Rudarsko-geološko-naftni zbornik	Vol. 6	str. 127–134	Zagreb, 1994.

UDC 622.245.422:666.9.015.4/7

Pregledni članak

The project »Optimization of dynamic seals in petroleum engineering« financed by the Ministry of Science and Technology of the Republic of Croatia

CEMENT SLURRIES FOR GEOTHERMAL WELLS CEMENTING

Nediljka GAURINA—MEĐIMUREC, Davorin MATANOVIĆ and Gracijan KRKLEC

Faculty of Mining, Geology, and Petroleum Engineering, Pierottijeva 6, 41000 Zagreb, Croatia

Key-words: Geothermal wells, Cementing, Cement slurry, Strength retrogression

During a well cementing special place belongs to the cement slurry design. To ensure the best quality of cementing, a thorough understanding of well parameters is essential, as well as behaviour of cement slurry (especially at high temperatures) and application of proven cementing techniques. Many cement jobs fail because of bad job planning. Well cementing without regarding what should be accomplished, can lead to well problems (channels in the cement, unwanted water, gas or fluid production, pipe corrosion) and expensive well repairs. Cementing temperature conditions are important because bottomhole circulating temperatures affect slurry thickening time, arheology, set time and compressive strength development. Knowing the actual temperature which cement encounters during placement allows the selection of proper cementing materials for a specific application.

Slurry design is affected by well depth, bottom hole circulating temperature and static temperature, type of drilling fluid, slurry density, pumping time, quality of mix water, fluid loss control, flow regime, settling and free water, quality of cement, dry or liquid additives, strength development, and quality of the lab cement testing and equipment. Most Portland cements and Class J cement have shown suitable performances in geothermal wells. Cement system designs for geothermal wells differ from those for conventional high temperature oil and gas wells in the exclusive use of silica flour instead of silica sand, and the avoidance of fly ash as an extender.

In this paper, Portland cement behaviour at high temperatures is described. Cement slurry and set cement properties are also described. Published in literature, the composition of cement slurries which were tested in geothermal conditions and which obtained required compressive strength and water permeability are listed. As a case of our practice geothermal wells Velika Ciglena-1 and Velika Ciglena-1a are described.

Ključne riječi: Geotermalne bušotine, Cementiranje, Cementna kaša, Smanjenje čvrstoće

Pri cementiranju bušotina posebno mjesto pripada dizajnu cementne kaše. Potpuno razumijevanje bušotinskih parametara, ponašanja cementne kaše (posebno na visokim temperaturama) i primjena provjerenih tehnologija cementiranja najveća su garancija za postizanje kvalitetne cementacije. Mnoge cementacije nisu uspjele zbog nepotpunog planiranja. Cementiranje bez razmatranja potrebnih parametara dovodi do nepoželjnih posljedica (kanalići u cementnom kamenu, nepoželjna proizvodnja vode ili plina i korozija kolone zaštitinih cijevi) i skupih popravnih radova. Temperaturni uvjeti cementiranja su važni jer temperature u cirkulaciji na dnu bušotine djeluju na vrijeme zgušćavanja, reološka svojstva, vrijeme vezivanja i razvoj tlačne čvrstoće. Poznavanje stvarne temperature tj. one kojoj će cementna kaša biti izložena tijekom procesa cementiranja, omogućava izbor odgovarajućih cementnih materijala za specifične aplikacije.

Na dizajn cementne kaše utječu; dubina bušotine, temperatura na dnu bušotine (tijekom cirkulacije), tip isplake, gustoća, vrijeme protiskivanja, kvaliteta vode za pripremu kaše, veličina filtracije, režim protjecanja, taloženje i slobodna voda, kvaliteta cementa i laboratorijske opreme. U geotermalnim bušotinama može se primjeniti većina potland cemenata i cement klase J. Cementne kaše dizajnirane za geotermalne bušotine razlikuju se od onih za konvencionalne visokotemperaturne naftne i plinske bušotine jer sadrže kremeno brašno umjesto kremenog pijeska, dok se lebdeći pepeo kao olakšivać izbjegava.

U radu je opisano ponašanje portland cementa na visokim temperaturama. Opisana su svojstva cementne kaše i kamena. Navedeni su, u literaturi objavljeni, sastavi cementnih kaša za cementiranje geotermalnih bušotina. Te cementne kaše su ispitane u geotermalnim uvjetima, a očvrsnule su u cementni kamen zahtijevane tlačne čvrstoće i propusnosti. Kao primjer iz naše prakse opisane su geotermalne bušotine Velika Ciglena-1 i Velika Ciglena-1a.

Introduction

Geothermal energy is considered renewable energy and it is utilized all over the world. Locations with thermal anomalies are potential sites for geothermal well drilling. Geothermal reservoirs usually have an exaggerated although irregular temperature gradient with depth. A geothermal field may have a temperature increase of 1,8°C per 10 meters, up to as high as to 1,8°C per one meter through limited vertical intervals (Bayliss, 1972). The nature of an economical geothermal reservoir is such that large quantities of hot water or steam must be produced from each well.

Geothermal well sites in California, Utah, New Mexico, Mexico, El Salvador, the Philippines, Indonesia, New Zealand, Iceland, Japan, Russia and Italy are at present considered the most significant geothermal projects in the world.

During oil and gas exploration in Croatia, some geothermal reservoirs have been discovered. A few of them are already producing geothermal water: Bizovac, Ivanić Grad and three well sites in south-west geothermal area of Zagreb. Some geothermal reservoirs with great potentials have been more or less explored: Lunjkovec-Kutnjak, Rečica, Velika Ciglena (Table 1) (Čubrić, 1993).

The geothermal reservoirs listed in Table 1 have been placed into two groups according to utilization of available energy:

A. Reservoirs with water temperature less than 120°C; water is used for heating, and for recreational and health purposes.

B. Reservoirs with water temperature over 120°C; whose energy potential can be used in electric power generation.

In order to bring geothermal water from a reser-

Table 1. Some data about the principal geothermal fields in the Republic of Croatia

Tablica 1. Neki podaci o glavnim geotermalnim poljima u Republici Hrvatskoj

	Reservoir/field *Ležište/polje*	Lithology *Litologija*	Well depth, m *Dubina bušotine, m*	Well head temperature, °C *Temperatura na glavi bušotine, °C*	Single well productivity, m^3/s *Produktivnost jedne bušotine, m^3/s*
A	Bizovac-TG	Gneis *Gnajs*	1800	96	0,0055
	Bizovac-S	Sandstone *Pješčenjak*	1800	90	0,023
	Madarinci	Gneis *Gnajs*	1900	96	0,01
	Ernestinovo	Sandstone *Pješčenjak*	1700	80	0,023
	Zagreb-M1	Carbonate *Karbonat*	1300	80	0,05
	Zagreb-B2	Carbonate *Karbonat*	1300	80	0,005-0,05
	Sv. Nedjelja	Carbonate *Karbonat*	1400	68	0,045
B	Lunjkovec	Carbonate *Karbonat*	2500	125	0,078
	Ferdinandovac	Carbonate *Karbonat*	2500	125	0,05
	Velika Ciglena	Carbonate *Karbonat*	2800	170	0,1156
	Rečica	Carbonate *Karbonat*	2500	120	0,05
	Babina Greda	Carbonate *Karbonat*	2500	125	0,10

voir to surface, a geothermal well should be designed, completed and properly cemented so as to be able to produce 20 or 30 years. Geothermal wells, along with deep oil and gass wells and thermal recovery wells, belong to high-temperature wells. In cementing those wells Portland cement, Class J cement, silica-lime systems and high-alumina cement are used. The type of cement depends on a type of high-temperature well. Listed cements are resistant to strength retrogression at high temperatures.

Geothermal Well Cementing

Geothermal wells are usually completed in much the same manner as a conventional oil and gas wells. However, the environment with which cements have to contend is frequently much more severe. The bottom hole temperature in a geothermal well can be as high as 370^0C. Corrosive water zones and very weak formations are not uncommon in geothermal wells. It is, therefore, important to consider chemical and physical properties of the formations when selecting ingredients for a cement mixture. Without careful modification of slurry design, the set cement may lose strength and gain permeability, potentially resulting in loss of zonal isolation.

The depth to which each casing string has to be set is influenced by geological conditions encountered and total depth to which the well is to be cased. Diameters of the holes drilled to set casings should be such that at least 3,81 cm (1 1/2 inches) thickness of cement surrounds the casing. If annular space is too wide, it can result in difficulty in obtaining good casing centralization which may cause channeling of the cement during placement. Typical liner-hole combinations such as 7 inch liner in 8 5/8 inch hole have proven to be successful (Shryock, 1984). In some cases, a slotted liner is hung through the production zone (Nelson, 1990).

Floating equipment, cementing plugs, stage cementing tools (DV-device), centralizers, and scratchers are mechanical devices commonly used when running casing and in the placement of cement in geothermal wells.

In cementing casings, the objective is to provide a complete fill-up of cement in the casing-hole annulus to resist specific environmental conditions and anchor the casings firmly to the ground and to each other. It is very important that at least one casing string is cemented to the surface to prevent elongation of casing because of thermal expansion when the well is brought into production.

Main problems in cementing a geothermal well arise from high temperatures, lost circulation zones and contamination of the cement slurry with mud. The best way to overcome these difficulties is to diagnose and combat them as they arise using necessary techniques and materials.

Cement Slurry Design

In most cases geothermal wells represent the most severe conditions for cements used in drilling. It is therefore impossible to avoid requirements made up for cements properties. Failure of wells in several geothermal fields has been directly attributed to cement failure.

Comprehensive studies are carried out in order to define such cement compositions which would met severe conditions (Shen, 1989).

To design a cement slurry for a geothermal well is a complex task which considers a careful choice of cements, retardes, fluid loss additives, dispersants, silica flour and extenders. Cement slurry should be properly placed in the annulus, while set cement should ensure adequate casing support and zonal isolation during the life of the well. In almost all geothermal wells cementing Portland cement is used and this is mostly the API Class G cement. In geothermal wells necessary characteristics of Portland set cement can decline and the rate of deterioration of it is affected by:

- temperature to which a set cement is exposed,
- amount of mix water (w/c ratio), and
- amount of reactive additives present in the cement slurry.

Portland cement is essentially a calcium silicate material, and the most abundant components are tricalcium silicate (C_3S) and dicalcium silicate (C_2S). After water is added these components hydrate forming a gelatinous calcium silicate hydrate named »C-S-H gel« giving necessary strength and dimensional stability to set cement. Also, a certain amount of calciym hydroxide is liberated in the process. In normal conditions set cement continues to hydrate and increases the strength pending a year, sometimes even longer, after which the strength remains almost constant supposing that there are no external disturbances for the cement. C-S-H gel is and excellent binding material for temperatures below 110^0C.

C-S-H gel at high temperature usually metamorphoses loosing compressive strength and increasing permeability of set cement. This phenomenon is known as strength retrogression. At temperature over 110^{0}C C-S-H gel often converts to alpha dicalcium silicate hydrate phase (α-C_2SH) characteristic for its weak porous structure. Changes in structure are most of all responsible for the strength decrease. Greater permeability of set cement due to a greater porosity makes it sensitive to corrosive formation fluids which is an equally serious problem as loosing the strength itself. Temperature increase speeds the said transformation which is going on slowly at temperature of 121^{0}C, during few weeks at 232^{0}C, and within few days at 316^{0}C. At temperature over 110^{0}C the cement acquires a maximum compressive strength during first few weeks, and at 177^{0}C during 24 hours (Dowell Schlumberger, 1984).

Nevertheless, so acquired compressive strength is than the one acquired at a lower temperature. Significant loss of compressive strength occurred within one month; yet the remaining strength is enough to support casing in a well (Suman and Elis, 1977). The real problem lies in the great increase of permeability. Class G cement of the normal density water permeabilities within one month were 10 to 100 times higher than the recommended limit, while in a lower density extended cement they were even higher (Nelson, 1990).

Table 2 presents compositions of both normal and low-density cement slurries which are often used in geothermal well cementing (API Task Group on Geothermal Well Cements, 1985).

Cement Slurry Properties

Most geothermal wells are not cemented under »geothermal« conditions. Circulation of drilling mud in the well for several hours prior to cementing can significantly decrease well temperatures. It is then dangerous that a circulation temperature is overestimated and a slurry over-retarded.

It is, therefore, very important in designing a cement slurry for a high temperature well to use the accurate static and circulation temperature values. Static temperature differentials in excess of 40^{0}C have been in many cases between the top and bottom of the cement column (Table 5). Sufficient amount of retarder must be added to the cement slurry to allow adequate placement time at the maximum circulating temperature. Because of that, such a slurry may be over-retarded at the top of the cement column, resulting in a very long waiting-on-cement (WOC) time. In geothermal wells, at least 2 to 3 hours of pumping time are usually required to allow adequate placement time.

Chemical and physical properties of a cement slurry must be maintained and development of a cement filter cake which could cause bridging in the annulus prevented. That is achieved by controling its filtration during pumping in. API fluid-loss rate between 50 to 100 ml/30 min is satisfactory in most primary cementing. Fluid loss is regulated with fluid loss additives.

Table 2. Compositions of typical geothermal cement systems
Tablica 2. Šastavi tipičnih geotermalnih cementnih mješavina

Sample *Uzorak*	Parts by Weight (kg) *Maseni udjeli (kg)*	Components *Komponente*	Slurry density (kg/m^3) *Gustoća (kg/m^3)*
1	100	API Class G cement *Cement API klasa G* (64,2C, 21,5S, 3,9A, 3,8F)	1810
	35	Silica flour/*Kremeno brašno*	
	1	Lignin-sugar/*Lignin-šećer*	
	54	Water/*Voda*	
2	100	API Clasa J cement *Cement API klasa J* (37,3C, 54,2S, 1,1A, 1,0F)	1850
	0,4	Lignin-sugar/*Lignin-šećer*	
	44	Water/*Voda*	
3	100	API Class F cement *Cement API klasa F*	1810
	40	Silica flour/*Kremeno brašno*	
	0,7	Lignin-sugar/*Lignin-šećer*	
	63	Water/*Voda*	
4	30	API Class J cement *Cement API Klasa J*	1650
	40	Pozzolan/*Pucolan*	
	30	Blast furnace slag/*Troska*	
	0,5	Carboxymethylcellulose/*CMC*	
	60	Water/*Voda*	
5	100	API Class G cement *Cement API klasa G* (64,2C, 21,5S, 2,9A, 3,8F)	1620
	35	Silica flour/*Kremeno brašno*	
	8,5	Perlite/*Perlit*	
	2	Bentonite/*Bentonit*	
	1	Lignin-sugar/*Lignin-šećer*	
	116	Water/*Voda*	
6	100	API Class G cement *Cement API klasa G* (64,2C, 21,5S, 3,9A, 3,8F)	1680
	35	Silica flour/*Kremeno brašno*	
	10	Diatomaceous earth/*Dijatomejska zemlja*	
	1	Lignin-sugar/*Lignin-šećer*	
	91	Water/*Voda*	
7	100	API Class G cement *Cement API klasa G*	1860
	40	Silica flour/*Kremeno brašno*	
	0,8	Dispersant/*Dispergator*	
	0,8	Fluid-loss agent/*Smanjivač filtracije*	
	0,4	Retarder/*Usporivač*	
	60,3	Water/*Voda*	
8	100	API Class G cement *Cement API klasa G*	1630
	100	Silica flour/*Kremeno brašno*	
	0,3	Retarder/*Usporivač*	
	85,1	Water/*Voda*	
9	100	*API Class G cement* Cement API klasa G	1850
	80	Silica flour/*Kremeno brašno*	
	0,5	Fluid-loss agent/*Smanjivač filtracije*	
	0,3	Retarder/*Usporivač*	
	76,8	Water/*Voda*	
10	100	API Class G cement *Cement API klasa G*	1890
	40	Silica flour/*Kremeno brašno*	
	1	Retarder/*Usporivač*	
	59,2	Water/*Voda*	

In Table 2 symbols means:
$A = Al_2O_3$, $C = CaO$, $F = Fe_2O_3$, $S = SiO_2$ in percent

Effective displacement of drilling fluid by cement is a critical factor in successful completion of geothermal wells. Primary cementing failures are predominantly created by channels of drilling fluid by-passed by the cement in annulus. These channels are highly dependent upon drilling fluid viscosity and filter cake deposits upon the permeable wellbore wall. To avoid such problems one ore more intermediate fluids (wash, chemical wash, spacer) are often pumped into the borehole in front of the cement slurry.

In most cases a cement slurry is designed to be pumped in turbulent flow what for dispersants are usually used. In designing a highly-dispersed slurry one must be careful to avoid sedimentation and free water development. This is particularly important at cementing highly deviated wells.

Uniformity of the cement sheath around pipe determines to a great extent the effectiveness of the seal between wellbore and casing.

Integrity of formations, in geothermal reservoirs ranges from poorly consolidated to naturally highly fractured. Geothermal reservoirs are characterized by permeability higher than 1 μm^2. Pore pressures seldom overcome hydrostatic pressure. Therefore a circulation loss often occurs.

The two stage method of cementing can be used to distribute a cement slurry over a long column when hole conditions does not allow circulation in one stage.

To prevent loss of a cement slurry, slow-density cement slurries are often used. Typical extenders used to prepare low-density cement slurry are fly ash, diatomaceous earth, bentonite and perlite.

Cements to which extenders are added sooner lose their properties than pure cements, because they contain more water. Cement degradation associated with fly ash has been observed at curing temperatures over 230°C (Nelson, 1990). When there is a demand for a cement slurry of a good quality with densities less than 1500 kg/m^3, microsphere-extended (ceramic or glass microspheres) or foamed (nitrogen) cement slurries are used.

Set Cement Properties

Once that cement slurry is successfully placed in the annulus, it is necessary to ensure that adequate casing support and zonal isolation will be provided throughout the life of the well. To prevent communication between zones, geothermal well cements are usually designed to provide at least 6.9 MPa compressive strength, and water permeability not higher than 10^{-4} μm^2 (API Task Group on Cements for Geothermal Wells, 1985). Besides, the set cement often must be resistant to degradation by salt geothermal waters.

Portland cement can be stabilized for geothermal environment by adding enough quantity of silica, an often applied method. In other words, the occurrence of $\alpha - C_2SH$ at temperature over 110°C can be prevented by reducing lime-to-silica ratio (C/S ratio) in the cement (Nelson, 1990). C-H-S gel has a variable C/S ratio, averaging about 1,5. By addition of 35 to 40% of silica (BWOC) the C/S ratio is lowered to about 1,0. At high temperatures subtly ground silica reacts and prevents generation of $\alpha - C_2SH$. At curing temperatures of 110°C and 149°C a mineral tobermorite is formed which maintains the great strength and low permeability of the C-S-H gel (Dowell Schlumberger, 1984). At even higher temperatures another favorable phase is formed and this is mineral xsonotlite being actually monocalcium silica hydrate and much stronger than α-dicalcium silicate hydrate. It not only maintains the strength, but prevents the growth of permeability. Except for the already mentioned chemical compounds that form in Portland cement cured at elevated temperatures, there are others which, even if in small quantities, can affect the performance of the set cement.

Set cement consisting mostly of calcium silicate hydrates with C/S ratios less than or equal to 1,0 are generally of higher compressive strengths and lower water permeabilities (Nelson, 1990).

When cement comes in contact with highly saline and corrosive geothermal water, particle size of the added silica is an important consideration. Silica is available in three different particle sizes, as silica sand, silica flour and silica fume (Table 3).

Table 3. Forms of silica
Tablica 3. Oblici kremena

Silica	Average particle size (µm) *Prosječna veličina čestica (µm)*
Silica sand *Kremeni pijesak*	175 do 200
Silica flour *Kremeno brašno*	15
Silica fume *Fini kremeni prah*	0,1

All three products stabilize Portland cement. Eilers and Nelson (1979) have investigated the effect of silica particle size on the performance of Class G cement formulations which cured at various temperatures in a geothermal brine. Salinity of the brine was 25000 mg/l TDS (total dissolved solids). Relationships between silica particle size and some parameters like compressive strength, water permeability and cement phase composition are shown in fig. 1. Cement slurry density was 1900 kg/m^3. Decrease in compressive strength and increase in water permeability occurred when the average silica particle size exceeded about 15 µm. Also, kilchoanite as a predominant phase replaced xonotlite. They have shown that the silica particle size had influence on the compressive strength and water permeability of a set cement, and this even more in lower density cement compositions.

Grabowski and Gillott (1989) studied the effects of silica fume added to Portland cement. In the same curing conditions (7 days, 230°C, 2,75 MPa), set cements to which silica fume was added developed a lower compressive strength, but due to changes in microstructure also a lower water permeability if compared with equivalent systems containing silica flour only.

Compressive strength of set cements prepared of low-density cement slurries (cement/pozzolan without silica, cement/bentonite) is lower when compared with those prepared of normal density slurries. Cement-pozzolan systems lose compressive strength, but still not so much as cement systems which contain bentonite, diatomaceous earth or perlite. Silica extenders, fly ash, bentonite or perlite can be applied to silica-stabilized slurries with safety to temperatures of about 232°C (Dowell Schlumberger, 1984).

Laboratory testing of long-term behaviour of typical low-density cement systems show that extenders have unfavourable influence on the set cement behaviour. This concerns fly ash in particu-

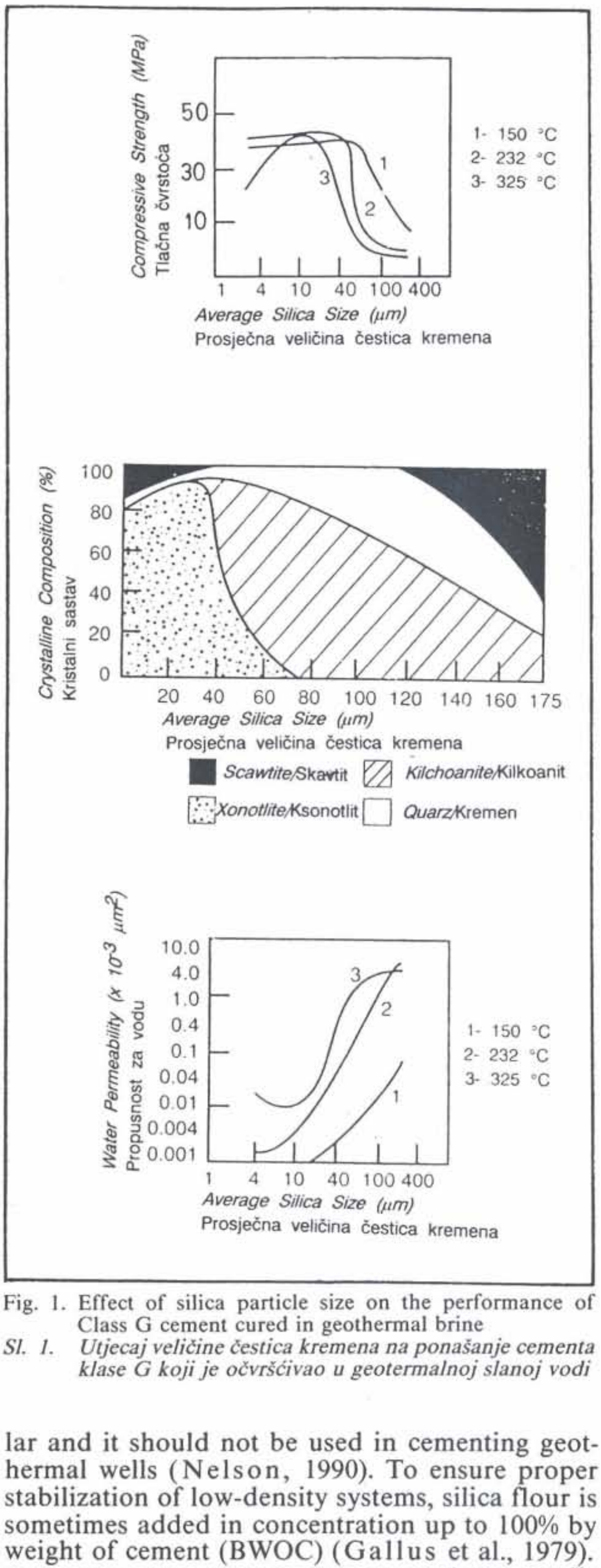


Fig. 1. Effect of silica particle size on the performance of Class G cement cured in geothermal brine

Sl. 1. Utjecaj veličine čestica kremena na ponašanje cementa klase G koji je očvršćivao u geotermalnoj slanoj vodi

lar and it should not be used in cementing geothermal wells (Nelson, 1990). To ensure proper stabilization of low-density systems, silica flour is sometimes added in concentration up to 100% by weight of cement (BWOC) (Gallus et al., 1979).

Addition of polymers, retarders and non reactive additives (i.e. kolite) to cements has no impact on the strength retrogression process.

Addition of water to a cement slurry or contamination with mud, or not enough silica in a cement slurry end up in weakening of set cement.

Reservoir Fluids Influence Set Cement

The chemistry of the reservoir fluids varies from fresh water to saline brines with greater than 200 000 mg/l total dissolved solids. Fluids from a geothermal well that produces dry steam contain relatively small quantity of salts and low concentrations of noncondensible gases, the most noticeable being H_2S. Reservoir brines often contain considerable quantities of carbonate and sulfate (Nelson, 1990).

a) Sodium Chloride

Sodium chloride in high concentration slows down a process of dissolving of silica (Nelson, 1990). Consequently, silica solids of larger dimension acquire dissolving speed that is not enough to ensure desirable calcium silica hydrates (C/S ratio <1). Dissolving speed can also be effected by dimension of solids in a solute. Silica solids of smaller dimensions have greater specific surfaces which allows enough quantity of silica.

b) Carbonates

Presence of carbonate in some geothermal waters presents a serious problem for Portland cement systems. Calcium silicate hydrates become instable in such chemical environment, even at ordinary temperatures. After they have been exposed to carbonates solutions, calcium silicate hydrates convert finally into a mixture of calcium carbonate and amorphous silica. The phenomenon has been observed in well cements by numerous researchers (Onan, 1984; Bruckdorfer, 1986; Shen, 1989).

Inquiries carried out by Hedenquest and Stewart (1985) showed that the traditional low — C/S ratio cement system with very low permeability were not suitable for geothermal wells with formations containing very high concentrations of CO_2.

Recent study by Milestone et al. (1986, 1987) has revealed the fact that tobermorite and xonotlite are among the least resistant cement phases to carbonation and that set cement deteriorate sooner if it contains bentonite. They have also found out that reducing silica flour concentration from 35% to 20% (BWOC) improves cement resistance to CO_2. Smaller quantities of silica give weaker and more porous calcium silicate hydrates, but a substantial quantity of calcium hydroxide remains in the system too. Upon substantial carbonation, calcium hydroxide reacts forming a protective layer of calcite, permeabitiy decreases and further attack is stopped.

c) Sulfates

Formation water usually contain magnesium and sodium sulfate. Magnesium and sodium sulfate react in contact with lime contained in cement and produce magnesium or sodium hydroxide and calcium sulfate. The calcium sulfate reacts with C_3A to produce calcium sulfoaluminat which is larger in volume and causes the cement to expand and disintegrate. Sulfate aggression ocures at temperature below 90°C (Dowell Schlumberger, 1984).

Water does not damage set cement at places where it is tightly bonded in all directions behing casing, but it is damaging at places of perforations or waterways causing expansion, strength retrogression, sloughing and cracking of set cement. In such circumstances large voids can be developed behind casing which is then exposed to corrosion.

Geothermal Wells Velika Ciglena-1 (VC-1) and Velika Ciglena-1a (VC-1a)

Geothermal reservoir aquifer of Velika Ciglena belongs to upper Triassic with dolomite and limestones. In the formation at the top of aquifer, within fractured dolomite breccias at depth of 2550 meters an extremely high temperature of 175^0C has been noted. It is 50^0C higher than expected according to thermal gradient of $0,043^0$C/m at the entrance of the aquifer.

In course of drilling of the VC-1 and VC-1a wells numerous data have been collected to evaluate prospects of the hot water reservoir (well productivity, composition and corrosiveness of reservoir water, presence of aggressive gases, behavior of installed equipment etc.)

The VC-1 well goes vertically to a depth of 4790 m. In drilling the well formations of carbonate compex of Triassic base have been drilled. Dolomites are reached at depth of 2550 m.

The VC-1a is directionally drilled and dolomites are reached at depth of 2640 m. Total depth is reached at 2956 m (true vertical depth is 2789 m).

VC-1 and VC-1a wells have similar technical characteristics from the top formation of reservoir to the surface (Fig. 2).

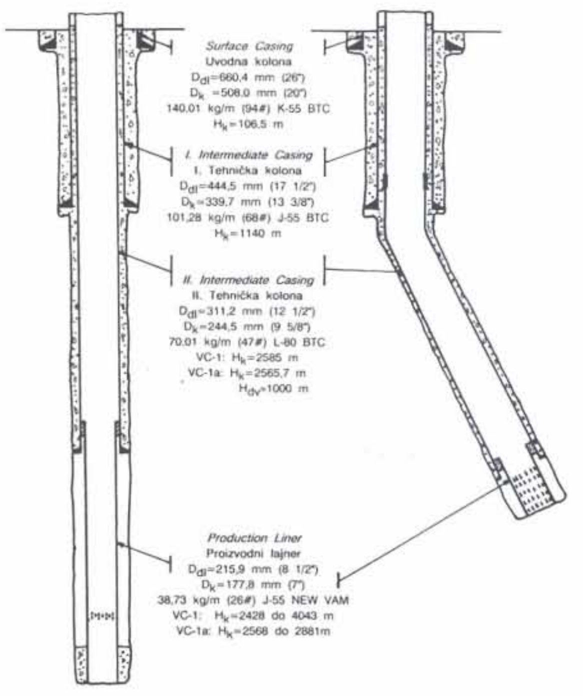


Fig. 2. Geothermal wells design VC-1 and VC-1a
Sl. 2. Konstrukcija geotermalnih bušotina VC-1 i VC-1a

The most porous part of the reservoir in the VC-1 well is protected by a liner of 177,8 mm in diameter from 2428 to 4043 m. The liner is hung in the previous tubing with hanger and packer, while further downhole 200 meters are cemented. The liner is additionally perforated at the interval from 3589 to 3595 m. In the VC-1a well a liner of 177,8 mm in diameter is set from 2568 to 2881 m. Liner is not cemented, and is slotted at following intervals: 2585—2644 m, 2678—2690 m, 2798—2822 m, 2834—2846 m, 2869—2881 m (intervals relate to measured depths).

Selected quality of steel for the casing ensures durability of installed equipment and secure activities in an environment with aggressive gases and liquids. Water of the geothermal reservoir of Velika Ciglena contains liquefied gases, mostly CO_2 ($GWR = 4 m^3/m^3$). Water compositon is shown in Table 4 (Valpotić, 1993).

Table 4. Results of water chemical analisys for wells VC-1 and VC-1a
Tablica 4. Rezultati kemijske analize vode iz bušotina VC-1 i VC-1a

Ions/*Ioni*	Velika Ciglena-1 (mg/l)	Velika Ciglena-1a (mg/l)
Cations/*Kationi*		
Amonia/*Amonij* (NH^+)	16	18
Sodium/*Natrij* (Na^+)	7584	8756
Potassium/*Kalij* (K^+)	320	330
Magnesium/*Magnezij* (Mg^{++})	48	15
Calcium/*Kalcij* (Ca^{++})	460	60
Strontium/*Stroncij* (Sr^{++})	9	10
Iron/*IŽeljezo* (total/*ukupno*)	88	5,5
Lithium/*Litij* (Li^+)	-	42
Anions/*Anioni*		
Chloride/*Klorid* (Cl^-)	11097	13252
Bromide/*Bromid* (Br^-)	-	76
Iodine/*Jodid* (J^-)	-	28
Hydrocarbonate/*Hidrogenkarbonat* (HCO_3^-)	2917	1064
Carbonate/*Karbonat* (CO_3^-)	-	-
Sulfate/*Sulfat* (SO_4^-)	193	81
Nitrate/*Nitrat* (NO_3^-)	-	13
Total dissolved salts *Ukupan sadržaj otopljenih soli*	22644	23750
Salinity/*Salinitet, NaCl*	18298	21291

Cementing of VC-1 well

Conductor casing of 508 mm in diameter was set to the depth of 106,57 m. It was equipped with a cement shoe (Halliburton), a bypass valve (Weatherford) at 101,65 m and 8 centralizers. Cementing was carried out through drilling pipes (inner string method). Cement slurry was displaced out of casing with 0,9 m^3 of mud. During displacing 8 m^3 of cement slurry has come out at the wellhead. Conductor casing was cemented to the surface.

First intermediate casing of 339,7 mm in diameter was set to the depth of 1140 m. It was equipped with a cementing shoe (Wetherford), a bypass valve (Weatherford) at 1115,89 m, 104 centralizers, 11 positive centralizers and 104 stop-rings. Cement slurry was displaced from the casing with 87,9 m^3 of mud. During displacing 5 m^3 of cement slurry has come out at the wellhead. The casing was cemented to the surface.

At drilling a borehole ($D_{dl} = 311,2$ mm) to set in the second intermediate casing, at depth of 2590 m a partial loss of mud occurred. 56 m^3 of polymer mud was lost. Setting a cement plug at the interval from 2490 to 2590 m the loss zone was restored. A cement plug was drilled and the casing of 244,5 mm in diameter was set to 2565,7 m. It was equipped with a cementing shoe (Halliburton), a bypass valve at 2543,74 m, a stop-link (Halliburton) at 2530,63 m, DV device (Halliburton) at 1000 m, 145 centralizers, 63 positive centralizers and 145 stop-rings. The casing was cemented in two stages. At the first stage cement slurry was displaced from the casing with 97 m^3 of mud. After the first stage was completed, DV device was opened and direct circulation initialized. During circulation 42 m^3 of cement slurry was displaced at the surface, what indicated that cement slurry density had been defined incorrectly. Circulation was continued during setting of cement while mud was replaced by water. At the second phase cement slurry was displaced from the casing through the openings on the DV device with 38 m^3. Ten m^3 of cement slurry was displaced at the wellhead.

Table 5. Some data about temperature during cementing and production in VC-1a well
Tablica 5. Podaci o temperaturama u bušotini VC-1a tijekom cementacije i proizvodnje

Casing string *Kolona zaštitnih cijevi*	Well head temperature (°C) *Temperatura na ušću (°C)*		Bottom hole temperature (°C) *Temperatura na dnu (°C)*	
	Cementing *Cementacija*	Production *Proizvodnja*	Cementing *Cementacija*	Production *Proizvodnja*
Surface *Uvodna*	12	150	16	151
I. Intermediate *I. tehnička*	12	150	52	160
II. Intermediate *II. tehnička*	12	150	140	172
Production *Proizvodna*	-	-	-	175

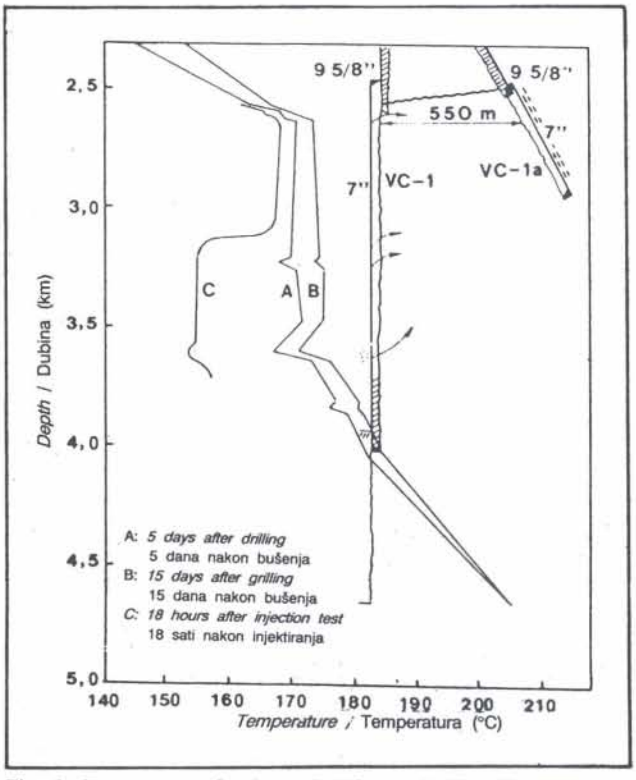
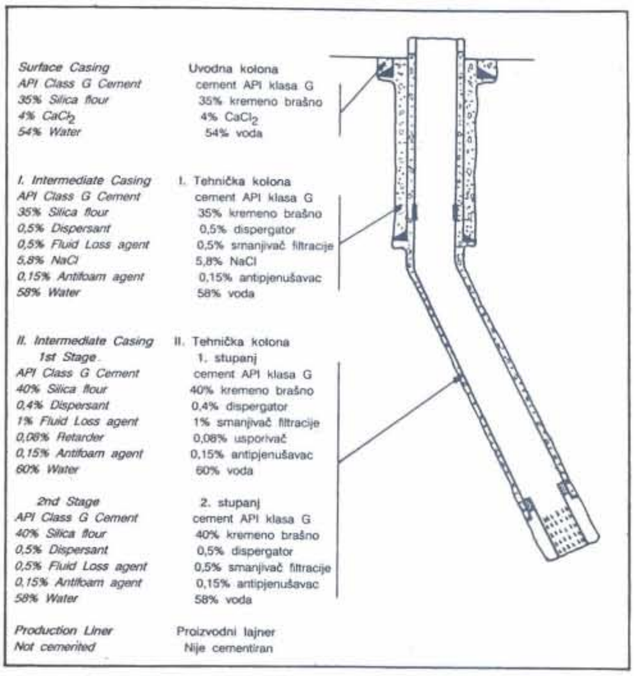


Fig. 3. Temperature in the well VC-1 at Velika Ciglena geothermal field
Sl. 3. Temperatura u bušotini VC-1 na polju Velika Ciglena



Surface Casing *API Class G Cement* *35% Silica flour* *4% CaCl$_2$* *54% Water*	Uvodna kolona cement API klasa G 35% kremeno brašno 4% CaCl$_2$ 54% voda
I. Intermediate Casing *API Class G Cement* *35% Silica flour* *0,5% Dispersant* *0,5% Fluid Loss agent* *5,8% NaCl* *0,15% Antifoam agent* *58% Water*	I. Tehnička kolona cement API klasa G 35% kremeno brašno 0,5% dispergator 0,5% smanjivač filtracije 5,8% NaCl 0,15% antipjenušavac 58% voda
II. Intermediate Casing *1st Stage* *API Class G Cement* *40% Silica flour* *0,4% Dispersant* *1% Fluid Loss agent* *0,08% Retarder* *0,15% Antifoam agent* *60% Water*	II. Tehnička kolona 1. stupanj cement API klasa G 40% kremeno brašno 0,4% dispergator 1% smanjivač filtracije 0,08% usporivač 0,15% antipjenušavac 60% voda
2nd Stage *API Class G Cement* *40% Silica flour* *0,5% Dispersant* *0,5% Fluid Loss agent* *0,15% Antifoam agent* *58% Water*	2. stupanj cement API klasa G 40% kremeno brašno 0,5% dispergator 0,5% smanjivač filtracije 0,15% antipjenušavac 58% voda
Production Liner *Not cemented*	Proizvodni lajner Nije cementiran

Fig. 4. Compositions of cement slurry during cementing in geothermal well VC-1a
Sl. 4. Sastav cementnih kaša pri cementiranju u geotermalnoj bušotini VC-1a

A liner of 177,8 mm in diameter was hung in the previous casing by hydraulic hanger (Brown) and a packer (CPH). Liner cementing was not predicted.

Temperature data from VC-1 well during cementing and production are presented in Table 5.

In Fig. 3 the compositions of cement slurries for cementing VC-1a well are listed.

Data on cementing the casings set in the borehole VC-1a shown in Table 6.

Table 6. Some data about casing cementing in VC-1a well
Tablica 6. Podaci o cementaciji kolona ugrađenih u bušotinu Velika Ciglena

Data *Podaci*	Surface casing *Uvodna kolona*	I Intermediate casing *I. tehnička kolona*	II Intermediate casing *II. tehnička kolona*	Production casing (liner) *Proizvodna kolona (lajner)*
Casing setting depth *(m)* *Dubina ugradnje (m)*	106,5	1140	2565,7	2568 to 2881
Casing diameter (mm) *Promjer kolone (mm)*	508,0	339,7	244,5	177,8
Cement slurry height (m) *Visina podizanja kaše (m)*	to 0,0	to 0,0	I st. to 1100 II st. to 0,0	- -
Slurry volume (m^3) *Volumen cem. kaše (m^3)*	40	117	135/45	-
Masa cementa (kg) *Masa cementa (kg)*	55000	157800	180000/60000	-
Waiting-on-cement-time (h) *Vrijeme čekanja na stvrdnjavanje cementa (h)*	18	36	24/48	-
Water/cement ratio *Vodocementni faktor*	0,54	0,58	0,60/0,58	-
Water/cement system ratio *Vodomješavinski faktor*	0,39	0,41	0,42/0,41	-
Thickening time (h) *Vrijeme zgušćavanja (h)*	2	2	3/2	-
Slurry density (kg/m^3) *Gustoća kaše (kg/m^3)*	1910	1880	1860/1890	-
Realized flow rate (m^3/s) *Postignuti obujamski protok*	0,016	0,036	0,04-0,03/ 0,03-0,012	
Type of flow *Tip protjecanja*	plug *čepoliko*	laminar *laminarno*	turbulent *turbulentno*	-

Conclusion

Geothermal cements encompass a wide variety of wellbore conditions and complex chemical processes. Many factors must be considered to determine optimal cement compositon for a particular situation. When static temperatures exceed 110^{0}C, 35% to 40% silica BWOC has to be added to Portland cements, otherwise, strength retrogression will occur. If saline geothermal brines are present, fine silica flour ($<15\mu$m particle size) should be added to Portland cements as a stabilizer. Silica sand does not reliably provide adequate protection. If high concentrations of CO_2 are present, Portland cement degradation can be inhibited by reducing silica concentration to 20% BWOC. If static temperature exceeds 232^{0}C, fly ash should not be used in Portland or Class J cement systems, but bentonite, perlite and diatomaceous earth are suitable. Microsphere and foamed cement systems made from a stabilized base slurry can be used in geothermal wells.

Laboratory testing (methods, conditions, cement, additives, water) is very important to provide successful geothermal wells cementing.

Received: 5.I. 1994.
Accepted: 9.VI. 1994.

REFERENCES

API Task Group on Cements for Geothermal Wells (1985): API Work Group Reports Field Tests of Geothermal Cements. *Oil and Gas Journal, Feb., 11,* 93—97.

Bayliss, B.P. (1972): Introduction to Geothermal Energy, paper SPE 4176.

Bruckdorfer, R.A. (1986): Carbon Dioxide Corrosion in Oilwell Cements, paper SPE 15176.

Buza, Ž. (1992): Izračunavanje zaliha geotermijske energije na primjeru ležišta Velika Ciglena, Diplomski rad, 75 pp. RGN fakultet (Faculty of Mining, Geology and Petroleum Engineering) Zagreb.

Cain, J.E., Shryock, S.H. & Carter, G. (1966): Cementing Steam Injecton Wells in California, *J. Pet. Tech., April,* 431—436, Dallas.

Čubrić, S. (1993): Power and energy of geothermal reservoirs in the Republic of Croatia, *Nafta, 44/9,* 459—470, Zagreb.

Dowell Schlumberger (1984): Cementing Tehnology, Nova Communicatons Ltd, 210 pp, London.

Eilers, L.H. & Nelson, E.B. (1979): Effect of Silica Particle Size on Degradation of Silica Stabilized Portland Cement, paper SPE 7875.

Eilers, L.H., Nelson, E.B. & Morgan, L.K. (1983): High-Temperature Cement Composition-Pectolite, Scawtite, Truscottite, or Xonotlite: Which Do You Want?, *J. Pet. Tech., July,* 1373—1377, Dallas.

Gallus, J.P., Pyle, D.E. & Watters, LT. (1978): Performance of Oil-Well Cementing Compositions in Geothermal Wells, paper SPE 7591.

Gallus, J.P., Pyle, D.E. & Moran, L.K. (1979): Physical and Chemical Properties of Cement Exposed to Geothermal Dry Steam, paper SPE 7876.

Grabowski, E. & Gillott, J.E. (1989): Effect of Replecement of Silica Flour with Silic Fume on Engineering Properties of Oil-well Cements at Norml and Elevated Temperatures and Pressures, *Cement & Concrete Res., 19,* 333—344.

Harms, W.M. & Febus, J.S. (1984): Cementing of Fragile-Formation Wells With Foamed Cement Slurries, paper SPE 12755.

Hedenquist, J.W. & Stewart, M.K. (1985): Natural CO- Rich Steam — Steam-Heated Waters in the Broadlands-Ohaaki Geothermal System, New Zealand: Their Chemistry Distribution and Corrosive Nature, Geothermal Resources Council, International Symposium on Geothermal Energy, 1—9.

Krklec, G. (1983): Cementne kaše za cementiranje geotermalnih bušotina, Diplomski rad, 56 pp, RGN fakultet (Faculty of Mining, Geology and Petroleum Engineering) Zagreb.

Milestone, N.B., Sugama, T., Kukacka, L.E. & Carciello, N. (1986): Carbonation of Geothermal Grouts — Part 1: CO_2 Attack at 150^{0}C, *Cement & Concrete Res. 16,* 941—950.

Milestone, N.B., Sugama, T., Kukacka, L.E. & Carciello, N. (1987): Carbonation of Geothermal Grouts — Part 2: CO_2 Attack at 250^{0}C, *Cement & Concrete Res. 17,* 37—46.

Milestone, N.B., Sugama, T., Kukacka, L.E. & Carciello, N. (1987): Carbonation of Geothermal Grouts — Part 3: CO_2 Attack on Grouts Containing Bentonite, *Cement & Concrete Res. 17,* 295—306.

Nelson, E.B. (1990): Well Cementing, Elsevier 340 pp. Amsterdam.

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

Ostroot, G.W. & Walker, W.A. (1961): Improved Compositons for Cementing Wells with Extreme Temperatures, *J. Pet. Tech., March,* 277—284, Dallas.

Shen, J.C. (1989). Effects of CO_2 Attack on Cement in High Temperature Applications, paper SPE 18618.

Shryock, S. H. (1984): Geothermal Well Cementing Technology, paper SPE 12454.

Shryock, S.H. & Smith, D.K. (1980): Geothermal Cementing — The State-of-the-Art, C-1274. Halliburton Services paper No. C-1274, Duncan.

Suman, G.O. & Ellis, R.C. (1977): Cementing Handbook, Gulf Publishing Co. 56 pp., Houston.

Valpotić, N. (1993): Mogućnost uporabe geotermijske energije sa nalazišta Velika Ciglena, Diplomski rad, 67 pp. RGN fakultet (Faculty of Mining, Geology and Petroleum Engineering) Zagreb.

*** Izvještaj o cementaciji zaštitnih kolona u bušotini VC-1a (1990), Stručna dokumentacija, INA-Naftaplin, Zagreb (unpubl.).