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RESEARCH NOTE

Considerations of Well Cementing Materials in High-pressure, High-temperature Conditions

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ABSTRACT

As worldwide demand of hydrocarbon is growing fast, the oil and gas companies have been forced to explore reservoirs with more hostile conditions, such as high-pressure, high-temperature conditions. Improved technology, material selection and testing procedures are required to overcome the common problems in these conditions. One of the main phases of well construction is cementing job. Appropriate selection of cementing material can guarantee a successful cementing job. Many researchers investigated the required cement properties for applications in high-pressure, high-temperature conditions. However, the focus of their work was on the mechanical properties of set cement, while the other properties have not been studied enough. The purpose of this work is to produce a high resistant cement system, which can satisfy the other essential requirements at the same time. The main other requirements include free fluid content, thickening time and expansion capability, which have been investigated in this work. The results show that although some cement systems have high mechanical resistant, but their application is limited due to undesirable values of other properties. Therefore, different additives have been used to adjust the properties of the final cement system. The high-resistant cement is produced by adding siliceous material. Free fluid content, thickening time and expansion capability of the high-resistant cements are adjusted by adding polyvinyl alcohol, lignosulfonate and MgO, respectively. The combined effect of these additives is investigated to develop a high-resistant system, which has optimum values of other essential properties too.

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1. INTRODUCTION

One of the most difficult and expensive phases of oil and gas well construction is cementing job. Cements are pumped inside the wellbore to fill the annulus space between the casing and surrounding rock formation, provide structural integrity to the wellbore, support casing, protect it against corrosion and prevent the unwanted migration of fluids from one layer to another. An effective cementing job can guarantee the long-term production life of the well and reduce the operational problems and costs of future workovers [1]. In practice, different design and composition of cement systems are utilized based on the available material and the geological condition inside the wellbore. In recent years with the fast development of petroleum exploration and drilling technology, wells have been drilled and completed in more complex environments, like high-pressure, high-temperature (HPHT) conditions. The well is situated at HPHT condition if the bottomhole pressure is more than 69 Mpa and/or bottomhole temperature is more than 150 ˚C. Despite the extensive technological development of cement materials, problems of cementing in these environments still remain.

Many researchers investigated different aspects of the above problem and studied the cement properties at elevated temperatures and pressures [2-7]. However, the main attention was on the mechanical and strength properties of the set cement. Krakowiak et al. [8] have worked on the mechanical and chemical properties of conventional oil well cements at temperatures up to 200 °C. They studied the micro-structure and micro-texture of neat oil well cement and silica-rich cement at elevated temperatures. In another work, Ulm and James

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[9] studied the effect of high temperature and pressure on the fracture toughness of a series of baseline oil well cement formulations. Pang et al. [10] tested a variety of different types of oil well cements to study the effects of curing temperature and pressure on their tensile test behavior. In the work of Le Saout et al. [11], the chemical structure of cement aged at normal and elevated temperatures and pressures have been studied.

This research studies not only the mechanical and strength characteristics, but also other important properties of especially formulated cement at elevated temperatures and pressures.

2. MATERIALS AND SLURRY DESIGN

The cementitious material considered in this work was ordinary Portland cement obtained from local providers inside the Russian Federation (composition (wt.%): 61.34 C_3S, 14.61 C_2S, 5.49 C_3A, 16.62 C_4AF). C_3A and C_4AF have little contribution to the cement strength development. C_3S is responsible for early strength development, while C_2S is responsible for final strength development of the Portland cement. With respect to high temperature and high pressure conditions, additives have been used to modify the cement properties. Sand and silica flour were added to the cement systems to provide high mechanical properties by optimizing the material compactness. Silica flour with a mean particle size of 20 μm was formed by grinding of quartz sand and contained more than 98% SiO_2. Manganese tetraoxide (Mn_3O_4) was used as the weighting agent to obtain cement slurries with density above 2000 kg/m^3. Manganese tetraoxide is a water-dispersible additive with narrow particle size distribution, high density (4.8 SG) and hardness. To prevent the set cement shrinkage magnesium oxide (MgO) was used to enhance the cement expansion capability.

Cements with expansion behavior result in improved annular sealing during well cementing and underground gas storage [12]. Other components of the mix cements included antifoaming agent, lignosulfonate retarder, a clay mineral (attapulgite) as anti-settling agent and polyvinyl alcohol as fluid loss control additive. The total mass of these additives was less than 6% by weight of the dry blend.

3. EXPERIMENTAL METHODS

3. 1. Sample Preparation The cement samples were prepared in accordance with standard procedures, which involved dry premixing of Portland cement, weighting material, silica sand or silica flour and magnesium oxide. The retarder, polyvinyl alcohol, attapulgite and antifoaming agent were added directly to the water and mixed manually. Then prepared dry composition and water were mixed for 3 minutes. The water-to-cement mass ratio for all systems was W/C = 0.5. W/C ratio can significantly affect the properties of the slurry (thickening time, flowability, free fluid content, etc.) and set cement (strength properties, permeability, etc.). W/C = 0.5 was considered as the most common value for the W/C, which is used in field applications. One part of the prepared mixture was taken for further investigations on the slurry. The other part was casted into cylindrical steel moulds (diameter 40 mm, height 40 mm) with the aid of jolting apparatus. For curing purposes the moulds were placed in a high temperature and pressure cell, where pressure was imposed with CO_2 gas. The rationale behind selecting the curing conditions is to simulate field conditions of oil wells based on published literature. After 24 hours curing, samples demoulded and left inside the water for 3 days before subjecting to different laboratory tests. Table 1 summarizes different cement compositions and curing conditions considered in this study.

TABLE 1. Composition and curing conditions of different cement systems

Composition	Blend materials, % mass concentration					Other additives, % by the weight of the blend				Curing conditions
	Portland cement	Mn_3O_4	Silica sand	Silica flour	MgO	Lignosulfonate	Attapulgite	polyvinyl alcohol	Antifoam agent	
1	85	15	-	-	-	-	2	-	0.5	Room condition
2	85	15	-	-	-	-	2	-	0.5	t= 120 °C, P= 150 psi (24 h)
3	70	15	15	-	-	-	2		0.5	t= 120 °C, P= 150 psi (24 h)
4	70	15	-	15	-	-	2	-	0.5	t= 120 °C, P= 150 psi (24 h)
5	70	15	15	-	-	-	2	2.5	0.5	t= 120 °C, P= 150 psi (24 h)
6	70	15	-	15	-	-	2	2.5	0.5	t= 120 °C, P= 150 psi (24 h)
7	70	15	-	15	-	1	2	2.5	0.5	t= 120 °C, P= 150 psi (24 h)
8	65	15	-	15	5	1	2	2.5	0.5	t= 120 °C, P= 150 psi (24 h)

3. 3. Free Fluid Test Minimizing the free fluid content of cements is essential to help to eliminate channels that may serve as pathways for formation fluids. These channels highly affect the quality of cementing job. In order to measure free-fluid content, the prepared slurry was stirred for 20 minutes at a speed of 150 r/min, and temperature of 25 °C in an atmospheric consistometer. After 2 hours the volume of developed supernatant fluid was measured and recorded as free fluid content. Later the milliliters of free fluid can be converted to a percentage of free fluid using following formula [14]:

$$\%FFC = \frac{V_{FF} \cdot \rho}{m_0} \quad (1)$$

in which V_{FF} is the recorded value of free fluid content in cm^3, ρ is the density of the cement slurry in g/cm^3 and m_o is the starting mass of cement slurry before stirring in consistometer in g.

3. 4. Thickening Time Thickening time is the duration between the beginning of cement preparation and when the cement attains 100 Bearden units (Bc) of consistency. Bearden units (Bc) of consistency are used to express the resistance of the cement to flow (pumpability). Cements with higher amounts of consistency are less pumpable in comparison with cement with lower values of Bc. The sufficient thickening time allows proper slurry placement in the annulus. The range of consistency is between 0 and a maximum of 100 Bc. Industrial data show that the optimum consistency range is 10– 30 Bc and for cement slurries with a consistency of larger than 70 Bc difficulties are considerable during pumping. The thickening time in this study is measured using a pressurized consistometer. The times of 30 Bc and 70 Bc, which are the optimum and maximum allowable consistency ranges respectively, are reported for all cement compositions.

3. 5. Expansion Capability It is known for a long time that the reaction of cement with water (hydration) leads to volumetric shrinkage of hardened paste, in result of which, pore space are developed around the cement body. These developed pore spaces and mechanical shocks, caused by milling inside the casing or tripping operations result in poor bonding between the cement and casing and subsequently fluid migration into the well [15]. Application of expandable cements can minimize these negative effects and increase the bonding quality between cement and casing. CaO and MgO are considered as the most used additives to create expandable cements with high bonding quality. However, MgO is used in this work due to its better performance at elevated temperatures [16]. Expansion cells are used to investigate the behavior of cement systems containing MgO as expandable additive. The cell is filled with the cement and then is cured for a specified time. As the cement expands, the sleeve of the cell moves along the cell pins. The expansion is calculated by measuring the distance between the pins, before and after cement hardening process.

4. RESULTS AND DISCUSSION

4. 1. Compressive Strength Compressive strengths of samples 1 to 4 are presented in Figure 1. Samples 1 and 2 are reference samples with no additive. The first sample is cured in room condition, whereas the second sample is cured at HPHT conditions.

It can be seen that the compressive strength is decreased in reference sample by increasing temperature and pressure. The problem of decreased strength is solved by adding silica content to the cement. In compositions 3 and 4, silica sand and silica flour are added to cement in a mass concentration of 15%. Samples containing silica flour developed more compressive strengths than samples containing silica sand. The difference in the strength development of these samples can be attributed to the fine particles of silica flour, which can be positioned more closely between cement particles, producing smaller pore spaces to improve the strength properties of the cement. Additionally silica flour particles can more effectively participate in pozzolanic reactions, due to the fact that the rate of these reactions is proportional to the amount of available surface area for the reaction.

4. 2. Free Fluid Content The percentage of free fluid content for the slurry compositions 1, 3, 4, 5 and 6 are presented in Figure 2. The results show more free water content for sample 3 which contains silica sand. The higher surface area of silica flour particles results in less free fluid content in sample 4. In samples 5 and 6 the polyvinyl alcohol is added to investigate its effect on the volume of free fluid content. Result demonstrate no free fluid in the samples containing polyvinyl alcohol with silica flour.

4. 3. Thickening Time Although cement compositions containing silica flour develope more compressive strengths and demonstrate no free fluid content using polyvinyl alcohol, but the pumping time of these slurries may not meet the requirement for HPHT applications. Figure 3 shows the consistency of measurements of samples 1, 5, 6 and 7. It can be seen that the thickening time (in which the consistency reaches 70 Bc) of slurry 6 containing silica flour is shorter than slurries containing silica sand. Lignosulfonate was added to sample 7 as a retarder to control the thickening time and adjust it based on the requirement of the HPHT environments.

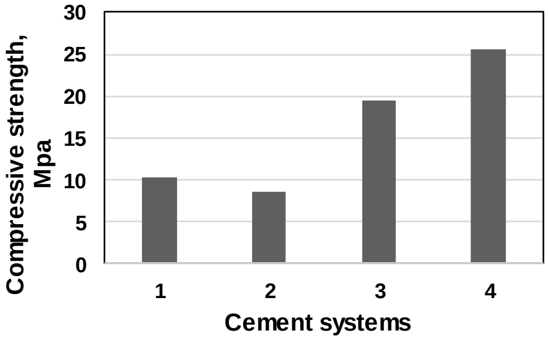

Figure 1. Compressive strength values of cement samples

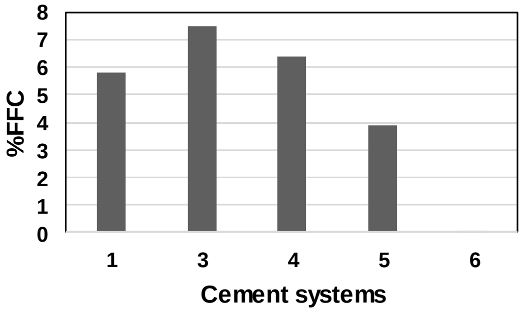

Figure 2. Free fluid content of cement samples

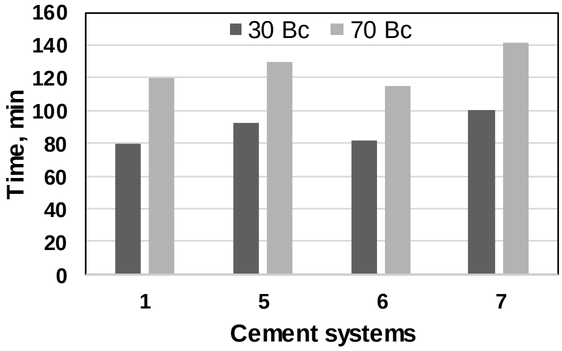

Figure 3. Thickening time of cement systems

4. 4. Expansion Capability Sample 7 containing silica flour, polyvinyl alcohol and lignosulfonate demonstrated reliable compressive strength, consistency values and no free fluid content. But due to the shrinkage of hardened cement, poor bonding quality between the casing and cement was expected. Therefore expanding additive was utilized to solve the problem. Adding MgO to the sample 7 resulted in an expansion value of 4.6%. MgO was selected based on its behavior at high temperature conditions, as expansion is more temperature-sensitive than pressur-sensitive. CaO expandable cements can hardly be applicable at temperatures above 80 °C.

5. CONCLUSIONS

A proper cement slurry design can significantly improve the quality of oil well cementing job. With complexities like HPHT conditions developing high quality cementing materials remains a challenge. Most attention in these conditions is on the high mechanical properties of cements, which are enhanced by adding silica contented materials. In this study, 8 cement slurries were formulated to investigate characteristics of the cements like free fluid content, thickening time and expansion capability.

The results show that cements containing silica flour represented better mechanical response and compressive strength values. Although these samples demonstrate less amount of free water due to their high surface area, but polyvinyl alcohol is essential to reach no free water content (0%). Silica flour also affects the thickening time of the slurries. Controlling the thickening time is possible by use of lignosulfonate retarder. Without a retarder, a cement system with silica flour may not meet the pumping requirements. Also to ensure a quality bond between the cement and casing, expansion capability of samples with MgO was investigated.

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چکیده

با افزایش نیاز جهانی به منابع هیدروکربنی، شرکت های نفت و گاز مجبور به اکتشاف و استخراج مخازن با شرایط سخت تر، نظیر شرایط فشار و دمای بالا گردیده اند. برای غلبه بر مشکلات رایج در این شرایط، فناوری، انتخاب مواد و روش های آزمایشگاهی بهبود یافته مورد نیاز است. یکی از مراحل اصلی ساخت چاه، عملیات سیمان کاری است. انتخاب مواد سیمان مناسب می تواند تضمین کننده عملیات سیمان کاری موفق باشد. محققان زیادی خواص مورد نیاز سیمان برای کاربرد در شرایط فشار و دمای بالا را مورد یررسی قرار داده اند. اما تمرکز کار آنها بر روی خواص مکانیکی سنگ سیمان است، در حالی که خواص دیگر به حد کافی مورد یررسی قرار نگرفته اند. هدف این کار تولید یک سیمان مقاوم است که می تواند خواص دیگر مورد نیاز را نیز تامین کند. خواص اصلی دیگر شامل محتوای سیال آزاد، زمان بندش و قابلیت انبساط هستند که در این پژوهش مورد بررسی قرار گرفته اند. نتایج نشان می دهد که اگر چه بعضی سیستم ها خواص مکانیکی بالایی از خود نشان می دهند، اما کاربرد آنها با توجه به مقادیر نامناسب خواص دیگر ممکن نیست. بنابراین مواد افزودنی متفاوت برای تنظیم خواص سیمان استفاده شده اند. سیمان با مقاومت بالا از طریق افزودن مواد سیلیکایی به دست می آید. محتوای سیال آزاد، زمان بندش و خاصیت انبساطی سیمان مقاوم به ترتیب با افزودن پلی وینیل الکل، لیگنوسولفانات و اکسید منیزم تنظیم می گردد. اثر ترکیبی این افزودنی ها با هدف توسعه سیستم مقاوم، همراه با مقادیر بهینه دیگر خواص ضروری، بررسی گردیده است.

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