb/gal
Class H	0.07 in.	0.03 in.	< 0.01 in.
Class H, 50% Fly Ash	0.23 in.	0.09 in.	< 0.01 in.

[†] 31-day carbonation period at 175°F, 3,000 psi.

Table 2
Compressive Strength and Carbonation Depth in One-Inch Diameter Portland Cement Samples

		Compressive Strength	
Cement[a]	Carbonation[b] Depth (in.)	Carbonated[b]	Control
Class A	0.067	6,220	5,970
Class C	0.054	6,150	6,420
Class H	0.083	5,040	5,820

[a] Slurry density = 15.6 lb/gal.

[b] 31-day carbonation period at 175°F, 3,000 psi.

Table 3
Portland Cement Strength Retrogression in Microsamples after Carbon Dioxide Carbonation at 175°F, 3,000 psi

Cement	% Strength Loss After Six-Week Carbonation
Portland C[a]	82
Portland H[a]	80

[a] Mixed at 15.0 lb/gal.

Table 4
Effects of Density on Portland Cement Strength Retrogression in Microsamples after Carbon Dioxide Carbonation at 175°F, 3,000 psi

Density (lb/gal)	% Strength Loss After Six-Week Carbonation
15	82
16	62

Table 5
Effect of D65 on Portland Cement Strength Retrogression in Microsamples after Carbon Dioxide Carbonation at 175°F, 3,000 psi

% D65[a]	% Strength Loss After Six-Week Carbonation
0.0	82
0.5	82
1.0	84

[a] Mixed at 15.0 lb/gal.

Table 6
Effects of Salt on Portland Cement Compressive Strength Retrogression in Microsamples after Carbon Dioxide Carbonation at 175°F, 3,000 psi

% Salt (BWOC)[a]	% Strength Loss After Six-Week Carbonation
0	82
18	86
37	82

[a] Mixed at 15.0 lb/gal.

Table 7
Effect of Density on Neat Portland Cement[a] after Carbon Dioxide Carbonation at 175°F, 3,000 psi

Density (lb/gal)	% Strength Loss	
	3 Weeks	6 Weeks
15	08	100
16	33	51
17	36	54

[a] Maryneal Class H cement.

Table 8
Effects of Fly Ash on Portland Cement Strength Loss after Carbon Dioxide Carbonation at 175°F, 3,000 psi

% Fly Ash[a]	Source	% Strength Loss 3 Weeks	 6 Weeks
0	--	33	51
35	La Due	36	66
50	La Due	24	57

[a] Slurry formulations were mixed with Maryneal Class H cement at 16.0 lb/gal density.

Table 9
Effects of 35% Silica Sand and Flour on Portland Cement Strength Loss after Carbon Dioxide Carbonation at 175°F, 3,000 psi

Silica[a]	% (BWOC)	% Strength Loss 3 Weeks	 6 Weeks
0	0	33	54
Sand	35	22	70
Flour	35	44	80
Sand[b]	35	06	56
Flour[b]	35	32	76

[a] Slurry mixed with Maryneal Class H cement at 16.0 lb/gal density.

[b] Slurry contained 0.5 gal/sk D108 fluid-loss additive.

Table 10
Effect of Magnesium Chloride on Portland Cement[a] Strength Loss after Carbon Dioxide Carbonation at 175°F, 3,000 psi

	% Strength Loss	
% Magnesium Chloride (BWOC)	**3 Weeks**	**6 Weeks**
0	33	51
2.5	24	49
5.0	09	75

[a] Maryneal Class H cement mixed at 16.0 lb/gal density.

Table 11
Strength Loss in Experimental Cement Formulations after Carbon Dioxide Carbonation at 175°F, 3,000 psi

	% Strength Loss	
Formulation[a]	**3 Weeks**	**6 Weeks**
Neat Maryneal H	33	51
XP-1A	-44	32
XP-1B	-55	26
XP-1C	-07	29

[a] Slurry mixed at 16.0 lb/gal density.

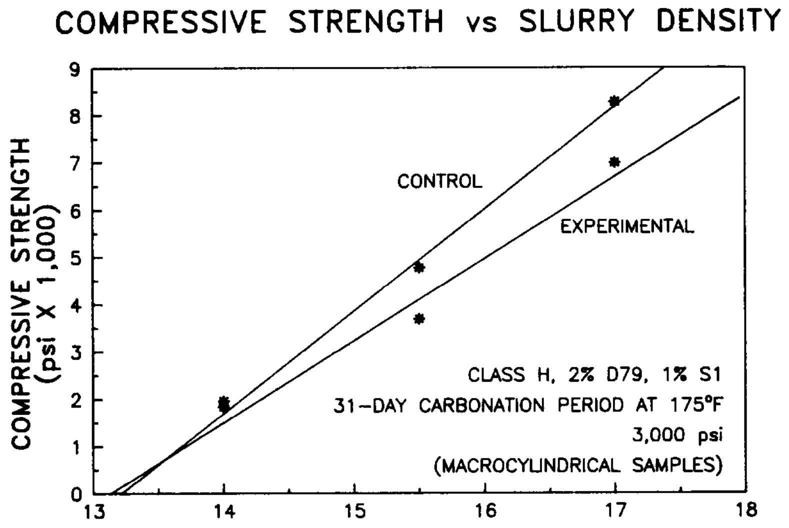

Figure 1 - Slurry weight (lb/gal)

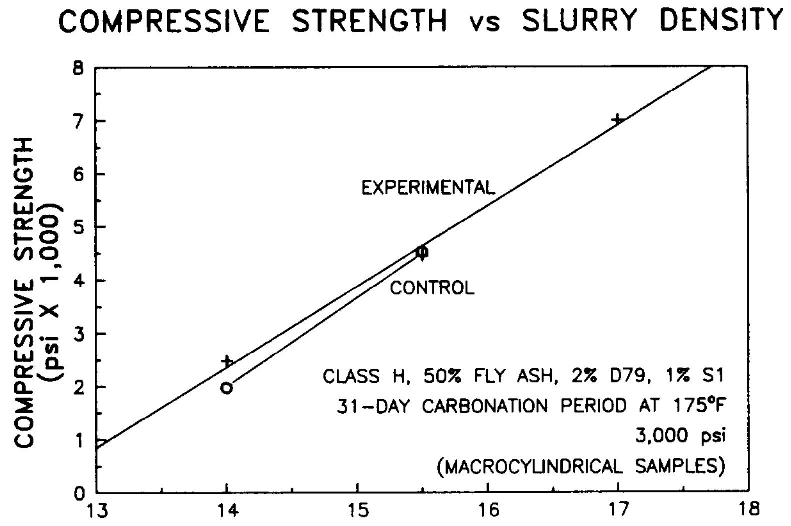

Figure 2 - Slurry weight (lb/gal)