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# Assessment of the Early Age Tensile Strength of the Oilfield Class G Cement under Effects of the Changes in Down-Hole Pressure and Temperature

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**Abstract:** An oil well in Darquain region of Khuzestan province in Iran was selected as a case study and contemporary changes in pressure and temperature according to real inside borehole conditions of this well have been simulated in curing the class G cement samples in the laboratory. The mentioned cement usually used for cementing the annulus between casing and rock formation in the oil well early age tensile strength of the samples were measured via Brazilian tension test in order to perform more precisely predicting tensile cracking of cement sheath. It is worth to mention that in this study no special additives used in cement slurry mixture in order to evaluate only the effects of environmental conditions in curing the cement samples. Results of laboratory tests showed that with the rise of the pressure and temperature up to 150°F and 1500 psi, earl age tensile strength is growing slightly while after that it experiences a decreasing treatment.

**Key words:** Tensile strength, borehole pressure, borehole temperature, class G cement slurry

## INTRODUCTION

Casing and cementing, among over all of the operations in the drilling procedure of an oil or gas well, specially cementing, are unquestionably the most critical and important works. The lifetime of the well, the quantity and quality of producing and the duration of portion are highly demanded to the proportion of success of these services. In the casing process, the borehole is layered with a specific steel tube and subsequently in cementing procedure; the annulus between the casing and the adjacent parapet rock formation is filled by specific cement slurry. Cement slurries which fill the outer side of the rims will be set by the time, usually after a few hours or a few days and the produced cement stone embraces back tubes like a strong sheath and join them to the formation. Oil well cementing is the process of mixing slurry of cement and water in an appropriated proportions and pumping it down through steel casing of critical points in the annulus around the casing or in the open hole below the casing string. Cementing is one of the most important and the most expensive procedures of drilling.

All of the important job of this cement sheath can be summarized into protection and prevention (Asadi, 1983). In addition to isolating of oil, gas and water producing zones, (1) cement also aids in protecting the casing from corrosion, (2) preventing blowouts by quickly forming a seal, (3) protecting the casing from shock loads in drilling deeper and (4) sealing off lost circulation or thief zones (Smith, 1990).

Reddy *et al.* (2005) mentioned in their research that there is a three stage manner for introduction of a well which can economically and in a risk free manner produce the required hydrocarbons. First stage is engineering analysis; second stage is to design and test cement slurry which can be able to cooperate with the evaluated properties of the cement sheath in the first stage. Third stage is to correctly and effectively replacing the cement slurry and to surveillance over the cement sheath during the lifetime of the well which is in order to achieving the effective zonal isolation.

## Effect of Additives on Class G Cement Mechanical Properties

Ravi *et al.* (2007) studied the effects of cyclic loads on the mechanical properties and integrity of the cement layer inside the oil or gas borehole through performing specific tests which he has designed for that reason. Furthermore, he has investigated the effects of well operation on cement sheath of different mechanical properties and discussed the results. In his work, the lower-density cement systems were considered and were showed how the density was lowered by incorporating conventional additives such as pozzolanic beads (cenospheres), hollow glass beads, gas bubbles, water-binding additives, silica fume and fly ash. All cement slurry formulations had a density of 12 lbm gal$^{-1}$ and were prepared according to API procedures and were cured under a pressure of 3000 psi for 72 h at 190°F, with the exception of cement system 1, which has cured in a water bath at 190°F for 72 h. The specimens prepared for tensile strength testing have dog-bone style. Ravi introduced six cement compounds in his study. Cement system 1 consisted of base slurry which was prepared from cement and water. Cement system 2 included primarily cement and water with sodium silicate. Cement system 3 comprised of cement, class F, fly ash, lime and bentonite. Cement system 4 consisted primarily of cement, fumed silica and glass beads of specific gravity 0.6. Cement system 5 involved primarily in cement ultrafine-particle-size cement and cenospheres, which were precrushed at a pressure of 6000 psi. Cement system 6 consisted of cement, class F fly ash, silica fume and bentonite. Resulted mechanical properties of these systems are shown in Table 1.

It is observed that cement system 4 has over all the most tensile and compressive strength. Heinold *et al.* (2002) investigated about several relatively common cement additives. The additives they used included organic materials as well as non-organic materials. They added these materials to oil well cement with water contents averaging from 50 to 66% By Weight of Cement (BWOC).

They used monogrammed API class G cement in their research. To study the effect which various cement additives have on mechanical properties of set cement, seven cementing additives usually implemented in oil and gas well cementing were considered for evaluation at 100 and 200°F which were as followed: polyvinyl alcohol (PVA), Silica Fume (SF), metakaolin (HRM), wollastonite, styrene butadiene latex, hydroxyethyl cellulose (HEC) and sodium metasilicate (SMS).

Table 1: Mechanical properties of cement slurry formulations (Ravi *et al.*, 2007)

| Cement systems | Poison's ratio | Young's modulus | Compressive strength load vs. displacement analysis | Tensile strength | Compressive strength crush test |
|---|---|---|---|---|---|
| | | | (psi) | | |
| 1 | 0.151 | 8.08E+05 | 1017 | 190 | 1190 |
| 2 | 0.084 | 04.000+8.20E | 337 | 50 | 320 |
| 3 | 0.139 | 3.28E+05 | 1008 | 80 | 1030 |
| 4 | 0.207 | 1.12E+06 | 5155 | 350 | 4160 |
| 5 | 0.220 | 1.07E+06 | 4136 | 380 | 2710 |
| 6 | 0.194 | 4.64E+05 | 1772 | 90 | 1210 |

Fig. 1: HPHT curing chamber

All mixtures were mixed at 15.0 ppg containing only one individual additive per test. All latex slurries were mixed at 16.0 ppg in order to generate stable cement slurry. Initial testing had shown that by using a 15.0 ppg system, significant settling happened and no stabilizer additive were implemented. All slurries were mixed at room temperature in rather one of the following orders.

- Fresh water + defoamer + dry blended cement
- Fresh water + defoamer + latex + cement

For measuring the mechanical properties of the set cement, all slurries were treated under simulated down-hole environment in a standard HPHT curing chamber (Fig. 1). For 72 h each specimen was exposed to a constant pressure of 3000 psi and temperatures of 100 and 200°F, respectively. All specimens for flexural, tensile and compressive strength test were cured simultaneously, with molds in a vertical orientation, in the same curing chamber throughout the testing process. Tensile strength testing was performed using briquette mold specimens commonly referred to as dog bones (Fig. 2). With a gradual increase in exerted force, the upper half of the fixture is pulling the cement sample slowly upwards, until mechanical failure of the specimen occurs. At the end of their study, the researchers concluded that not all additives, when used separately in Portland cement, contribute to develop flexural and tensile strength properties of higher density cement systems. Furthermore, additives known to improve flexural and tensile strength properties in low to medium density systems may not be as beneficial in higher density systems. And, currently available testing methods using ASTM equipment is not adequate and may influence overall testing results.

## Common Tension Tests of Class G Cement

A research was conducted over the basic tests of the tension of concrete which is commonly used for oil and gas well cementing (Heinold *et al.*, 2003). These testing methodologies are Splitting Tensile Strength (STS) and Uniaxial Tensile Strength (UTS).

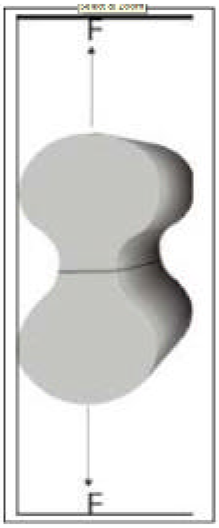

Fig. 2: Briquette molds (dog bones) (Heinold *et al*., 2002)

Heinold *et al.* (2003) mentioned that if there are sufficiently induced stresses to cause a mechanical failure of the set cement, failure will likely be of a tensile nature. They also said in the study that even though the American Petroleum Institute (API) established recommended methods for the testing of oil and gas well cement compressive strengths, no similar standards currently exist for the testing of the tensile strength of oil and gas well cements. Heinold *et al*. (2003) announced, it becomes very difficult for design engineers to utilize induced stress data to determine if a given cement system possesses sufficient tensile strength to resist the tensile forces. They used monogrammed API class G cement, commercial lightweight cement and a mineral fiber additive, along with a defoamer in their research. The mineral fiber implemented for this study is a white calcium-silicate powder. This additive can typically be used over a wide temperature range from 32 to 400°F in concentrations ranging from 10 to 50% By Weight of Cement (BWOC). The defoamer used for this investigation was a silicon-based emulsion. The following four cement slurry systems were chosen for the evaluation process:

- 15.8 ppg class G+0.02 gal sk$^{-1}$ defoamer
- 15.8 ppg class G+20% BWOC fiber+0.02 gal sk$^{-1}$ defoamer
- 13.5 ppg TLW+0.02 gal sk$^{-1}$ defoamer
- 13.5 ppg TLW+20% BWOC fiber+0.02 gal sk$^{-1}$ defoamer

All slurries were mixed with fresh water and were cured for 48 h in an atmospheric water bath at 130 to 180°F, respectively. They chose a water bath over a High-Pressure, High-Temperature (HPHT) curing chamber, since, earlier work indicated that the de-pressurization and also the cooling down of such a chamber might have profound effects on the overall results of such a study. Finally, after obtaining results, they could not confirm the assumption that a STS test provides similar results to a direct UTS test. But, they could confirm that with increasing the sample size a reduction in STS occurs. And, they found that the ratios between direct UTS and indirect STS measurements appear to remain relatively unaffected by the curing temperature of the specimens.

Cement static tensile behavior under down-hole conditions was looked over (Dillenbeck *et al*., 2005). To simulate cement tensile behavior data that is more reflective of actual down-hole performance, Dillenbeck *et al*. (2005) developed an automated, microprocessor controlled testing equipment that cures and mechanically tests the cement under pretended down-hole conditions. Once slurry is positioned in the testing device and the temperature and pressure is raised to reproduce down-hole curing conditions, the samples never get back to ambient conditions again until the end of testing. The microprocessor controls and automated data acquisition unit also allow for the determination of tensile stress-strain relationships, prior to testing the sample to ultimate (mechanical) failure in tension.

Boukhalifa and James (2008) studied ways for determining cement tensile behavior in another attempt. The purpose of their work was to provide a well-defined set of methods to measure the mechanical parameters of cured cement systems for input into a cement stress analysis model. For tensile test measurements the researchers suggested the Brazilian test in which a sample with a length-to-diameter ratio of 0.5 is required. Samples are first cored and then the ends are cut perpendicular to the cylinder length by use of a rotating saw. Throughout the preparation process the samples must be kept saturated with water to avoid cracking related to dying shrinkage. The press that was used for the work presented herein is a computer-controlled electromechanical press. They provided the experimental methods and data analysis approaches to finish the key cement behavior parameters (Young's modulus, Poison's ratio, UCS and tensile strength) for input into cement sheath stress-analysis applications in their study. They concluded that estimation of the tensile strength as 10% of the UCS (Uniaxial Compressive Strength) is a conservative calculate of the tensile strength. The Brazilian measurements yields tensile strength values 50 to 75% higher than the rule-of-thumb method. Therefore, if Brazilian test results are not available, use of the rule-of-thumb will provide an added safety factor. A sample of a bad and a good failure in Brazilian test are shown in Fig. 3 and 4, respectively.

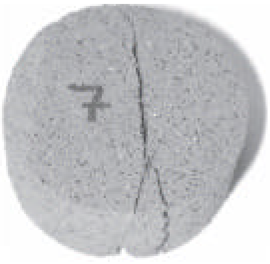

Fig. 3: Bad failure in a Brazilian test Boukhalifa and James (2008)

Fig. 4: Good failure in a Brazilian test that has subsequently generated a second crack Boukhalifa and James (2008)

Earlier works are perfectly shown the importance of cement design and operation in an oil well. H owever, in none of them the contemporary effects of changing both pressure and temperature borehole environment on the net class G cement slurry were attended. Therefore, in the p resent study, this contemporary effect is assessed. Since, in an actual oil well, with Increasing of the depth, both pressure and temperature are increasing, the simultaneously assessment of these to factors gives a more precise and reliable analysis of cement tensile cracking behavior in an oil or gas well.

## MATERIALS AND METHODS

### Down-hole Pressure and Temperature Conditions

In order to simulate actual down-hole pressure and temperature conditions needs for curing the cement specimens, real qualifications of a well in Darkhouein field in Khouzestan province, 40 km North of Abadan city, along the West coast of Karoun river, is assessed. Final depth of this well is 5400 m and its bottom-hole temperature and pressure are 310°F and 16979 pounds per square inches (psi).

Since, the cement slurry from the time it is synthesized and pumped into the well till the time that it gains its final static pressure is under the progressive rise of temperature, both Bottom-Hole Static Temperature (BHST) and Bottom-Hole Circulating Temperature (BHCT) have effects over the design of the cement. Circulating temperature encountered when the slurry pumps into the well and the static temperature is formation temperature which the slurry faces it after the circulating movement stopped for a time period. In this study, only the BHCT is considered because the total time period of curing being assessed is the 48 h. In order to design and evaluate long term stability or the amount of expansion of the compressive strength of the cement slurry, static temperature should be taking into account (Shahri, 2005). This temperature is important in the case of deep wells and especially where the difference of temperature between the top and the bottom of the cement column might be very much.

The profile of the changes in the pressure and temperature, which is shown in Fig. 5, was determined based on the qualifications of the mentioned well. It is worth to mention that this data gathering and processing has been done in 2009. According to limitation of device serviceability, five individual points has been selected from this profile to assign in the simulation procedure. The temperatures of these points are 22, 49, 65, 82 and 104°C and the contemporary pressures are as atmospheric pressure, 1000, 1500, 2000 and 3000 psi, respectively. Because of the limitations of the measurement device which couldn't resist the pressures more than 3000 psi, we were obliged to choose points in a range of pressure

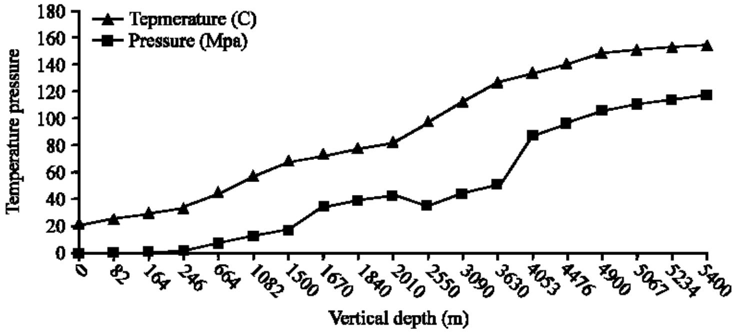

Fig. 5: The changes of pressure and temperature in the bottom-hole of the case study well

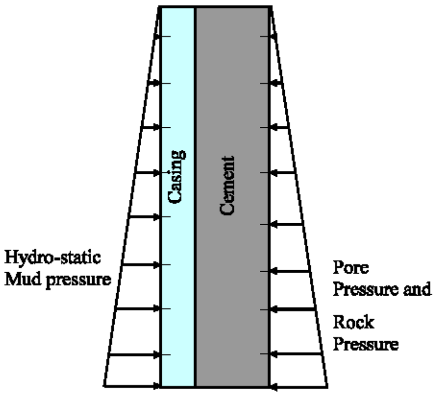

Fig. 6: The schematic changes in the bottom-hole pressure

between the atmospheric pressure to 3000 psi. So, in this study we can evaluate the tensile strength of oilfield cement from top of the oil well case study to the depth of approximately equal to 1550 m below the ground surface.

The schematic changes of the bottom-hole pressure as a function of the depth of the well is shows in Fig. 6.

Equation 1 can directly calculate the quantity of the down-hole hydrostatic pressure (Asadi, 1983):

$$P_{Hyd} = 9.607 \times Y_{Mud} \times TVD \tag{1}$$

Specimens, in the laboratory, are under hydrostatic pressure which is being calculated with the Eq. 1.

$P_{hyd}$ = Down-hole hydrostatic pressure (Pa)
$Y_{Mud}$ = Mud density (kg $m^{-3}$)
TVD = Total vertical depth (m)

## Design of the Cement Slurry

Design of the slurry usually consists of formulation of the cement additives in order to reach a desirable density, fluid loss control, rheology at the time of pumping, appropriate transition time and enough strength at the time of setting. The slurry used in this study was API class G cement, additives and water. According to the API there are 8 different classes of well cement which are: A, B, C, D, E, F, G and H class which every of them is used in a specific pressure and temperature (API Recommended Practice 10B, 1997). Class G and H cements are known as basic cement because; no additives, except calcium-sulfate or water or both should be added to the clinker at the time the clinker is being made. Major phases of class G cement clinker are made of 50% tricalcium-silicate ($C_3S$), 30% dicalcium-silicate ($C_2S$), 5% tricalcium-aluminate ($C_3A$) and 12% tetracalcium-aluminferrite ($C_4AF$). So with adding the additives like appropriate accelerators we can change the transition time of slurry and so expand their area of usage and use them in a wider range of depth, pressure and temperature (Asadi, 1983; Nelson, 1999).

Table 2: Cement systems used in the tested slurries

| | Condition | | | | |
|---|---|---|---|---|---|
| Test No. | Pressure (psi) | Temperature (°F) | Slurry weight (pcf) | Volume (cc) | Composition |
| 1 | atm | Environment (73) | 115 | 800 | cmt.G.un+$CaCl_2$ |
| 2 | 1000 | 1.20E+02 | 115 | 800 | cmt.G.un+$CaCl_2$ |
| 3 | 1500 | 1.50E+02 | 115 | 800 | cmt.G.un+$CaCl_2$ |
| 4 | 2000 | 1.80E+02 | 115 | 800 | cmt.G.un+silicaflour+D-O13 |
| 5 | 3000 | 220 | 115 | 800 | cmt.G.un+silicaflour+D-O13 |

Table 3: Percentage of the materials used in the tested slurries

| Test No. | Material | Amount | Unit |
|---|---|---|---|
| 1 | cmt.G.un | 976 | g |
| | $CaCl_2$ | 9.76 (1% bwoc) | g |
| | Water | 4.88E+02 | cc |
| 2 and 3 | cmt.G.un | 9.69E+02 | g |
| | $CaCl_2$ | 19.38 (2% bwoc) | g |
| | Water | 485 | cc |
| 4 and 5 | cmt.G.un | 746 | g |
| | Silica flour | 261 (35% bwoc) | g |
| | D-O13 | 2.23 (0.3 bwoc) | g |
| | Water | 465 | cc |

cmt.G.un: Class G cement of the UAE, $CaCl_2$: Calcium-choloride, D-013: Retarder, BWOC: By weight of cement

The only additives used in this system were calcium-choloride as an accelerator for the transition time of the cement slurry in environmental pressures and temperatures, D-013 as a retarder for the transition time of the cement slurry in high pressures and temperatures and also silica-flour (Asadi, 1983).

According to the aim of this study, we used additives which had the least effect on cement tensile strength and at the same time be capable of producing rheological properties and transition time in a relatively appropriate condition and close to the conditions of slurries used in executives. Cement systems and the percentage of the materials used for providing of the tested cement slurry are illustrated in Table 2 and 3.

In all systems, water cement ratio was assumed 0.5 and cement slurry specific weight was considered 1.84 g $cm^{-3}$ which was in the range of neat cement slurry densities (neat cement slurry densities are between 1.79 and 1.92 g $cm^{-3}$). Slurries in a lower and higher range of densities in compare with neat slurries are lightweight and heavyweight slurries, respectively.

## Measuring Cement Tensile Strength

For measuring cement tensile strength, as it mentioned in literatures, we can use direct tensile test method or Brazilian indirect tensile test method and in our research the second method is used. First the specimens were cured in a curing chamber, under mentioned pressure and temperature and then were tested with a hydraulic press. For each condition of environmental curing, at least three correct tests have been conducted in order to preserve the statistical rules in averaging calculation. Using this device, firstly the specimens should be placed in it in a horizontal position (side face) and the compressive force (P) should be applied diagonally on them monotonously. When cement tensile strength is reached, the specimens will chop into two halves. It is proved in elasticity theory that the cement tensile strength is (Timoshenko, 1930, 1941):

$$f_{ct} = 2p \div (\Pi \times \text{diameter} \times \text{length}) \tag{2}$$

Curing chamber is used to make samples from cement slurries. This device is consisted of water-filled empty spaces and is capable of curing the slurries under the given pressure and temperature which must be given to device. A hydraulic press and cells of curing chamber are shown in Fig. 7 to 11 and a curing chamber has been shown earlier in Fig. 1.

Fig. 7: Unassembled sample cell of a curing chamber

Fig. 8: Assembled sample cell of a curing chamber

Fig. 9: A set of assembled sample cells of a curing chamber

Fig. 10: A bonnet of the cell of a curing chamber

Fig. 11: Hydraulic press

## RESULTS

### Test No. 1: 22° C Temperature, Atmospheric Pressure

This test has been done under atmospheric pressure and environmental temperature (73°F or 22°C) and water bath is used instead of curing chamber. During test procedure, one of the specimens has been broken while emitting of the sample and the obtained hydraulic pressures from the other three remaining samples were: 1000, 1200 and 1400 psi. Then by use of Eq. 1, tensile strength of the samples, were evaluated as follow: 136, 163 and 190 psi, respectively. At the end, an average tensile strength of 163 psi has reached.

### Test No. 2: 49°C Temperature, 1000 psi Pressure

Second test has been done at the pressure of 1000 psi and the temperature of 120°F or 49°C and one of the samples has broken in this test improperly, but the compressive force for the remaining 3 sample has been determined as follow: 1200, 1300 and 1600 psi. Calculated tensile strength for the above tests was 163, 176 and 217 psi, respectively. The average tensile strength was obtained as 185 psi.

### Test No. 3: 66°C Temperature, 1500 psi Pressure

Third test has been performed at the pressure of 1500 psi and the temperature of 150°F or 66°C. The compressive pressure for 4 samples has been determined as follow: 2000, 2000, 2000 and 1600 psi. The tensile strength for the above forces was calculated 272, 272, 272 and 217 psi, respectively. The average tensile strength was obtained 258 psi.

### Test No. 4: 82°C Temperature, 2000 psi Pressure

Forth test has been done at the pressure of 2000 psi and the temperature of 180°F or 82°C and the compressive force for 4 samples has been determined as follow: 1200, 1200, 1200 and 1500 psi. Tensile strength for the above forces was calculated as 163, 163, 163 and 204 psi, respectively. The average tensile strength was obtained 214 psi.

### Test No. 5: 104°C Temperature, 3000 psi Pressure

Fifth test has been done at the pressure of 3000 psi and the temperature of 220°F or 104°C and again one of the samples has been broken. But the compressive force for the remaining 3 sample was determined as follow: 1200, 1200 and 1000 psi. Tensile strength for these samples was calculated 163, 163 and 136 psi, respectively. The average tensile strength was obtained 154 psi.

It is worth to mention that to get more reliable results, we obtained the tensile strength in another way in which we determined an average compressive force for each test and then we evaluated the tensile strength from that average force. We observed that both results were the same.

## DISCUSSION

As it is noted in the abstract of this study, in this work we are going to evaluate the actually environmental effects inside the oil well case study on the tensile strength of the cement class G pumped in the annulus without any special additives. After determining the tensile strength of the specimens according to the way reported in section 2 and 3, we derived an important curve which has been shown in Fig. 12. Two horizontal rows in the bottom of the diagram are indicating contemporary pressure and temperature curing condition and the vertical column showing the quantity of obtained tensile strength of cement in pounds per square inch. As it is obvious from the results, from first to third test, the quantity of the tensile strength of cement is rising, but in the fourth and fifth test which has been done in the pressure of 2000 and 3000 psi and the temperature of 82 and 104°C respectively, the quantity of the tensile strength is falling.

It can be observed that under effect of combination of temperature and pressure up to point 65°C and 1500 psi, the tensile strength of class G cement is improved but after that this combined effect can lead to decrease in mentioned mechanical property. Loss of tensile strength is observed can be interpreted as follows:

Class G cement has tricalcium silicate (Ca3S) and dicalcium silicate (Ca2S) component in his chemical texture. When it is mixed with water, both components hydrate to form calcium silicate hydrate (Ca-S-H) gel. The Ca-S-H gel can provide good tensile strength for the cement up to some limit of circumferential temperature and pressure. However, it can be estimated that after 65°C and 1500 psi combined condition, the Ca-S-H gel starts under metamorphosis condition forming a phase called alpha dicalcium silicate hydrate (a-Ca2SH), which reduces tensile strength and of set cement.

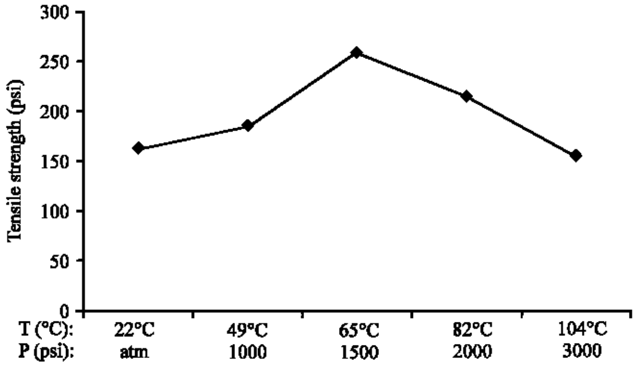

Fig. 12: The effect of the pressure and temperature on tensile strength

It is important to note that as it was said in the beginning stages of this study and it was shown to some extent in aforementioned literature reviews, in earlier works, the combined effect of borehole temperature and pressure on net class G cement tensile strength was not examined. So, this work may be unique in this area and due to this, the obtained results can not be compared with the data placed in the literatures. Getting back to Fig. 12, the results indicate that from top to depth of 1500 m of the oil well case study, the environmental effects (borehole's temperature and pressure) would improve the early age tensile strength of the class G cement but after that with increasing the depth of the well, these effects would aim in degradation of mentioned strength. So, we need to incorporate the effective special additives in cement slurry mixture at lower depths (below 1500 m) to avoid the danger of tensile cracking of cement sheath.

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