

## Effects of Additives and Conditioning Time on Compressive and Shear Bond Strengths of Geothermal Well Cement

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**Key Words:** compressive strength, shear bond strength, conditioning time

### ABSTRACT

Waiting on cement in the cementing operation of geothermal wells is usually conducted from 8 hours to 24 hours after displacement of cement into an annulus of casing. After that, the quality of cement is evaluated using the CBL (Cement Bond Log) test. Evaluation results of the compressive strength and shear bond strength that is interpreted at 24 hours does not reflect the final strength of the cement.

The laboratory experiment for 7-day measurement indicated that extending additives to API class G cement could increase the compressive strength and shear bond strength of cement immediately for about 3 days. After that the compressive strength slightly changed or stable until the seventh day, whereas the shear bond strength still increased in lower level.

The experiment was carried out at a temperature of 150°C and pressure 2000 psi in a curing chamber that was contaminated with formation fluid of the Kamojang Field.

### 1. INTRODUCTION

Major problems that are usually encountered in geothermal well cementing are high temperature, high pressure, and corrosive formation fluid due to high concentration of minerals such as sulfate and bicarbonate and gas contents such as CO<sub>2</sub> and H<sub>2</sub>S. Chosen cementing materials and using special additives for suitable geothermal well condition are very important for the success of geothermal well completion. This requires knowledge of the correct cement materials relative to the conditions they will be used under. The cement of production casing experiences the most extreme conditions. The basic material of cement that is selected for the casing is usually API Class G cement. The material has high resistance of sulfate and contains 35% to 40% silica flour.

The strengths of cement are divided into compressive strength (CS) and shear bond strength (SBS). The stability of the strengths is required to support well performance during the well life. The properties of the basic materials of the cement may not be compatible with all conditions in the well. Therefore some additives should be added to improve the properties to fulfill the requirements.

This paper reports the amount of silica SSA-1 that should be added into cement slurry to raise the compressive strength and shear bond strength of cement to a certain level. Other additives also seem to affect the strengths. The strength of the cement is investigated for 7 days to study its stability.

### 2. GEOTHERMAL WELL CEMENTING

#### 2.1. Geothermal Well Condition

Geothermal reservoirs are usually naturally fractured reservoirs that have permeability more than 1 Darcy. The fractures consist of primary fracture and followed by secondary fracture in upper adjacent formation. The integrity of the formation rock ranges from poorly consolidated to highly fractured. The fracture gradient of the formation is low, so that lost circulation frequently happens. Temperature and pressure at the bottom hole may attain 300°C and 1800 psi respectively. Reservoir fluid is usually salt water with total dissolve more than 2000 mg/l. Vapor from the dry steam contains salt and H<sub>2</sub>S and CO<sub>2</sub> as well as low to high concentration of non condensable gas. Liquid from that contains a lot of carbonate and sulfate.

#### 2.2. Design of Geothermal Well Cement System

Damage to the geothermal wells is mainly caused by damage to the cement (Herianto, 1994). Research is required to obtain the appropriate cement composition to the geothermal well condition to cope with the problem.

In 1978 Brookhaven National Laboratory (Edward et al, 1982) determined the cement properties for geothermal well cementing as follows.

Shear bond strength to casing is more than 100 psi

Permeability is less than 0.1 mD

Compressive strength is more than 1000 psi after 24 hours placement

The strength does not decrease or the permeability does not increase after contaminating with 25% salt water or vapor at temperature until 750°F.

In addition to the above properties, the cement should be compatible with the drilling fluid and not be corrosive to the casing.

The use of cement at high temperature is treated by adding silica on portland cement. Silica flour with an average particle size of 15  $\mu\text{m}$  creates more stability. Eiler and Nelson in 1979 investigated the relation of silica particle size to the performance of API class G cement at several temperature levels, where the geothermal well contained 25000 mg/l TDS. They found that if silica particle size is more than 15  $\mu\text{m}$ , then compressive strength decreases and permeability increases (Eiler et al, 1983).

Portland cement suffers a serious problem due to the presence of carbonate in geothermal, where calcium silica hydrate is not stable in the chemical environment, even at

normal temperature (Taylor 1964). In the carbonate area, calcium silicate hydrate changes to calcium carbonate and amorphous silica. High alumina cement also experiences an alteration in carbonate area (Herianto, 1994).

Basically, the performance of cement is maintained by the placement of cement at a low ratio of C/S that has low permeability. This effort can be relied upon given normal geothermal condition, but in areas with high concentrations of carbonate, the performance is not affected.

### 2.3. Composition of Geothermal Well Cement

The composition of geothermal well cement is usually developed from that of oil well cement. The materials of cement used in a deep oil well with a bottom hole temperature (BHT) of 500°F may be applied in shallow geothermal wells with a BHT of around 600°F.

The high formation temperature after a long period may result in a compressive strength retrogression and permeability increasing, hence the function of the cement as an isolator of the casing from the formation decreases. The retrogression is characterized by composing tubermorite. Tubermorite may restrain the cement phase from alteration due to the high temperature effect. An additive such as perlite can be used to reduce density of the cement suspension in order to decrease hydrostatic pressure for controlling lost circulation during cementing. An appropriate retarder is chosen based on the actual temperature of the reservoir to adjust the waiting on cement (WOC). Cement friction reducer (CFR) is required in cement to facilitate the cement displacement. Table 1 shows the various cement slurries that are applied in geothermal wells.

### 2.4. Cement Retrogression

Portland cement, which contains primarily calcium silicate, if mixed with water can form a gel known as C-S-H gel. After this gel is crystallized, the produced material possesses high compressive strength and low permeability after cement hardening. At high temperature (higher than 110°C) the gel may change to alpha dicalcium silicate hydrate ( $\alpha$ -C<sub>2</sub>SH), which has reverse properties. The phenomena are known as "Strength Retrogression" (Swayze, 1954). Cement contamination at an earlier hardening process with formation fluid, which has high sulfate and bicarbonate contents, and gasses such as CO<sub>2</sub> and H<sub>2</sub>S can affect the strength of the cement.

The minimum strength that is recommended by API to continue drilling operation is 6.7 Mpa (1000 psi). The strength of the cement is expected to protect and support the casing to restrain high hydrostatic pressure, to isolate the casing from corrosive formation fluid, and to isolate inter permeable layers.

## 3. EXPERIMENTS

The cement strength experiments in the laboratory are conducted using curing chamber and hydraulic mortar. The curing chamber can condition cement at a high temperature and high pressure. Then the strength of the cement is tested by hydraulic mortar. The apparatuses used in the experiment are shown in Figures 1 and 2.

### 3.1. Effect of Silica and Conditioning Time on Cement Strength

In this experiment API Class G type HSR cement was used. The amount of silica SSA-1 was varied to determine the appropriate composition. The medium formation fluid was

obtained from Kamojang Field (West Java, Indonesia). The effect of extending additive on cement slurry is purposed to improve certain physical properties of the cement slurry. Extending silica flour can increase the cement strength at high temperatures (more than 110°C). Therefore, the experiment was conducted at temperature 150°C and pressure 2000 psi. Compressive strength was examined for conditioning at day 1, day 2, day 3, and at day 7. The diagram of the experiment is shown in Figure 3.

### 3.2. Effect of Alternative Cement Compositions and Conditioning Time on Cement Strength

Determining the suitable silica SSA-1 is purposed to obtain the percentage of silica with the most strength. Compressive strength of the cement suspension should be greater than 1000 psi as recommended by Brookhaven National Laboratory (Edward et al, 1982). Using the cement suspension with the most strength, the experiment was continued to investigate the effect of other additives such as retarder, accelerator, lost circulation material, and filtration reducer to the compressive strength and shear bond strength. The amount of the additives is varied. The three compositions of cement slurry that were used in the experiment are given in Table 2. The table shows that the densities that contributed by all components in the three cements are 1.9, 1.7, and 1.6. The same condition of operational temperature and pressure as set in the first experiment is applied i.e. 150°C and 2000 psi, respectively.

The formation fluid used in this experiment was obtained from three wells in Kamojang field i.e. KMJ-11, KMJ-14, and KMJ-17. The analysis of the formation fluids indicates that the compositions are composed by different percentages of their compounds. The compositions of the fluid obtained from the wells are shown in Tables 3 and 4.

## 4. RESULTS AND DISCUSSION

### 4.1. Effect of Silica and Conditioning Time on Cement Strength

The experimental results of compressive strength with various compositions of SSA-1 and conditioning times are shown in Table 5 or Figure 4. The experiment results indicate that compressive strength of cement are affected by both the percentage of SSA-1 and the conditioning time. The figure shows that the compressive strength of the cement slurry with 0% SSA-1 experiences a slight reduction. Since there is no SSA-1 contained in the cement slurry, the retrogression of compressive strength is merely resulted from contact with formation fluid under the experimental temperature and pressure condition. Extending SSA-1 into the cement can increase compressive strength from the first day. The compressive strength values change at the 7-day measurement. The obvious change of compressive strength happens within the first 3 days. After that the change tends to become small. The effect of 10% SSA-1 can be ignored since the curve tends to pile with the curve with 0% SSA-1. The effect of 20% SSA-1 is estimated to disappear immediately after 7 days. It is pointed out here that there is a critical percentage of SSA-1 to increase the compressive strength of cement. The effect of 30% SSA-1 is more than that of 40% SSA-1 for 7 days. However, the compressive strength of 30% SSA-1 slightly decreases after 3 days, whereas that of 40% SSA-1 slightly increases with time. It may be an optimum percentage of SSA-1 to attain the maximum compressive strength for the cement slurry.

#### 4.2. Effect of Alternative Cement Compositions and Conditioning Time on Cement Strength

The formation fluids that were obtained from the three wells KMJ-11, KMJ-14, and KMJ-17 contains Na, K, SO<sub>4</sub>, and SiO<sub>2</sub> and gases contents such as CO<sub>2</sub> and H<sub>2</sub>S. The substances may affect the cement quality significantly. Dissolved CO<sub>2</sub> in water can form H<sub>2</sub>CO<sub>3</sub> and disentangled H<sup>+</sup> and HCO<sub>3</sub><sup>-</sup>. When C-S-H gel reacts to H<sub>2</sub>CO<sub>3</sub> and H<sup>+</sup> to form CaCO<sub>3</sub> and H<sup>+</sup> and finally CaCO<sub>3</sub> and amorphous silica gel are formed that can break the structure of the Portland cement bond. CO<sub>2</sub> that reacts to calcium carbonate (CaCO<sub>3</sub>) change to form calcium bicarbonate [Ca(HCO<sub>3</sub>)<sub>2</sub>] that dissolved in water. Then, the calcium bicarbonate reacts to calcium hydroxide to form calcium carbonate and water. The released water can dissolve calcium bicarbonate that decreases the quality of the cement. In this case, adding Portland to the cement slurry can maintain the quality of geothermal well cement at high concentration of CO<sub>2</sub> in formation fluid.

Table 6 or Figure 5 shows that the change of compressive strength is strongly related to the density (specific gravity) of cement. Since the weight of SSA-1 is constant in the three cement slurries, this means that the other additives also contribute the change. Here, the compressive strength increases as the density increases. However the significant increase of the compressive strengths happens until the second day. After that the compressive strength tends to be constant with time.

The effect of the cement compositions to shear bond strength is shown in Table 7 or Figure 6. The figure indicates that the shear bond strength increases with time for 7-day measurement. The increase of the shear bond strength is approximately proportional in the first 3 days. After that the slope of the curves tends to decrease especially for cement with density of 1.9.

In designing proper cement for a geothermal well, the properties of the cement should be compatible to that of the environment of the well. Some additives may be added to the basic material of the cement. Since an additive may affect more than one property, extending some additives can result in complex effects. For instance, a retarder (HR-6L) is added to retard waiting on the cement but on the other hand it tends to decrease the cement's strength. Therefore, the cement properties should be controlled when several additives are added to the cement slurry.

#### 5. CONCLUSION

In order to increase the cement strength to a certain level, the appropriate amount of silica SSA-1 can be determined in a laboratory experiment. There is a critical percentage of SSA-1 to increase the compressive strength of cement. The density of the cement has a strong relation to compressive strength and shear bond strength. Therefore, extending other additives may change the strengths.

The conditioning period for the cement should be carried out for at least for 3 days since the significant change of the compressive and shear bond strengths of the cement happens over these days.

Since the compressive strength may decrease after 3 days, the shear bond strength still increases for 7 days, the special interest should be taken, concerning the compressive strength.

#### NOMENCLATURE

C	= CaCO <sub>3</sub>
CFR	= cement friction reducer
CS	= compressive strength
H	= hydrogen
HSR	= high sulfate resistance
S	= SiO <sub>2</sub>
SBS	= shear bond strength
TDS	= total dissolved solid
WOC	= waiting on cement

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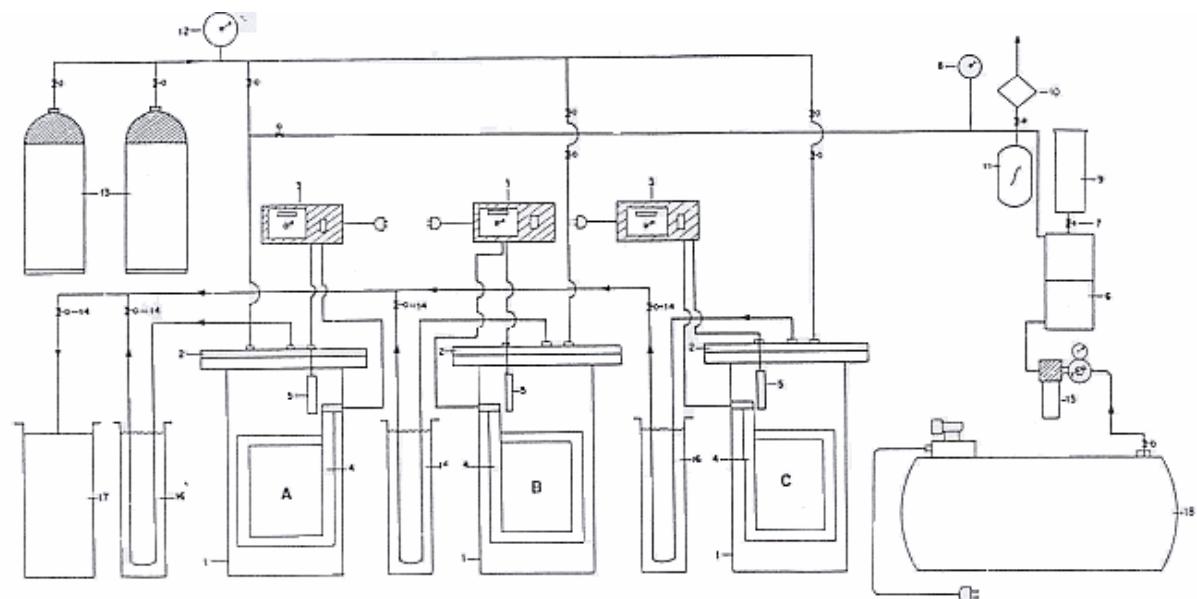


Figure 1. Schema of physical model that used to condition cement suspension (Herianto and Rudi, 1994)

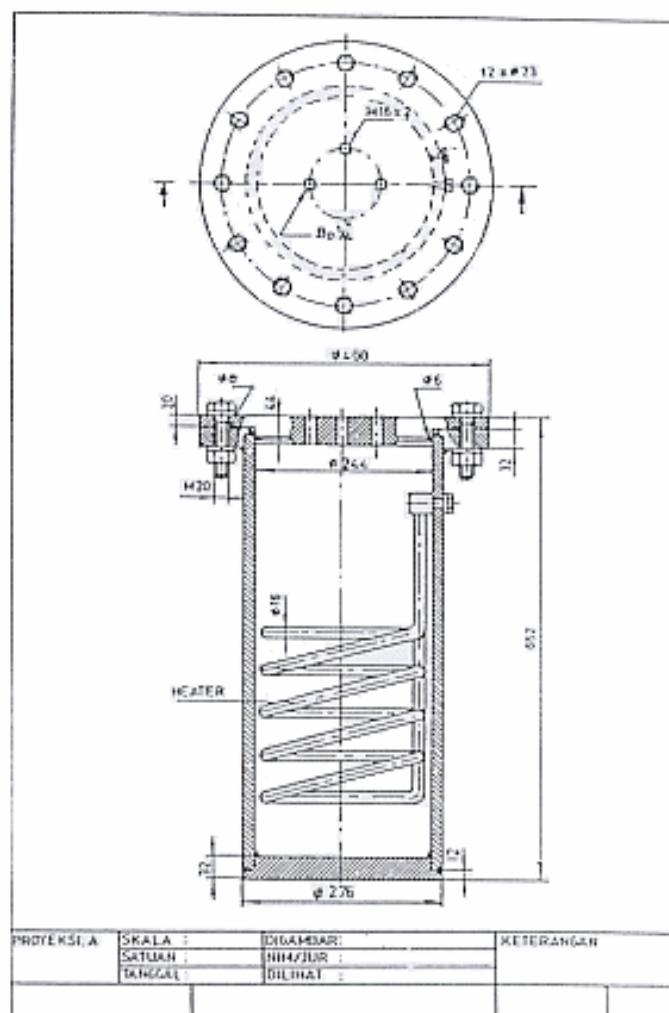


Figure 2. Simulator Chamber (Herianto and Rudi, 1994)

**Table 1 Compositions of geothermal well cement (Herianto, 1988)**

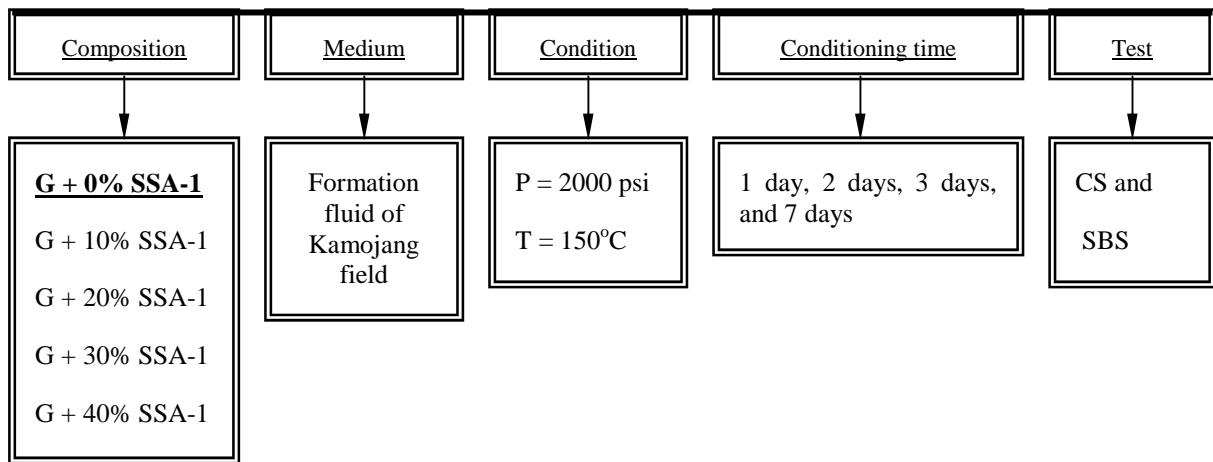
TYPE OF OPERATION	SLURRY NO.	CEMENT SLURRY USED	SLURRY YIELD CU.FT/SAK	SLURRY WT. LBS/CUFT
Surface Pipe	1	API Class "G" + 3% CaCl2	1.15	118
	2	API Class "G" + 40% SSA-1 + 2% CaCl2	1.62	116
Casing Job	3	API Class "G" + 1-1% Perlite + 40% SSA-1 + 3% Gel + 0.6% CFR-2 + Retarder	2.12	106
	4	Tall-In: API Class "G" + 40% SSA-1 + 0.6% CFR-2 + Retarder	1.62	116
Liner Job	3	API Class "G" + 1-1% Perlite + 40% SSA-1 + 3% Gel + 0.6% CFR-2 + Retarder	2.12	106
	4	Tall-In: API Class "G" + 40% SSA-1 + 0.6% CFR-2 + Retarder	1.62	116

**Table 2. Composition of cement suspension of Kamojang (KMJ) Field**

Composition	KMJ-11	KMJ-14	KMJ-17
Cement G, HSR, g	300	300	300
SSA-1, g	120	120	120
Pozzoland, g	-	75	150
Hallad -22A, g	1.75	2.5	2.4
CFR-2, g	1.2	2.5	1.2
HR-6L, g	0.67	0.65	0.85
D-Air-2, g	0.12	0.12	0.12
MgO, g	30	30	30
Aquadest, ml	185	307	400
Density (SG)	1.9	1.7	1.6
WCR, GpS	6.9	11.5	15
Plastic Viscosity, cp	80	25	14
Free water	0.6	1.2	1.4

**Table 3. Dissolved solid composition of Kamojang formation fluid**

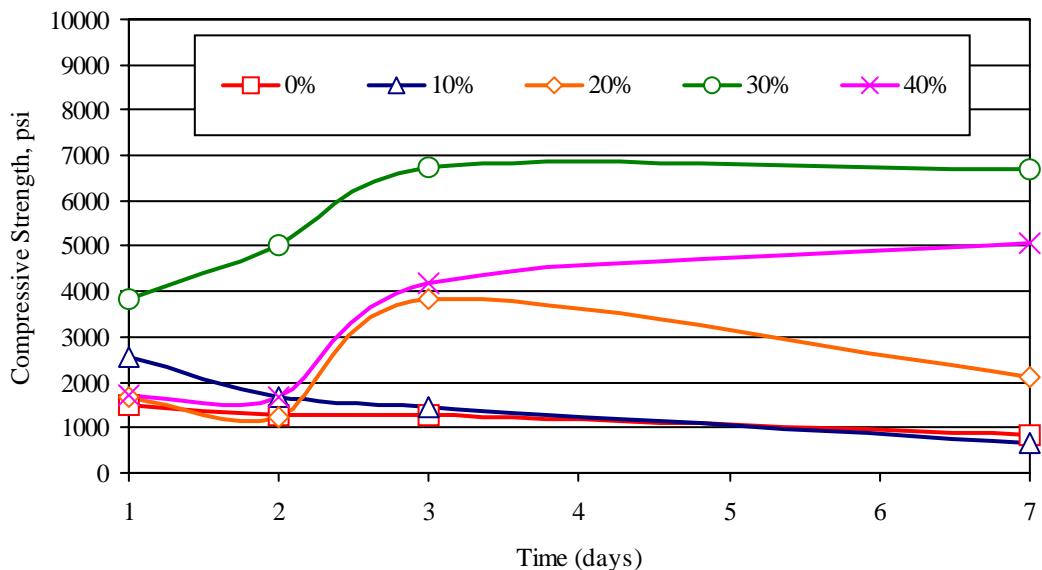
Chemical Composition	KMJ -11	KMJ-14	KMJ-17
PH	4.26	4.62	4.53
Natrium ( $\text{Na}^+$ ), g/liter	2.77	2.10	1.92
Kalium ( $\text{K}^+$ ), g/liter	0.34	0.24	0.28
Calcium ( $\text{Ca}^{+2}$ ), g/liter	0.33	0.49	0
Magnesium ( $\text{Mg}^{+2}$ ), g/liter	0.22	0.37	0
Bicarbonate ( $\text{HCO}_3^-$ ), g/liter	1.97	8.77	8.04
Chlorida ( $\text{Cl}^-$ ), g/liter	0.11	0	0
Sulfat ( $\text{SO}_4^{+2}$ ), g/liter	7.99	8.23	12.46
Silika ( $\text{SiO}_2$ ), g/liter	7.52	6.59	22.66

**Figure 3. Experiment diagram to examine effect of silica and conditioning time on cement strength****Table 4. Kamojang formation gas composition**

Gas Component (m mol / 100 mol condensate)	KMJ -11	KMJ-14	KMJ-17
CO <sub>2</sub>	74.8	92.29	221.5
H <sub>2</sub> S	10.73	11.05	12.85
Other gases (N <sub>2</sub> , CH <sub>4</sub> )	5.28	4.56	7.25
Total gas	90.81	105.9	241.6
Mol ratio CO <sub>2</sub> /H <sub>2</sub> S	7.02	8.38	17.24
% Volume	0.09	0.11	0.25
% Weight	0.21	0.25	0.57

**Table 5. Compressive strength for several SSA-1 contents and conditioning times**

Cement Composition	Compressive Strength (psi)			
	1 day	2 days	3 days	7 days
G + 0 % SSA-1	1494.1	1276.1	1268.0	845.1
G + 10% SSA-1	2559.1	1691.0	1470.0	675.3
G + 20% SSA-1	1694.3	1251.8	3830.0	2102.2
G + 30% SSA-1	3830.0	5032.0	6754.2	6691.2
G + 40% SSA-1	1698.3	1680.0	4200.0	5045.2



**Figure 4. Compressive strength cement vs. conditioning time for several SSA-1 contents**

**Table 6. Compressive strength for alternative cement compositions and conditioning times**

Cement Composition	Compressive Strength (Psi)			
	1 day	2 days	3 days	7 days
KMJ-11 (SG = 1.9)	2552	3327	3354	3372
KMJ-14 (SG = 1.7)	1700	2523	2507	2481
KMJ-17 (SG = 1.6)	1485	1690	1672	1640

**Table 7. Shear bond strength for alternative cement compositions and conditioning times**

Cement Composition	Shear Bond Strength (Psi)			
	1 days	2 days	3 days	7 days
KMJ-11 (SG = 1.9)	139	1445	1502	1618
KMJ-14 (SG = 1.7)	112	694	1433	1870
KMJ-17 (SG = 1.6)	484	650	1108	1474

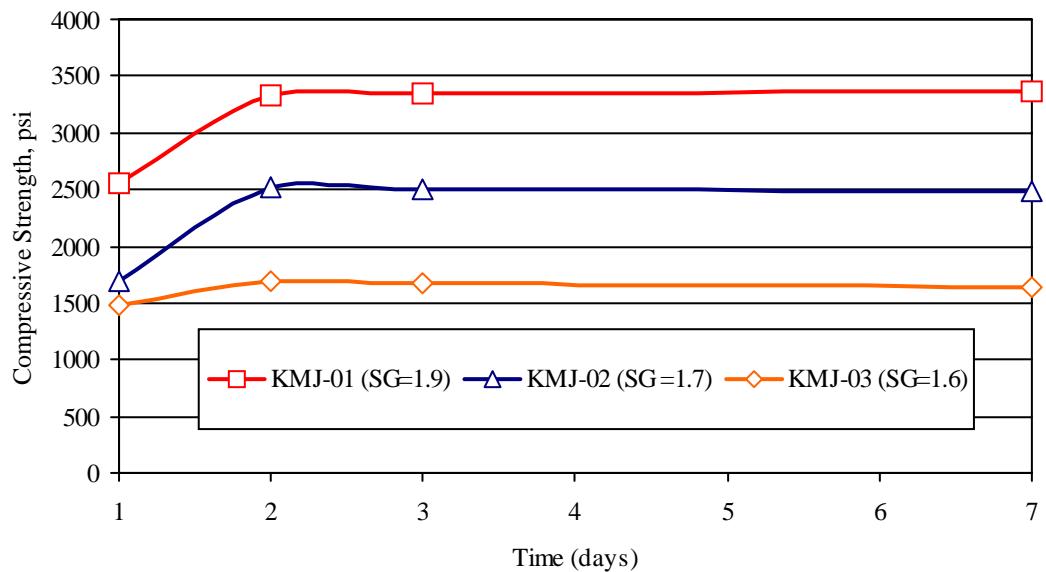


Figure 5. Compressive strength cement vs. conditioning time for alternative cement compositions at SSA-1 30%

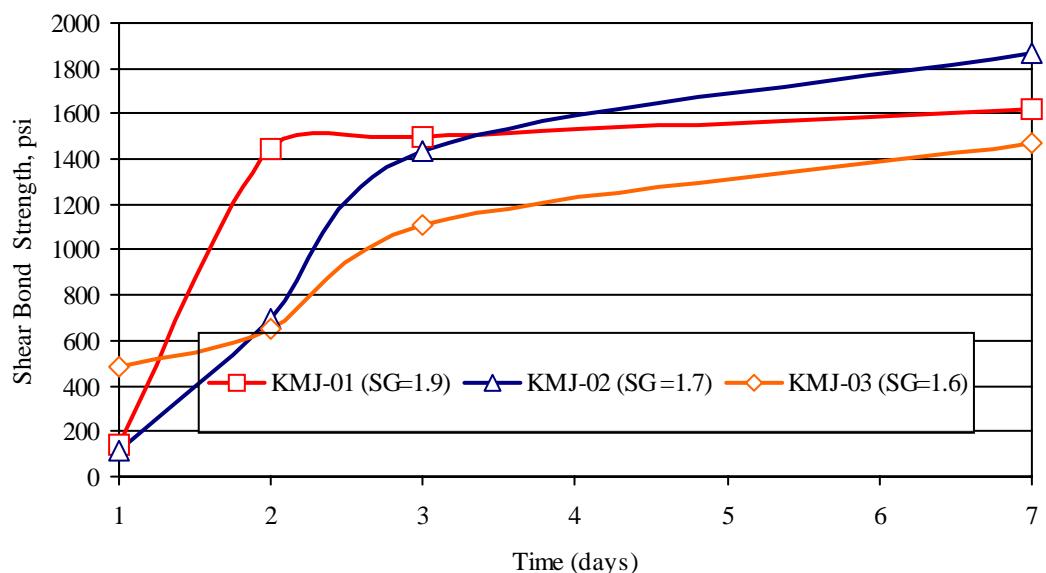


Figure 6. Shear bond strength vs. conditioning time for alternative cement compositions