Journal of Petroleum Science and Technology

Application of Particle Size Distribution Engineering and Nano-technology to Cement Recipes for some Highly Deviated Wellbores in Iran

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ABSTRACT

The design of cement slurry for horizontal wellbores is challenging as it must present very high quality cement slurry properties e.g. zero free water, less than 50 cc API fluid loss value, appropriate rheology and yield point for effective displacement, adequate compressive strength, which is critical for lightweight slurries, and finally stable cement column behind casing. The main objective of these requirements is to provide unique cement sheath in the upper side of annulus as well as the lower side and to guarantee complete zonal isolation.

These requisite conditions could be rarely met especially when lightweight cement is needed. Four cement recipes were made and named as RIPI-1 through RIPI-4 representing standard slurry with a density of 118 pounds per cubic feet (pcf), traditional lightweight slurry with a density of 90 pcf, lightweight slurry with engineered PSD and nanoparticles in a liquid form, and finally another type of PSD and nanopowder respectively. These slurries were tested at the temperature and pressure of Iranian Balal, Soroush, and Siri oilfields and finally were compared with those slurries previously used in the oilfields. According to the results, reductions in yield point up to 84% and in fluid loss value up to 44% were recorded by the recipes. Moreover, an increase in compressive strength up to 82% was measured and the maximum strength of 2500 psi was obtained for slurry RIPI-4. All the slurries designed showed adequate stability. However, significant improvements were achieved by slurries RIPI-3 and RIPI-4 with engineered PSD and nanoparticles.

Keywords: Horizontal Cementing, Nanosilica, Particle Size Distribution, Compressive Strength Development

INTRODUCTION

The history of horizontal wells to increase production from reserves backs to 1920's and during several decades it has been under development. The potential applications of horizontal drilling are numerous. They can be related to the targeted location, reservoir characteristics, the nature and properties of formation fluids, or even to an overall field development plan. Nowadays, there is no doubt in their commercial viability. The productivity of a horizontal well can be up to six times more than what a typical vertical well may produce. This significant difference makes it worthy to study horizontal wellbores cementing.

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Article history

Received: December 21, 2013
Received in revised form: April 23, 2014
Accepted: July 27, 2014
Available online: July 26, 2015

Journal of Petroleum Science and Technology **2015**, 5(2), 70-83 http://jpst.ripi.ir

At present, most horizontal wellbores are designed to be completed without cementing. The horizontal section is often lined with a slotted liner, pre-perforated liner or, in some cases, wire wrapped sand control liners. In such conditions, the formation lithology must show sufficient integrity to prevent collapse or sloughing, particularly when the producing formation is approaching depletion. In some cases, these wells are left open hole without any aforementioned completion methods. The previous highly deviated intermediate casing must have a good cement job. However, there are some circumstances that horizontal wells and production intervals must be cased off and cemented, and some forms of isolation must be initiated. Some of these situations are 1) multi-interval stimulation treatments, 2) where water cones or gas coning problems are likely, and 3) when water or gas breakthrough in producing formation may occur [1].

The design of cement slurry for deviated or horizontal sections is challenging as it must present very high quality cement slurry tested and designed according to tough test conditions and standards. For example, cement slurry to be used in horizontal well must have zero free water in all inclinations since little amounts of free water can cause severe lack of zonal isolation especially in upper sections of annulus (Figure 1). In addition, cement shrinkage, gas or water intake from formation to cement sheath, and high fluid loss from cement slurry to formation may lead to improper zonal isolation. These tough requirements could be rarely met especially when lightweight cement is needed. In this study, all the relevant data of some offshore oil fields of Iran such as Balal, Soroush, and Siri have been reviewed and the properties of cement slurry used in the wells have been collected. Then, the cement slurry, which can meet the requirements of horizontal cementing according to standards, has been designed and finally a comparison is made between the traditional cement system previously used in the fields by service companies and the one designed by RIPI.

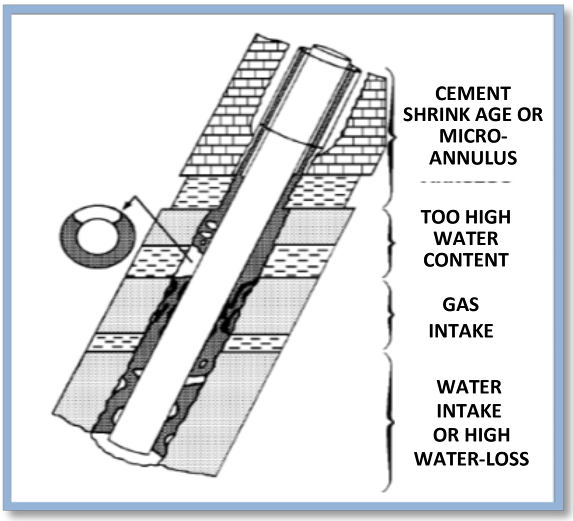

Figure 1: Challenges of cementing in a highly deviated wellbore

Design Challenges of Cement

All cement slurry properties must be kept within the acceptable ranges defined by the API standard for horizontal cementing. For example, the amount of fluid loss for normal cementing conditions (e.g. vertical wells or low inclination) should be less than 100 milliliters per 30 minute of testing, which is considered standard fluid loss but it should be half for horizontal cementing purposes. The pattern of thickening time for slurry should be in the right angle mode to decrease the possibility of excessive gel development and gas migration phenomena. In addition, the compressive strength development pattern in the slurry should be in such a way that the optimum *wait on cement* (WOC) with a reasonable final strength is available. However, the most important design criterion in the lab is the slurry stability. Stability can be divided into two categories: free water content and settling tendency of solid contents (density segregation) in slurry. It was not until 1978's [2, 3] that the industry began to explore the possible relationship between flow-after cementing and changes in hydrostatic pressure due to the accumulation of free water. Most of the research up to this period of time was conducted without considering the effect of increased temperature, pressure, and deviation. However, later research included elevated temperature and found as much as an 8% increase in free water over tests conducted as per API Section 6 at 80 °F (26.7 °C). When the effect of deviation was included, further research found the vertical API test to be very optimistic, and the authors suggested that procedural modifications should be considered to test and free water at a 45° angle [4]. It was found that free water was controlled by temperature, pressure, and the angle of deviation. Even the mixing energy and annular dimension had an impact on free water content. Higher shear stress applied by mixing procedure can decrease the free water. This free water content is directly changing with the angle of deviation, but at deviations higher than 45 degrees, no substantial increase was observed. Pressure shows higher direct effect on solid settling rather than on free water [2,4]. For testing the density segregation, the procedure stated by API Spec 10 A can be used [5]. In this method, the cement slurry is cured under down hole conditions for 24 hours and then the set cement is cut to 3 or 4 similar sections and the density of each section is measured via Archimedes law as follows:

$$\rho_{section}=\frac{m_a}{m_w} \qquad (1)$$

where, m_a is the weight of set cement section in the air and m_w stands for the weight of set cement section when hanging in water.

Then, the relative density of each section is compared to the density of slurry before curing and a stability profile is established. The ideal profile is a flat one, which shows similar density between the top and bottom of the set cement column. If lower sections show higher density, then, there is density segregation in the cement column. In lightweight and heavy weight cements, there is a tendency for solid segregation; in fact, in lightweight cement the lightweight additives tend to float on top, while in heavy weight cements, weighting agents tend to settle.

For this study, the cementing program of Iranian hydrocarbon fields such as Balal, Soroush, and Siri was studied carefully and tested in lab again. Based on these data, it was clarified that two cement systems were needed if one would design cementing program for horizontal or highly deviated wellbores in these oil and gas fields. In addition to standard cements with a density of 118-120 pounds per cubic feet (1.89-1.92 S.G), a lightweight cement system with a density of 85-95 pcf (1.36-1.52 S.G) was also desired.

Generally, conventional lightweight cements present high free water and fluid loss. They suffer from low compressive strength and delayed strength development. Definitely, these cement systems are not suitable candidates for cementing horizontal sections as they are very likely prone to formation fluid migration and lack of zonal isolation. Therefore, the main challenge at this stage is to formulate a lightweight cement system, which meets all sever standard requirements for cementing horizontal wellbore intervals.

Lightweight Cement Systems

Three methods, which can be used to prepare lightweight cement systems, are as follows:

1. Using extender additives (additives which adsorb water to reduce the density);

2. Lightweight additives (low density additives to decrease the overall density of the solid content [6]);

3. Nitrogen system (pumping nitrogen to cement and reducing the weight).

The most famous extenders to be used for lightweight systems are bentonite, diatomite, pozzolan, perlite, and microsilica. These additives viscosity the cement slurry and do not pose solid segregation problems, but the cement system does not show adequate compressive strength and free water and fluid loss control properties. In addition, most of these solids represent strength retrogression [6-8].

In RIPI, it took great effort to achieve to a lightweight slurry system, which showed significantly improved test results, using nanotechnology and particle size distribution (PSD) engineering. For PSD purposes, D124 or Litefill system was used. It consists of hollow spherical solid particles filled with nitrogen or CO_2 to be light enough to reduce the density of solid fraction of slurry [9]. The diameters of the spheres range between 60 to 315 microns. These spheres consist of Al_2O_3 (35%) and SiO_2 (65%) and they can be applied to cement powder in dry blend. It does not take additional water, thus the compressive strength is increased and the overall porosity is reduced. With these particles, the slurry weight can vary between 67 to 90 pcf according to the design. Figure 2 shows the SEM image of Litefill additive.

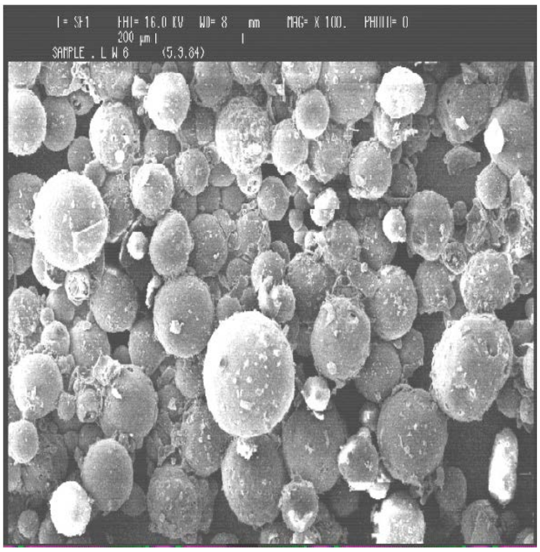

Figure 2: The SEM image of Litefill particles with 100X magnification

Another constituent of the RIPI novel system is a liquid extender which is mainly composed of especially processed amorphous inorganic microsilica with a diameter of 0.15 microns and a specific area of 21 m^2/gr. It reacts with calcium hydroxide released by cement hydration to form calcium silicate hydrate (C-S-H), which results in higher bonding between particles and improved compressive strength. Figure 3 shows the SEM image of this special liquid extender called Microblock™.

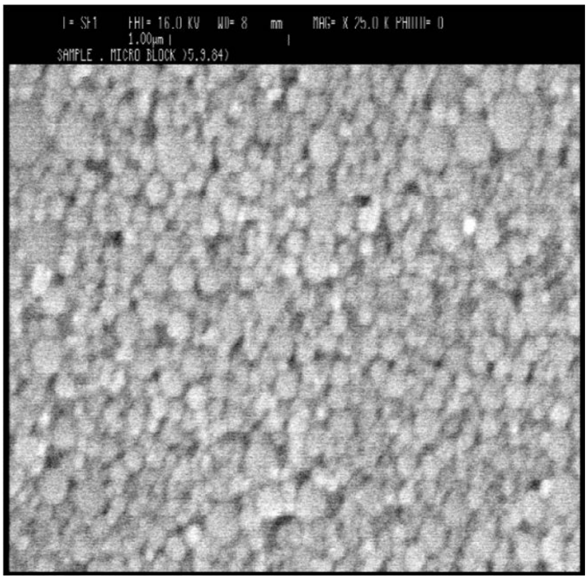

Figure 3: The SEM image of Microblock with 75X magnification

The benefits of using Microblock and the related mechanisms are as follows:

1. Zero free water: as Microblock proposes high surface area, it acts like a strong water-wet material;

2. Reduced fluid loss: since Microblock reduces the overall porosity of the filter cake, the amount of fluid loss is reduced as well;

3. Low friction (viscosity): very fine particles of Microblock reduce the friction between solid particles in such a way a lubricant does and thus the equivalent circulation density is decreased, which is beneficial in long radius horizontal and low-diameter wellbores;

4. High early and final compressive strength: due to high pozzolanic reactivity and silica content and surface area, the compressive strength is

sometimes 30 percent higher than the API recommended compressive strength;

5. Higher stability: due to higher surface tension between particles, Microblock helps maintaining floating forces and prevents solids from settlement or segregation.

Another magic particle with a different size in a nanorange is a kind of hydrophobic silica which is called HSL. This product, which is processed in RIPI, exhibits superior properties in term of compressive strength, free water, fluid loss control ability, and cement stability profile. The mechanism of improvement is similar to what can be seen by Microblock, but in a more effective way. This material is basically a pure non-crystallized silica powder combined with plenty of other constituents with a significant surface area (100 m^2/gr), which is contributing to its remarkable successful applications. Figure 4 shows the SEM image of HSL particles.

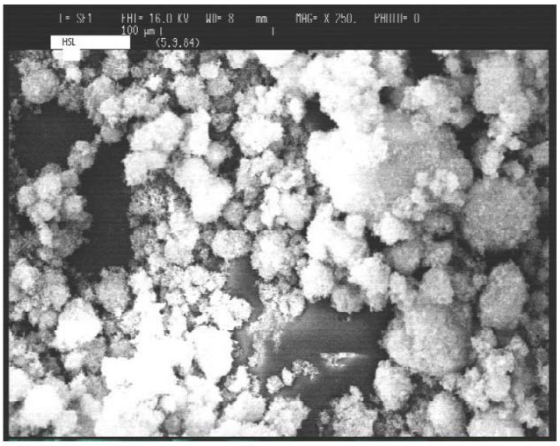

Figure 4: The SEM image of HSL particles with 750X magnification

The Optimum Cement Design

The main idea in cement design by RIPI is based on applying particles with a nonuniform size, which is known as particle size distribution (PSD). Finer lightweight additives fill between cement particles and increase the solid content in the unit volume of cement slurry and reduce the porosity of set cement. Due to lower water to solid ratio, it results in faster and higher compressive strength progression. The size of HSL particles are around 0.1 micrometer and fill between cement particles with a diameter of 50 microns, Litefill additive with a size of 60 to 315 microns, and Microblock particles with a size of 0.5 microns. With this particle size distribution, the cement designed by RIPI presents lower porosity, permeability, free water, and fluid loss value and higher compressive strength. Figure 5 shows a schematic of particle size distribution technology (PSD) [9].

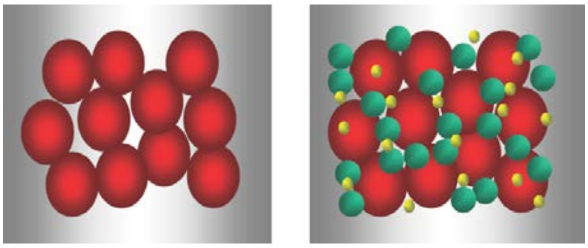

Figure 5: A comparison of void spaces between optimum cement design with a PSD (right) and traditional design (left)

In addition to particle size, another difference between HSL particles and microspheres is their reactivity in cement slurry. Most of lightweight additives such as microspheres are chemically neutral and used just as filler in between other solid particles. Since they increase the volume of water in cement, the final compressive strength is inversely affected. Nanoparticles propose higher surface area and they increase the rate of chemical reactions taking place in cement slurry during hydration. Even at low temperatures, these particles react with the lime content in cement powder to produce a cement phase, and thus they increase the compressive strength [6,7].

EXPERIMENTAL PROCEDURES

Tables 1 and 2 show the slurry composition designed by Schlumberger (Dowell) for Balal and Soroush oil fields respectively. It should be noted that Sor.20-26 refers to well numbers 20 to 26 in Soroush oil field. The first step to design cement slurry is to determine the range of density and applicable pressure and temperature. Based on the data of the aforementioned oil and gas fields, two slurries with a density of 90 and 118 pcf were proposed. The range of bottom hole static temperature (BHST) falls between 70 to 90 °C and the bottom hole circulating temperature (BHCT) is in the range of 50 to 70 °C. In addition to standard cement with a density of 118 pcf (RIPI-1), two types of lightweight cement slurry were designed. One contains D124 as hollow spherical solid particles without any particle size distribution and nanotechnology (RIPI-2), while the other type of cement slurry, based on D124 lightweight additive, uses an engineered PSD and contains nanoparticles (RIPI-3).

Table 1: Slurry composition for Balal oil field wells

Well ID.	CMT G (gr)	Water (cc)	Fluid Loss Controller (gr)	Dispersant (gr)	Retarder (gr)	Antifoam (cc)	Para Gas (cc)
Balal 7I. 7" & 4.5" Liner	1000	417	4	5.5	2.5	1.33	26.6
Balal 8I. 7" Liner	1000	404	3	2	5	1.33	39.95
Balal 9I. 7" Liner	1000	417	4	5.5	3	1.33	26.63
Balal 10I. 7" Liner	1000	404	3	2	4.5	1.33	39.95

Table 2: Slurry composition for Soroush and Siri oil field wells

Well ID.	CMT G (gr)	Water (cc)	Fluid Loss Controller (cc)	Dispersant (cc)	Retarder (cc)	Antifoam (cc)	Anti settling Agent (BWOC)	Para gas (cc)
Sor.20-26	1000	390	-	11.3	4.5	0.8	0.1	-
Sor.27 7" Liner	1000	390	76	11.3	1.5	0.8	0.05	-
Sor. 28 7" Liner	1000	390	4	7.5	7.5	0.8	-	-
Siri DPH-8	1000	460	-	% 0.35 BWOC	% 0.38 BWOC	1.33	-	30

Table 3: Composition and rheological properties of slurry RIPI-1

<table>
<tr><th colspan="9">Slurry Formulation</th></tr>
<tr><td>Cement G (Lb)</td><td>FLC (Lb/Sk)</td><td colspan="2">Dispersant (Lb/Sk)</td><td colspan="2">Retarder (Lb/Sk)</td><td>Fresh Water (Gal/Sk)</td><td colspan="2">Slurry Weight (pcf)</td></tr>
<tr><td>110</td><td>0.44</td><td colspan="2">0.33</td><td colspan="2">0.165</td><td>6.07</td><td colspan="2">118</td></tr>
<tr><th colspan="9">Rheological Properties</th></tr>
<tr><td></td><td></td><td>θ 3</td><td>θ 6</td><td>θ 100</td><td>θ 200</td><td>θ 300</td><td>PV (cp)</td><td>YP (lbf/100ft^2)</td></tr>
<tr><td rowspan="3">Before Heat</td><td>R.U. Readings</td><td>1</td><td>2</td><td>26</td><td>50</td><td>76</td><td rowspan="3">72</td><td rowspan="3">4</td></tr>
<tr><td>R.D. Readings</td><td>2</td><td>3</td><td>30</td><td>54</td><td>76</td></tr>
<tr><td>Average</td><td>**1.5**</td><td>**2.5**</td><td>**28**</td><td>**52**</td><td>**76**</td></tr>
<tr><td rowspan="3">After Heat</td><td>R.U. Readings</td><td>1</td><td>3</td><td>40</td><td>70</td><td>98</td><td rowspan="3">85</td><td rowspan="3">13</td></tr>
<tr><td>R.D. Readings</td><td>4</td><td>5</td><td>43</td><td>74</td><td>98</td></tr>
<tr><td>Average</td><td>**2.5**</td><td>**4**</td><td>**41.5**</td><td>**72**</td><td>**98**</td></tr>
</table>

Table 4: Test results of slurry RIPI-1

Slurry Properties, W=118 pcf						
Gel 10 sec (lbf/100ft^2)	Gel 10 Min (lbf/100ft^2)	FL (cc) P=1000 psi T= 158 °F	Thickening Time (min) P=5000 psi T= 158°F	Compressive Strength UCA (psi) 24-hour P= 3000 psi T=194 °F	Free Water (%)	Permeability (md)
3.5	6.5	50	328	2640	0	0.0629

Slurry with a Density of 118 pcf (RIPI-1)

Typical cement slurry with a density of 118 pcf was designed by RIPI. Table 3 shows the composition and rheological properties of the slurry. The lab results of this slurry are presented in Table 4. Figure 6 shows the stability profile of slurry RIPI-1. As can be seen, a relatively flat profile was established.

Lightweight Slurry without a PSD and Nanoparticles (RIPI-2)

The first type of the lightweight slurry was prepared just with D124 spherical particles. Neither particle size distribution nor nanotechnology was used for its design. Tables 5 and 6 show the composition and test results of slurry RIPI-2. The stability profile of this slurry is presented in Figure 7. This profile shows an acceptable density difference between the top and bottom of the cement column.

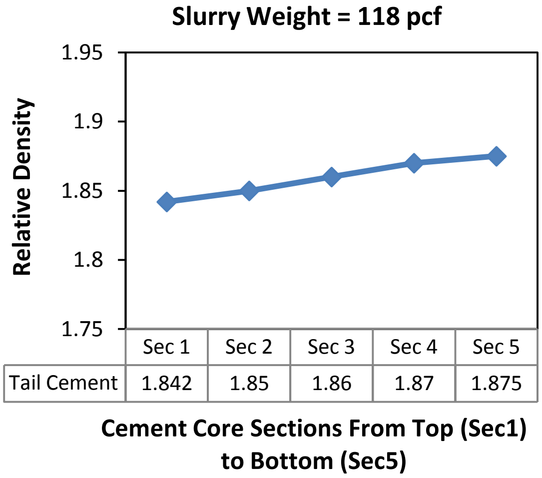

Figure 6: The stability profile of RIPI-1 set cement

Table 5: Composition and rheological properties of slurry RIPI-2

Slurry Formulation						
Cement G (Lb)	D124 (Lb/Sk)	FLC (Lb/Sk)	Dispersant (Lb/Sk)	Retarder (Lb/Sk)	Fresh Water (Gal/Sk)	Slurry Weight (pcf)
110	30.58	0.88	0.33	0.08	8.58	89

Rheological Properties								
		θ 3	θ 6	θ 100	θ 200	θ 300	PV (cp)	YP (lbf/100ft^2)
Before Heat	R.U. Readings	4	8	67	128	183	177	6
	R.D. Readings	2	5	63	128	183		
	Average	3	6.5	65	128	183		
After Heat	R.U. Readings	6	11	73	131	184	167	17
	R.D. Readings	4	7	72	129	184		
	Average	5	9	72.5	130	184		

Table 6: Test results of slurry RIPI-2,

Slurry Properties, W=89 pcf						
Gel 10 sec (lbf/100ft^2)	Gel 10 Min (lbf/100ft^2)	FL (cc) P=1000 psi T= 158 °F	Thickening Time (min) P=5000 psi T= 158°F	Compressive Strength UCA (psi) 24-hour P= 3000 psi T=194 °F	Free Water (%)	Permeability(md)
5	10	48	283	2500	0	0.0537

Table 7: Composition and rheological properties of slurry RIPI-3

Slurry Formulation, Slurry Weight = 89 pcf								
Cement G (Lb)	D124 (Lb/Sk)	HSL (Gal/Sk)	FLC (Lb/Sk)	Disp. (Lb/Sk)	Retarder (Lb/Sk)	M.B Gal/Sk	Gas Block (Gal/Sk)	Fresh Water (Gal/Sk)
110	30.58	0.8	0.55	2.2	0.55	1.90	0.79	6.6
Rheological Properties								
		θ 3	θ 6	θ 100	θ 200	θ 300	PV (cp)	YP (lbf/100ft^2)
Before Heat	R.U. Readings	4	7	49	88	135	130.5	4.5
	R.D. Readings	4	6	47	88	135		
	Average	4	6.5	48	88	135		
After Heat	R.U. Readings	13	21	67	122	160	145	15
	R.D. Readings	3	6	60	115	160		
	Average	8	13.5	63.5	118.5	160		

Table 8: Test results of slurry RIPI-3

Slurry Properties, W=89 pcf						
Gel 10 sec (lbf/100ft^2)	Gel 10 Min (lbf/100ft^2)	FL (cc) P=1000 psi T= 158 °F	Thickening Time (min) P=5000 psi T= 158°F	Compressive Strength UCA (psi) 24-hour P= 3000 psi T=194 °F	Free Water (%)	Permeability (md)
4	15	28	120	1970	0	0.0211

Lightweight Slurry Using a PSD and Nanoparticles (RIPI-3)

The other type of the lightweight slurry was prepared by implementing particle size distribution engineering and nanotechnology. The additive called Microblock was used in conjunction with nano-HSL particles. Tables 7 and 8 present the composition and properties of slurry RIPI-3. Figure 8 shows the stability profile of slurry RIPI-3

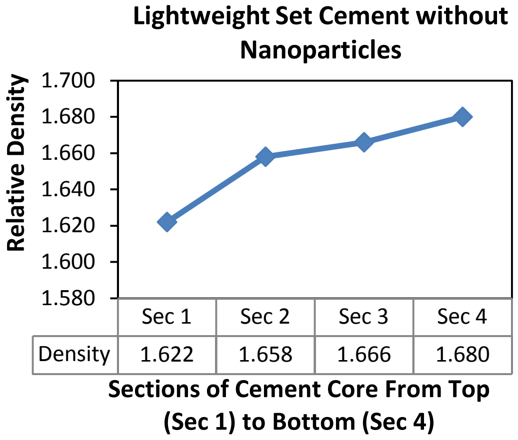

Figure 7: The stability profile of lightweight set cement without nanoparticles

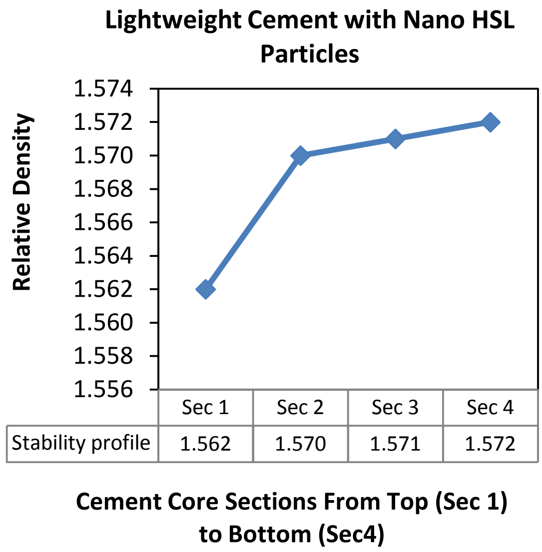

Figure 8: Stability profile of slurry RIPI-3

Lightweight Slurry Using New Type of Nanoparticles and PSD for High Temperature Wells (RIPI-4)

Another adjustment for the lightweight slurry to be used in high-temperature wells was made by RIPI and the slurry was named as RIPI-4. The idea of implementing PSD engineering and nanotechnology was also used. However, the type and quantity of the additives were changed as listed in Table 9. As can be seen, different fluid to solid ratios can be obtained, which results in improved cement properties.

Table 10 presents the summary of test results for each cement slurry compositions.

RESULTS AND DISCUSSION

Based on the results obtained, different cement properties could be evaluated. Thus each category has been discussed separately.

Rheological Properties

The first important slurry property is rheology. The ramp up/down method of reading rheology helps establish a rheology profile, which is informative of slurry tendency to settle or segregation at a glance.

If the ratio $\frac{\text{R.U Reading}}{\text{R.D Reading}}$ is close to 1 for all reading velocities, the slurry does not show the settling tendency and rheological properties are independent of time. If this ratio is higher than 1, there is a settling tendency in the slurry in the test pressure and temperature conditions. Finally, if the ratio is less than 1, gelation behavior has been developed in the cement slurry [5]. For slurry RIPI-1 with a density of 118 pcf, this ratio is around 1 and no settling is observed as well. For slurries RIPI-2 and RIPI-3, this ratio is a little over 1. To make sure that no segregation has happened, we should take a look at the results of free water test and the stability profile of the set cements. According to Figures 7 and 8, the density difference between the top and bottom of the set cement for slurry RIPI-2 is higher (0.06) compared to RIPI-3 (0.01), in which nanoparticles was used.

Table 9: Composition and properties of slurry to be used in high-temperature wells (RIPI-4)

Slurry Formulation								
Cement G (lb)	D-124 (lb/sk)	HSL (lb/sk)	Microblock (gal/sk)	Anti Gas Migration (gal/sk)	Fluid loss controller (lb/sk)	Retarder (lb/sk)	Dispersant (lb/sk)	Water (gal/sk)
110	50	4.5	2.17	0.72	0.48	1.2	2.4	6.5

Slurry Properties								
YP ($lbf/100ft^2$)		Gel Strength ($lbf/100ft^2$)		Thickening Time (min) T=200°F P=5000psi	Compressive Strength (psi) T=230°F, P=3000 psi	Free Water (%)	Fluid Loss (cc) T=200°F P=1000psi	Permeability (md)
Before Heat	After Heat	10 sec	10 min					
14	18	19	35	160	2550	0	18	0.01

Table 10: The summary of test results of all cement slurry compositions

Well ID.	Casing/Liner	Inclination Angle(°)	Slurry Weight (pcf)	BHT (°C)	API Fluid Loss (cc)	T.T. (min)	YP (lbf/100ft^2)	Free Water (%)	Compressive Strength (psi/24 hours)
Balal **7**	7	57	118	75	32	292	40	0	2375
Balal 7	4 1/2	71	118	77	34	259	95	0	-
Balal 8	7	59	118	71	24	265	76	0	500
Balal 9	7	59	118	71	32	260	47	0	50
Balal 10	7	61	118	71	24	260	86	0	0
Soroush 20-27	9 5/8	87	118	82	358	250	10	0	3411
Soroush 28	9 5/8	84	118	40	376	300	6.5	1.6	0
Siri DPH-8	7	88	115	88	87	267	10	0	4600
RIPI-1	-	90	118	90	50	328	4	0	2640
RIPI-2	-	90	90	90	48	283	6	0	2500
RIPI-3	-	90	90	90	28	120	4.5	0	1970
RIPI-4	-	90	90	110	18	160	14	0	2550

However, for both slurries the segregation is negligible. It seems that nanoparticles can fill between larger constituents and prevent them from being packed. In addition, these particles could increase the viscosity of the slurry and provide enough suspending force to prevent solid particles from settling. The other important rheological property is the yield point, which represents the amount of force needed to make the slurry to flow. It is recommended that the slurry for horizontal sections should be designed with a yield point below 20 lbf/100ft^2 [8]. Those slurries designed by RIPI and the one used for Siri and Soroush oilfields meet this requirement. However, the slurry used for Balal oilfield presents a very high viscous rheology, which is not suitable for the low side annulus of horizontal sections.

Stability Test

To make judgment about the stability of slurries, one should take into account the free water content, fluid loss value, and the stability profile of them. For RIPI-1 with a density of 118 pcf, fluid loss value is 50cc / 30 min of the test (Table 9), which meets the requirements for horizontal sections. The free water content in 90 degrees inclination is zero as needed. Figure 6 shows a density difference of 2 pcf between the top and bottom, which is acceptable by industry standards.

For RIPI-2 with a density of 90 pcf and without nanoparticles, the fluid loss value and free water content are similar to RIPI-1. According to Figure 7, the density difference between the top and bottom of the set cement is 3.7 pcf, which was predictable based on rheological readings and the ratio explained in section 6-1. Slurry RIPI-3 and RIPI-4 use nanoparticles and PSD engineering. This has led to a lower fluid loss value (28 and 18cc/30min) and zero free water. The stability of this system shows a significant improvement since the density difference between the top and bottom is as low as 0.12 pcf. This situation presents totally stable cement slurry. Although, the temperature of slurry RIPI-4 is higher than RIPI-3, the stability profile of these two slurries were similar to each other. Figure 9 compares the stability profiles of slurries with and without nanoparticles.

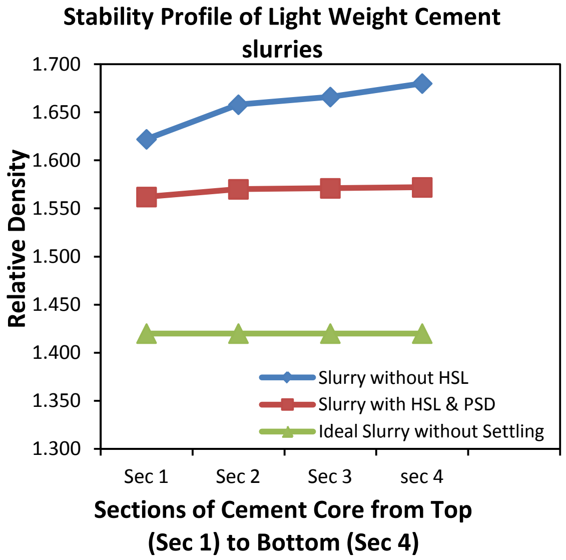

Figure 9: Comparison of stability profiles of slurries with and without nanoparticles

Based on Figure 9, the densities of the tested slurries (red and blue curves) are higher than the original designed slurry (ideal slurry without settling). When the slurry with lightweight additives (hollow spheres) undergoes the curing pressure of 3000 psi, these spheres may collapse to some extend and, as a result, the total volume of slurry is reduced and the density is increased.

The application of nanoparticles and particle size distribution engineering has led to better performance of the cement slurry under down hole conditions. As can be seen in Figure 9, the amount of density change in slurries RIPI-3 and RIPI-4 (red curve) is less compared to slurry RIPI-2 (blue curve), which is just using the lightweight additive. This phenomenon is affected by the presence of nanoparticles and PSD technique, by which finer particles of nanomaterials and Microblock fill the pore spaces and prevent the solid content from collapse and contraction during compressive strength development (see Figure 5 as well). This improved performance of the cement slurry when located behind casing or liner strings will result in better cement/pipe or formation bonding, which is definitely critical to provide zonal isolation.

Compressive Strength Development

Figure 10 compares the compressive strength development of different slurry systems. Those slurries designed during this study have been compared to Balal well No.9 cement slurry.

According to Figure 10, the compressive strength of all the lightweight cement slurries (RIPI-2, 3, and 4) are competing with the standard slurry with a density of 118 pcf (RIPI-1). Since traditional slurries with a density of 90 pcf rarely show significant compressive strength, the improvement to strength is directly related to the application of nano and silicate-based additives (such as Microblock and hollow spheres).

As previously mentioned, the higher compressive strength of slurry RIPI-2 in comparison with RIPI-3 might be related to the performance of nanoadditives and particle size distribution engineering employed to prevent the solid constituents from contraction and avoid the collapse of hollow spheres (Figure 9). The more the compaction of hollow spheres in the lightweight slurry systems is, the higher the density is and the higher the compressive strength, measured by sonic waves, becomes. Both slurries RIPI-2 and RIPI-3 developed a compressive strength after 8 hours, and during the first 24 hours the ultimate strength has been reached. Since slurry RIPI-4 has implemented different PSD and type of nanomaterial, its compressive strength started to rise after 6 hours until the final strength after 24 hours of test run. One of the advantages of these three novel slurries is the rapid compressive strength development, which greatly reduces the wait on cement time (WOC) and decreases the chance of fluid migration through cement sheath. This process happens faster when nanoparticles have been used.

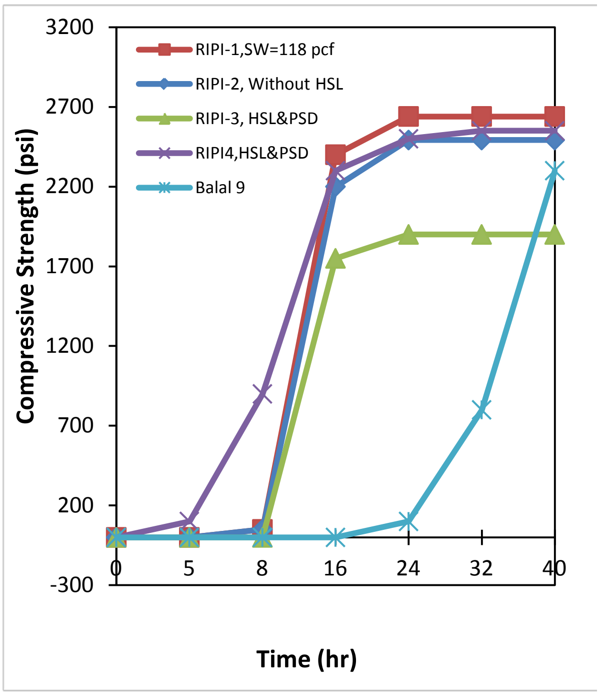

Figure 10: Comparison between compressive strength (UCA) of all the slurry systems

Figures 11, 12, and 13 present respectively comparative information of fluid loss value, total compressive strength development, and the time needed to develop strength from 50 psi to 500 psi. The later one is a representative of WOC and setting off the next phase drilling and can be used as one of the criteria for accessing fluid migration through cement sheath behind casing.

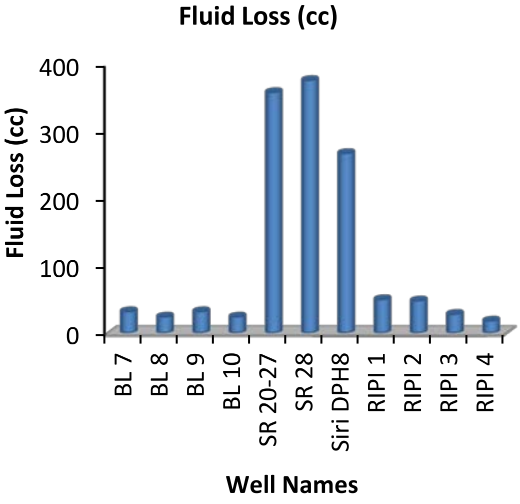

Figure 11: Fluid loss value of all the cement slurry systems

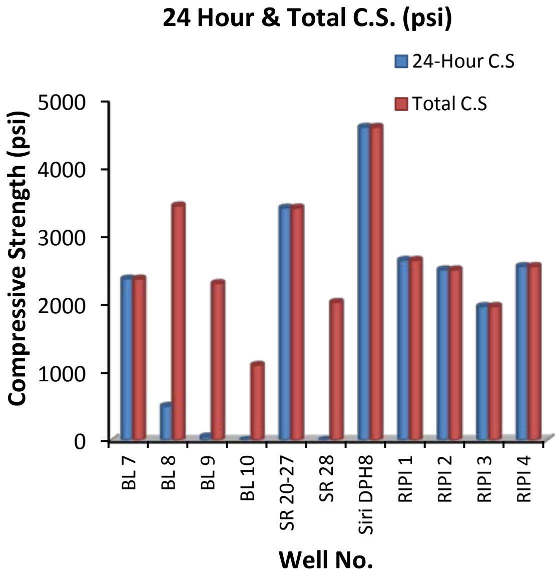

Figure 12: Compressive strength development for all the cement systems

As can be inferred from Figure 13, the best slurry is the one with an earlier start compressive strength (50 psi) and a faster development of compressive strength until the next phase drilling could be commenced (500 psi) as slurries RIPI-3 and RIPI-4 show. Note that by applying nanoparticles and particle size distribution engineering to the lightweight cements, the rapidest compressive strength growth has been obtained.

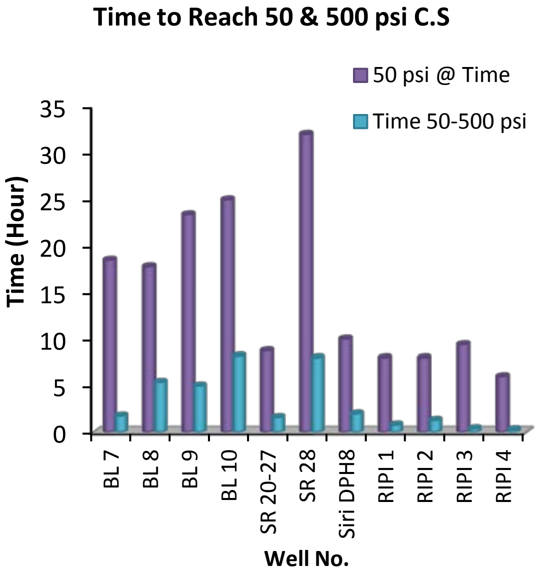

Figure 13: Early strength development and minimum WOC time

CONCLUSIONS

According to the study carried out on some cement slurry recipes, the best slurry for horizontal wells in Iran oilfields has been selected. The proposed recipe for horizontal or highly inclined wells should meet tough standard and operation conditions e.g. zero free water, less than 50cc/30 min test fluid loss value, appropriate rheology and yield point for effective mud displacement prior to cement placement, adequate compressive, strength which is critical for lightweight slurries, and finally stable cement column behind casing. Three lightweight slurries have been designed. One of them was designed as traditional slurry (RIPI-1), for the other one (RIPI-2), nanoparticles in the liquid form and particle size distribution engineering were implemented and finally the slurry with a different PSD (compared to RIPI-2) and nanoparticles in a powder form with different physical and chemical properties was made (RIPI-4). Comparing these slurries with those used in Balal, Soroush, and Siri oilfields, which were basically standard weight slurries, a reduction in yield point up to 84% and a drop in fluid loss value up to 44% were recorded. Besides, an increase in compressive strength up to 82% was measured in some cases. All the slurries designed in RIPI showed adequate stability and they were totally confirmed for application in horizontal wells in Iran oil and gas fields.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Mortazavi, the head of Drilling and Well Completion Research Group of RIPI as well as Dr. Kazemzadeh, the head of Petroleum Engineering Division. We also thank Mr. Bahmani, Mr. Babaloie, and Mr. Miri for providing oilfield data. Finally, we would like to appreciate the great efforts of Mr. Fathi, Mr. Saiedi, Mr. Tajik, and Mr. Karimi in the cement laboratory of RIPI.

NOMENCLATURES

PSD	: Particle Size Distribution
pcf	: Pound per Cubic Foot
psi	: Pound per Square Inch
Gal/Sk	: Gallon per Sack
WOC	: Wait On Cement

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