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LABORATORY RESEARCH ON THE INFLUENCE OF SWELLING CLAY ON THE QUALITY OF BOREHOLE CEMENTING AND EVALUATION OF CLAY-CUTTING WELLBORE TOOL PROTOTYPE

ABSTRACT

Swelling clay phenomenon is frequently observed during oil and gas drilling operations and has a significant impact on the quality of cementing procedure. Certain types of clayey minerals increase their volume in contact with water-based drilling fluids. After drilling is completed, borehole remains unsupported and filled with water-based drilling fluids for several hours, before a casing string is inserted and secured with cement. In the period of time between completing the drilling and inserting the casing string the clay can expand hindering proper cementing or blocking the casing string in a wellbore. Filling the annular space between a casing pipe and wellbore walls with cement is crucial for further exploitation of a well. An improper performance of displacement work (primary cementing) may cause both financial losses and environmental damage. The aim of this study is to describe the impact of distorted annular space geometry on cement sheath quality and to examine the possibility of improving the distorted geometry with a prototype wellbore tool. The tool was designed to be mounted as a first pipe section on the casing string (cementing shoe/reamer shoe). Two test stands were designed and constructed. The first one simulates the well cementing process, while the second one simulates the downward movement of the casing pipe in the well (run in hole process) drilled in expansive clay. Six distorted annular space sections were cemented using the first test stand. The sections were scanned with μXCT (computed micro-tomography) to locate discontinuities in the cement sheath. This research has confirmed an adverse influence of annular space obstructions on the cement sheath quality, thus the necessity of removing them before cementing. The obstructions can be removed by means of newly designed clay cutting wellbore tool. Therefore, the prototype of such a tool was tested on the second test stand. The experiment allowed to evaluate an influence of a swollen clay obstruction on the force needed to push the prototype tool through the obstruction. The same experiment was conducted with a standard cementing shoe in order to obtain comparative data. Hole geometry improvement, ability to fragment and remove clay cuttings have been observed. The research has confirmed that the prototype tool efficiently improves the borehole geometry and, consequently, improves the cement sheath quality.

Key words:*clay minerals; cementing job; wellbore integrity; μXCT;oil&gas; borehole tool; reamer shoe*

1. INTRODUCTION

1.1. Fundamentals of Cementing

Cementing is a process of placing a cement sheath around casing strings in a well. It is a critical part of well construction and the process is extensively designed and fully engineered. Cementing fills in the space between the well casing and drilled wellbore, isolating different subsurface zones and providing structural support for the well. Cementing has crucial meaning for the well integrity throughout its life and protects the casing from potential corrosion.

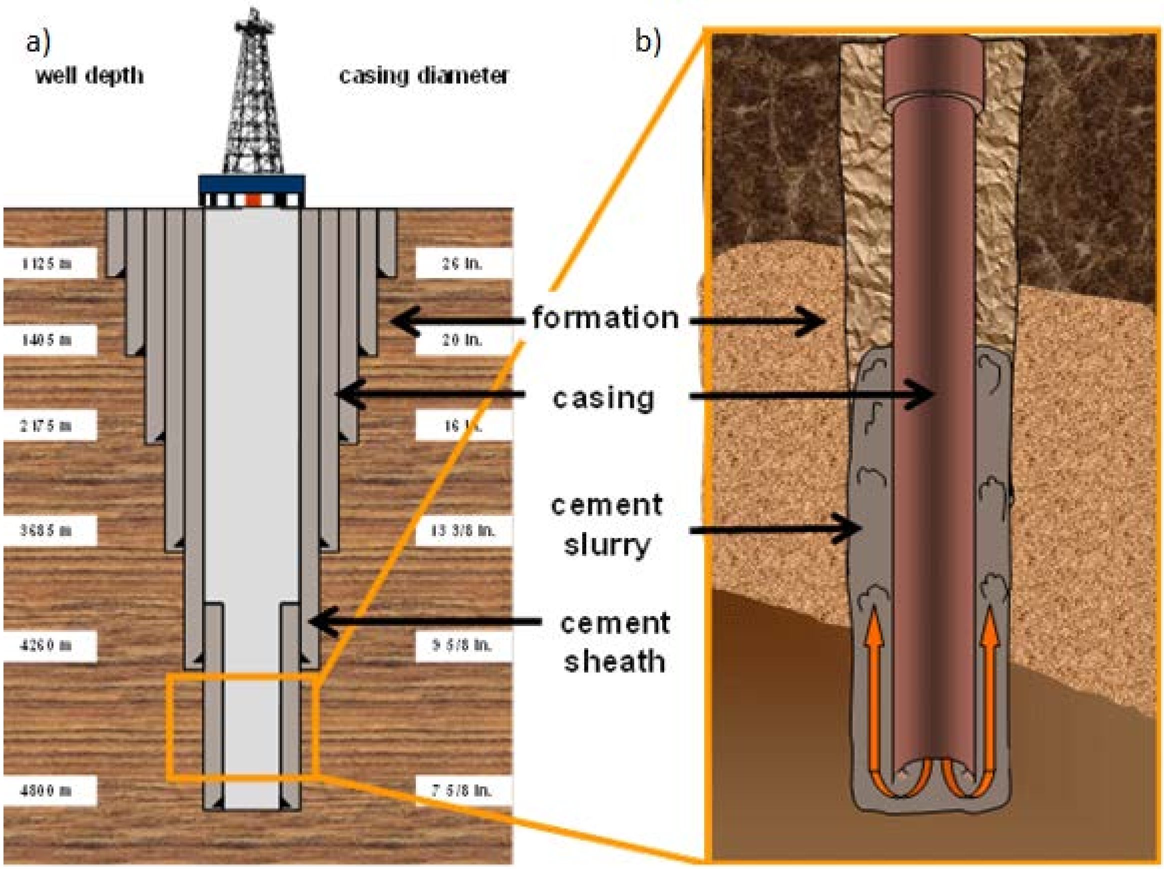

Fig. 1. Schematic of a cased and cemented oil well (a); principle of placing the cement slurry between the casing and the rock formation(b) [1].

Proper design and realization of lowering and cementing each column of casing within the borehole, especially tubing, have significant impact on the efficiency of exploration work and the efficient usage of drilling consumables for both operating and newly discovered fields. Failure to achieve proper zonal isolation can have a significant economic effect in terms of lost well productivity[2, pp. 1–1]. Lack of hydraulic seal can also cause environmental contamination followed by expensive rescue and recovery actions and payment of possible compensation.

Zonal isolation relies on effective mud removal: the displacement of drilling fluids and accompanying debris from the casing – borehole wall annulus [3]. Good operational practices have essential meaning for proper cementing. Two most important factors ensuring good cementing are: centring the casing by densely mounted centralizers and forcing reciprocal or rotational movement of the casing during the cementing operation. It is important to insert the casing at a speed that will not fracture the rock formation. Another important factors are: using proper displacement techniques, such as a pre-flush and applying spacers and cement plugs [4].

To qualify as properly cemented, a well needs to feature a continuous and impermeable hydraulic seal, isolating each zone along the wellbore, within the annulus. . To obtain such a seal, cementing operations must prevent the cement from bypassing, mixing with or being contaminated by fluids in the annulus.

1.2. Cement failures

Cement is a well-known material whose properties are well documented. However, some of these properties prevent this material from handling the well integrity challenges related to loss of pressure and leakage of fluids. These challenges include: cement shrinking, gas migration during setting, fracturing after setting and long term degradation by exposure to temperature and chemical substances in a well [5].

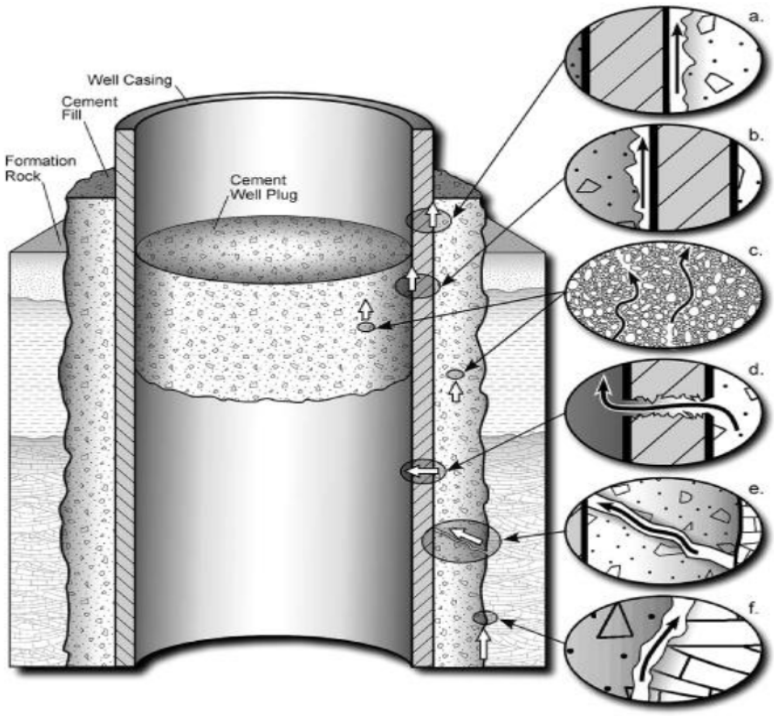

Fig. 2. Example of possible leakage paths and failures in a cased wellbore: between cement and casing (paths a and b), through the cement (c), through the casing (d), through fractures (e), and between cement and formation (f)[6].

According to the classification[7] criteria listed below there are several reasons for wellbore integrity issues. The ones having the highest impact on cementing job quality and hydraulic seal have been listed and described below. Explanations are based on references [8, pp. 137–144], [9]–[13].

- *Inadequate drilling mud removal* - During cementing operations, a cement slurry is pumped into a well in which the annulus is filled with drilling fluid. Displacing mud with cement through a narrow annulus several thousand meters deep is not easy. Drilling muds are non-Newtonian fluids which typically show thixotropy which means that they build a gel-like structure under low shear rates (low flow or no flow). This behaviour is meant to prevent an accumulation of cuttings at the bottom of the well in periods without circulation. After this period, the gel structure has to be broken up and the flow has to be ensured further in the well. Otherwise, mud pockets will compromise the integrity of entire well. The flow regime of the fluids is also an important factor(Fig. 3.).

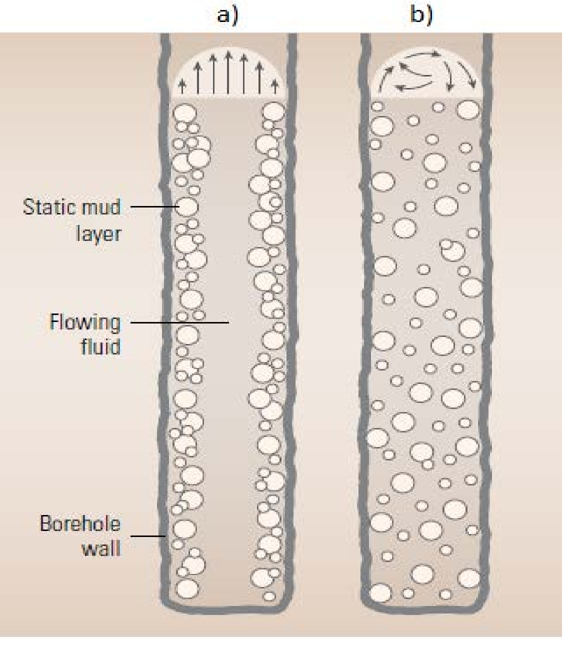

Fig. 3. The two flow regimes. In laminar flow (a), all fluid particles move parallel to the pipe axis with a curved velocity profile. In turbulent flow (b), the velocity profile is more uniform because the fluid particles are swirling around [3].

In laminar flow, viscous friction forces dominate hence, the maximum velocity is at the centre of the borehole, and its value gradually drops to zero at the wellbore wall. In turbulent flow, the particles move in an erratic circular motion and, in this case, the velocity of the fluids along the walls is nearly the same as at the centre of the borehole. In most cases, turbulent flow is preferred for drilling fluid removal, because turbulent flow’s uniform-like velocity profile and swirling motion is considered to enhance mud removal. To maximize displacement, the flow must be turbulent all around the annulus. However, this requires higher pump rates in eccentric annuli, which may not always be attainable.

- *Contamination of cement by mud or formation fluid* - Another factor significantly impeding cementing is the fact that cement slurries and drilling fluids are usually chemically incompatible. Their mixing may result in forming a thickened or gelled mass at the interface which is difficult to remove from the wellbore and possibly prevents placement of a uniform cement sheath throughout the annulus. However, complete replacement of mud with cement is crucial to the viability of a well and its future stability[12]. Therefore, engineers employ chemical and physical means to maintain fluid separation. Chemical washes and spacer fluids may be pumped after the drilling fluid and before the cement slurry. These fluids contribute to better cleaning of the casing and rock formation surfaces which helps to obtain good cement bonding [13].

- *Casing centralization (incomplete cementing)* – In case of insufficient centralization of the casing, the cement might not fully displace the mud from the annulus during cementing operation. It has been found that uneven velocity distribution around eccentric casing causes possible coexistence of different flow regimes in a given annular cross section (Fig. 4.). Cement flows in the wide opening of the well rather than in its narrow opening. This results in cement eccentricity and non-uniform cement thickness.

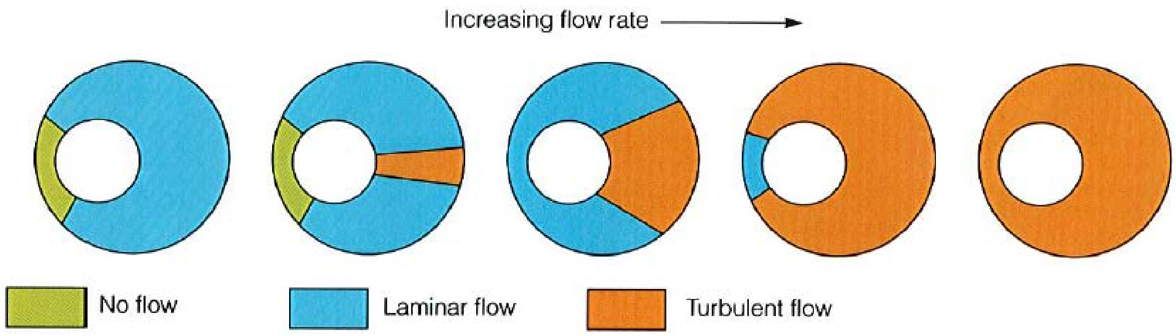

Fig. 4. Flow regimes for fluids with yield stress flowing in an eccentric annulus [12].

- *Swelling clay minerals* - Water-based drilling fluids are increasingly being used for oil and gas exploration and are generally considered to be more environmentally acceptable than oil-based or synthetic-based fluids. Unfortunately, certain types of clay minerals increase their volumes in contact with water-based drilling fluids. In this case, the wellbore diameter is reduced which hinders proper cementation (displacement) and can even block casing string in a wellbore (Figure 5).

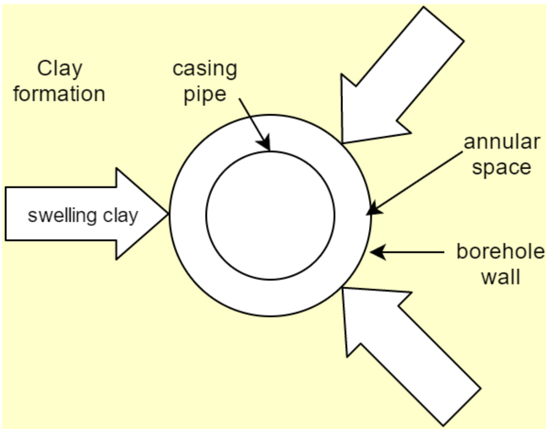

Fig. 5. Wellbore instability due to swelling clay.

1.3.Swelling clays in oil & gas industry

Two main problems that occur due to swelling clays are: wellbore instability and formation damage[14].

Problems caused by shale in petroleum activities are not new. In the beginning of 1950s, many soil mechanics experts were interested in swelling of clays which are important for maintaining wellbore stability during drilling, especially in water-sensitive shale and clay formations[15]. Instability of a wellbore is the most significant source of trouble, loss of time, and cost overruns during drilling. The expansion of clay into the hole significantly influences the quality of cemented pipe sections. Deposition (sticking) of clay with high viscosity to the surface of pipes preventing proper bonding of cement or casing contacting clay stones is merely one of many threats shortening the life of the hole and incurring additional expenses for a company. Clay swelling during the drilling of a well can have a tremendous adverse impact on many other drilling operations. The increase in bulk volume impedes the removal of cuttings from beneath the drill bit, increases friction between the drill string and the sides of the borehole, as well as inhibits deposition of thin filter cake that seals rock formations. Clay swelling can also create other drilling problems, such as loss of circulation of drilling fluids[16]. The swelling of clays and the problems that may arise have been reviewed in the literature[17]–[19].

Formation damage occurs when (hydraulic) permeability of a reservoir rock (producing formation) decreases due to any reason. Reduced permeability limits the outflow of hydrocarbons from the rock. It is an undesirable operational and economic problem that can occur during various phases of oil and gas recovery from reservoirs including drilling, production, hydraulic fracturing, and work over operations[11]. Statistics show that fines migration and clay swelling are the primary reasons for formation damage measured as permeability impairment[20]. Research on rock formations[21] determined that poorly lithified and tightly packed formations having large quantities of authigenic, pore-filling clays sensitive to aqueous solutions, such as kaolinite, illite, smectite, chlorite, and mixed-layer clay minerals, are especially dangerous. With the drilled depth, the percentage of mixed layers and illite increases, while that of smectite decreases. In deposits of Silurian, Ordovician and Cambrian origin, illite is dominant. Also, mixed package minerals contain smectite. The stability of a borehole depends largely on interactions between the drilling fluid and exposed shale formations. Interactions between the mud filtrate and the clays present in producing horizons may restrict productivity of the well if the wrong type of mud is used. All of these indicate the need for knowledge of clay mineralogy[22].

Typical clay minerals are described in Table 1 [23], [24]. However, near-wellbore formation may also contain other substances, such as mud, cement and debris which may be introduced during drilling, completion, and work over operations .

Table 1. Description and typical problems caused by Authigenic Clay Minerals[14], [24].

Mineral	Chemical Composition	Morphology	Surface area (m^2/gm)	Major reservoir Problems
Kaolinite	$Al_4[Si_4O_{10}](OH)_8$	Stacked plate or sheets	20	Breaks apart, migrates and concentrates at the pore throat causing severe plugging and loss of permeability.
Chlorite	$(Mg, Al., Fe)_{12}[(Si, Al)_8O_{20}](OH)_{16}$	Plates, honeycomb, cabbage-head rosette or fan	100	Extremely sensitive to acid and oxygenated waters. Will precipitate gelatinous $Fe(OH)_3$ which will not pass through pore throats.
Illite	$(K_{1\text{-}1,5}Al_4[Si_{7\text{-}6,5}Al_{1\text{-}1,5}O_{20}](OH)_4)$	Irregular with elongated spines or granules	100	Plugs pore throats with other migrating fines. Leaching of potassium ions will change it to expandable clay.

Smectite	(1/2Ca, Na)$_{0,7}$(Al, Mg, Fe)$_4$[(Si, Al)$_8$O$_{20}$]•nH$_2$O	Irregular, wavy, wrinkled sheets, webby or honeycomb	700	Water sensitive, 100% expandable. Causes loss of microporosity and permeability.
Mixed-Layer	Illite-Smectite and Chlorite-Smectite	Filamentous morphology	100-700	Breaks apart in clumps and bridges across pores reducing permeability.

The stability of shales is governed by a complex relationship between transport processes (e.g., hydraulic flow, osmosis, diffusion of ions, pressure) and chemical changes (e.g., ion exchange, alteration of water content, swelling pressure). Shales have the ability to absorb water, thus causing the instability of wells either because of the swelling of some minerals or because the supporting pressure is suppressed by modification of the pore pressure. The response of a shale to a water-based fluid depends on its initial water activity and the composition of the fluid [15].

1.4.Research areas relevant to wellbore integrity and cement failures

Design methodologies for primary cementing that consider the rheology of the fluids have had a long history. In the beginning, possibility of forming a mud channel on the narrow side of the annulus was identified [25]. Further works have led to whole systems of design rules for laminar displacements[26]–[29]. Displacement of drilling fluids (pseudo-plastic, visco-plastic), has also been widely studied and described[30]. Displacement tests were conducted on specially designed lab scale facility which allowed careful investigation of the phenomenon. Displacement characteristics of drilling fluids were studied[31]. A single fluid flow with various models of rheological fluids and displacement tests, especially visco-plastic fluids representing drilling and cementing fluids was conducted at different eccentricities, pipe inclinations, and over a range of flow rates and cylinder rotational speeds. The results from laboratory tests were validated with computer simulations. In general, these rule sets state that the flow rate must be sufficiently high to avoid a mud channel on the narrow side of the annulus, that there should be a hierarchy of the fluid rheologies pumped, (*i.e.* each fluid should generate a higher frictional pressure than its predecessor) and that there should be a hierarchy of the fluid densities (each fluid heavier than its predecessor)[32].

In all the papers mentioned above, authors have used the aqueous solutions of polymers with rheology similar to drilling fluids, but not actual drilling fluids like cement slurry and drilling mud.

There are number of studies relating to the cement integrity. Most of these works are related to destructive influence of CO_2 on the quality of the bond between cement and casing, cement and rock formation. Laboratory tests exploring the impact of this factor were conducted by multiple researchers[33]–[35]. Studies have also been carried out in order to understand the alterations that take place in cement with mechanical defects, such as fractures and voids. Research[36] showed that gaps in bonding and cement cracks can lead to a significant increase in the effective permeability of cement which can result in the leakage of CO_2 and/or CO_2-saturated brine.

There is a lack of studies on poor drilling mud removal and low cementing job quality resulting from swelling clay expansion carried out with real drilling fluids like cement slurry and water based bentonite drilling muds.

This phenomenon has not been investigated with three-dimensional (3D) reconstructions obtained by computed microtomography (μXCT) method. The μXCT method was used in related research areas to predict properties of porous materials (e.g. rocks, sandstones, cores specimens).The method has also been successfully applied in studies of Mancos shale[37] and Portland G cement[38]. The specimen size determines the obtainable resolution when using μXCT[39], thus, the larger the specimen is, the less detail can be observed in the image[40]. Studies[41]–[44] have shown that the μXCT is capable of providing non-destructive visualizations of the spatially heterogeneous degradation of cement, including the density and pore structure changes due to CO_2 attack under geologic sequestration conditions. This method enables the visualization of potential leakage pathways which can be formed at the cement–rock interface, as a consequence of degradation processes. Authors reported that the obtained results seem to be very useful for predicting the integrity of a wellbore, in case of different caprock and reservoir rock[45].

In the last decade, digital rock physics(DRP) method has been widely implemented to estimate rock properties, such as porosity, permeability and elastic moduli in oilfield rocks. DRP procedure consists of three main stages. First, rock specimen is scanned through X-Ray scanner to produce a 3D image where each voxel represents density displayed as grey scale derived from the X-Ray attenuation and related directly to the rock density [46]. Darker shades of grey represent solid frame and lighter shades of grey represent pore space. Secondly, pores and grains are separated using an image analysis technique called segmentation. Finally, the simulation of rock properties is carried out using segmentation results as input data. Recently, there was a study[47] on modelling several rock properties such as porosity, density, formation factor and volume of clay along cores using neural network system that processed 2D X-ray images of the core specimens. Recent development in computational methods and progress in image acquisition techniques using X-Ray Computed and Micro-Computed Tomography scanners have improved characterization of porous media[48]–[50].

1.5. Aim of the paper

The aim of this paper is, firstly, to study the influence of wellbore geometry imperfections, especially those resulting from swelling clay expansion, on poor drilling mud removal and low cementation process quality. Secondly, the ability of a newly designed wellbore tool to eliminate such problems and their causes is to be examined. Dedicated test stands have been designed and constructed to allow reaching both objectives. Contemporary method of uXCT was chosen for cement sheath examination. Detailed description of experiments and their outcomes are presented.

2. METHODOLOGY

Two types of experiments were carried out. The first one aimed at describing a relation between corrupted annular geometry and cement sheath quality. The second one was conducted in order to evaluate the force needed to push the casing string through expanded clay obstruction and clear it. Both experiments, alongside with tested tool are described in this section.

2.1. The cementing experiment

Fluid rheology and the presence of obstacles in centric annuli were considered to be the most important variables in the dynamics of flow in the annuli and to have the biggest impact on cementing quality. A test stand capable of pumping cement and other viscous fluids into a simulated wellbore section was designed and constructed. The flow of fluids obtained in the test stand can reflect phenomena present in real cementing operation in oil well completions.

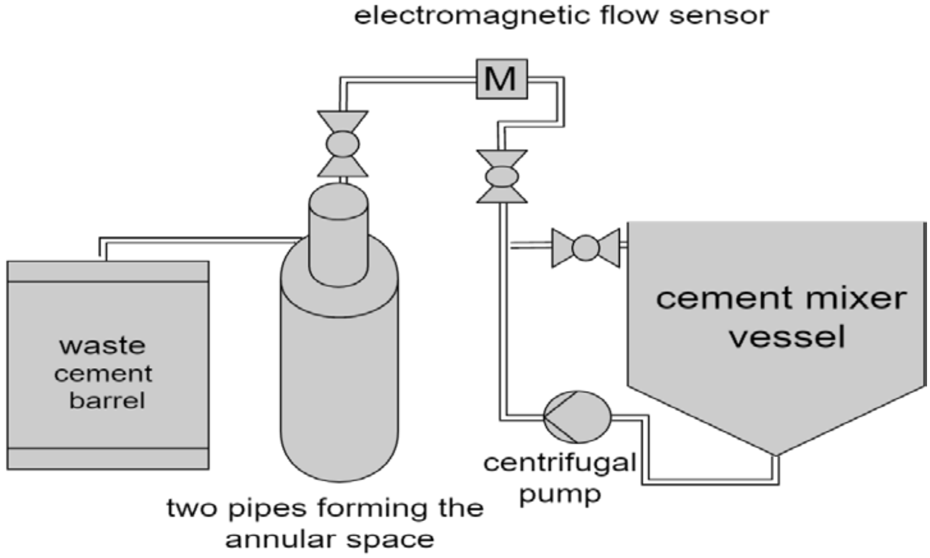

Fig. 5. Schematic drawing of cementing test stand.

The experimental flow system consisted of a mud/cement mixer, a centrifugal pump, an electromagnetic flow rate sensor and an exchangeable annular section composed of two aluminium alloy coaxial pipes. The outer pipe was closed at the bottom, while the inner pipe had cut outs in its lower part to allow the flow of fluid. The fluids were pumped into the inner pipe and collected from the annular part on the top using detachable connections. The corruption of annular space was achieved by placing 3d printed plastic inserts (obstacles) inside. The dimensions of annular space were 75mm x 104mm x 700mm, while the height of the obstacle was 100mm. Figure 6A shows a schematic drawing of the exchangeable section, 6B its implementation, while Figure 5 shows a schematic drawing of the whole flow system. Please note that when the valve on the top of the vessel is open and the one placed before the EM sensor is closed, the slurry is circulating in closed circuit allowing it to get mixed. In the opposite situation, the slurry is pumped through the stand into the waste barrel.

2.2.Experimental procedure

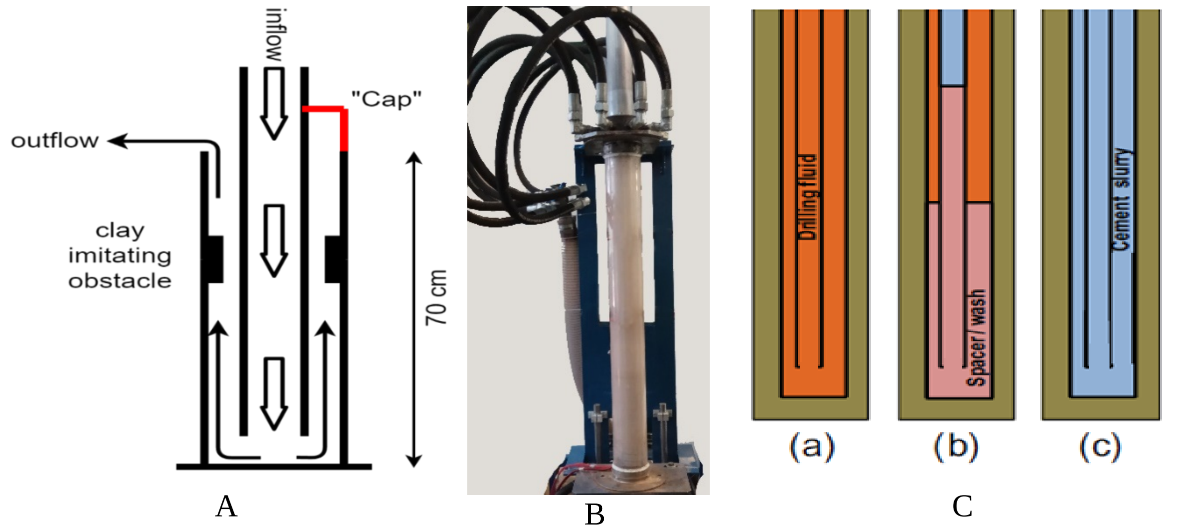

Fig. 6. A - Schematic diagram of the laboratory cementing test with obstacle and flow directions. B –physical implementation of the diagram. C- experimental procedure: a) Drilling fluid in eccentric annuli; b) A spacer/wash fluid followed by cement slurry is pumped into the aluminium alloy ; c) Cement is allowed to set.

First, 7 annular sections were prepared. Six of them were fitted with 3d printed plastic inserts (obstacles). Each obstacle was characterized by a different degree of obstruction of the annular space. Three types of closure and three types of narrowing obstacles were used. The obstacles cross-sections are shown on Figure 7.

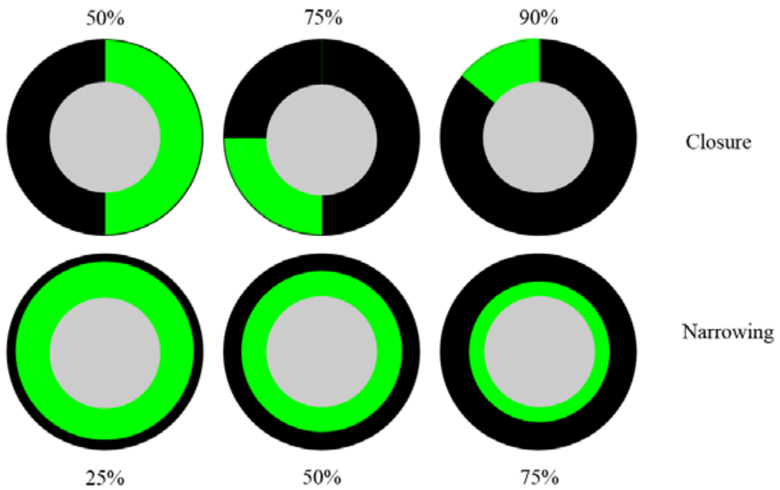

Fig. 7. Cross section of obstacles imitating expanded clay. Black colour means obstacle.

After that the prepared sections were filled with the drilling mud (Figure 6Ca). The visco-plastic drilling mud was prepared from the aqueous solution, by composition given by Müller et al. 2004 [51][55](Table 2) that is commonly used drilling mud composition for testing the lubricants. Then, washer/spacer fluid was carefully introduced into the inner pipe. Special care was taken during the filling step to minimize initial mixing of the two fluids (spacer and water-based drilling mud) at their interface (Figure 6Cb). For washer/spacer fluid, 30% cement slurry solution was used. After that, the fluid to be displaced (cement slurry) was prepared in a cement mixer vessel in closed circuit and some of it was introduced manually from the top into the annulus (Figure 6Cb). Portland cement CEM I 32,5 R (Ożarów)' has been used to prepare cement slurry. water to cement ratio in cement slurry was 0,5. The composition of cement is shown in Table 4.

Table 2. Composition of Water-Based Drilling Mud[51] [55].

Water	4 l
Xanthan gum	20 g
Bentonite	56 g
CMC (CarboxymethylCelulosis)	40 g
Barite	1.8 g

The test started as soon as the filling period was completed, in order to reduce intermixing of the test fluids. The valves were switched to open mode and the centrifugal pump was switched on to deliver the cement slurry into the inner pipe. The series of drilling mud, spacer fluid and cement slurry were displaced through the test stand. (Figure 6Cc) When there was only cement visible in the outflow (waste cement barrel), the pump was switched off and the experiment was repeated on another section. Finally, the specimens were left for 72 hours for cement to set.

Table 4. Composition of CEM I 32,5 R (Ożarów).

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl^-
% wt	20	5.1	2.8	62.5	1.3	2.8	0.13	0.85	0.08

2.3.Specimen investigation method- uXCT

The specimens were scanned with Phoenix v|tome|x s240 X-ray computed scanner, a versatile high resolution system for 2D x-ray inspection and 3D failure- and structure analysis. It consists of x ray-tubes, CNC manipulator holding the specimen, detector matrix and two computer units - one for control and the other for reconstruction and processing purposes. The system is enclosed in lead housing to contain radiation. Once the specimen is placed inside the device and process parameters are set, the acquisition of 2D images starts. Hundreds of images are being taken while the specimen slowly rotates. When the rotation is over, images are sent to the reconstruction computer. Reconstruction software (Phoenix datos|x) combines 2D images into a 3D image. It uses digital filters to enhance the outcome quality. Different shade of grey is assigned to each voxel of 3D image. This shade is proportional to its ability to absorb x-ray which, in turn, is proportional to density. Such 3D image can be additionally processed to extract desired information.

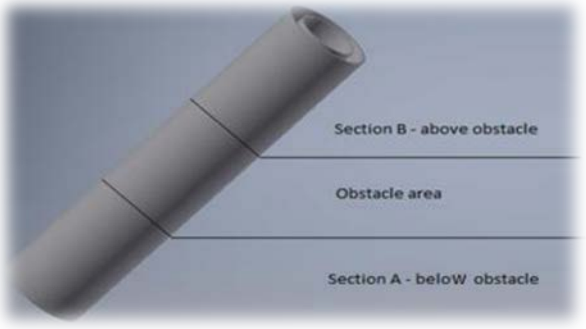

Fig. 8. Section cuts schematic drawings and a specimen inside the scanner

After 72 hours of cement setting, specimens were cut into shorter sections that could fit into the tomography station. The sections measured 400mm and contained the obstacle with an even amount of space directly above and below the obstacle. Seven cemented specimens were scanned to obtain 3D images. Scanning parameters are listed in Table 6. Then, the images were divided into sections. Each section contained 100mm area either below or above the obstacle (Fig8). In the case of control specimen the extracted area was in the middle of it. This operation yielded 13 3D images of the mentioned sections. The inner pipe with cement and outer pipe were digitally cut out from each of the images. Eventually, the images represented only the volume of annular space (Fig 14). The threshold algorithm was used to detect cementing imperfections based on grey scale(density). The voxels with the values below the threshold were assumed to be voids, whereas those above the threshold were assumed to be solid cement. After thresholding, the images were inspected manually in search of visible leakage paths (vertical), gelled drilling mud areas and paths between inner and outer surface of annular space (Figure 2). Computations were conducted using Volume Graphics VGStudio Max 2.2 with Porosity/Inclusions Analysis Module.

Table 6. Scanner setting parameters.

Parameter	Value
Accelerating voltage	210 kV
Current	420 µA
Voxel size	120.001 µm
Magnification	1.667
Number of images	1400
Exposure time	333.1 ms
Radiation filter	0.5 mm Cu

3. DESCRIPTION OF TESTED CLAY CUTTING TOOL

When the adverse influence of corrupted wellbore geometry on cement sheath was confirmed (Section 4.1), a tool aimed at improving the geometry was designed and its prototype was manufactured[52]. The tested tool is a reamer shoe type tool. It was designed for wellbore diameter calibration during casing/tubing run into a hole. Its main tasks are:

- Enabling pipe lowering down the wellbore at the locations of decreased hole clearance/diameter
- Wellbore diameter calibration by removing mud cakes and swollen rock material
- Improving concentricity between a casing and a wellbore

The tool features two groups of blades to cut excessive rock. Additionally, it uses an ejector to suck in and fragment rock material. The tool's geometry along with standard cementing shoe is presented in Figure 8. The tool's full name is Protector Against Swelling Clays further referred to as Protector.

Fig. 8. Protector tool geometry and standard cementing shoe

3.1. The run in hole experiment

A test stand simulating the process of lowering casing pipes into the wellbore (run in hole process) was designed and constructed. The test stand allows to check the ability of borehole shoe type tools to push through obstructed section of a well. When filled with expansive clay, the test stand allows to evaluate tools prototypes in terms of swollen clay cutting performance in conditions that imitate wellbore environment. It also implements a mud circulation system that is a part of every real-life drilling and run in hole operation. Mud circulation is crucial for the performance of Protector.

Basic components of the test stand:

- 1.5m long tank imitating a section of wellbore(blue).
- Trolley (yellow) – enables linear displacement of the tool.
- Two hydraulic cylinders(grey)–producing 15kN of maximum load.
- Hydraulic system – feeds hydraulic cylinders.
- Mud circulation system - closed circuit of drilling mud through the tool during the test.
- Measurement System.

The principle of operation is shown in Figure 13, a detailed description of the components of the hydraulic system and the mud circulation system are listed in Table 2. Physical implementations of the systems are shown in Figure 7.

A B

Fig. 7. Clay-cutting laboratory testing station at Gdansk University of Tehcnology: A – hydraulic system, B – mud circulation system.

Table 2.Components of hydraulic and mud circulation systems.

Hydraulic system (Figure 7a)	Mud circulation system (Figure 7b)
▪ Two 4-way flow diverters – providing a change of direction the hydraulic cylinders move. ▪ Gear flow dividers –ensuring equal flow for both cylinders. ▪ Powerful pump – ensures up to 20 MPa pressure and excessive flow capability- supplying cylinders. ▪ Pressure sensors for cylinder force measurement	▪ High shear mixer – preparation of drilling mud. ▪ Centrifugal pump of the mixer providing mud circulation –0.6 MPa. ▪ Flexible collar – diverts the mud circulation back to the high shear mixer ▪ Electromagnetic flow sensor for drilling mud. ▪ Ultrasonic displacement sensor

3.2.Run in hole test procedure

The prototype Protector was designed to be mounted on Ø180mm (7”) casing pipes. For this casing size a default diameter of well is Ø205mm.. The maximum span of protector outer blades is Ø203mm. It was decided that the full closure case i.e. when wellbore diameter is equal to casing string diameter and “blocking” case when the wellbore diameter (Ø160) is smaller than the casing diameter will be investigated. Please note that the test with a Ø 180mm standard shoe on a Ø180mm wellbore would not yield any useful data as the tool would pass through without any resistance. Thus only three tests were scheduled(Table 7)

Table 7. Test schedule.

Well diameter/tool	Protector (max Ø203mm for Ø180mm)	Standard shoe(Ø 180mm)
Ø 160	Test 1	Test 3
Ø 180	Test 2	x

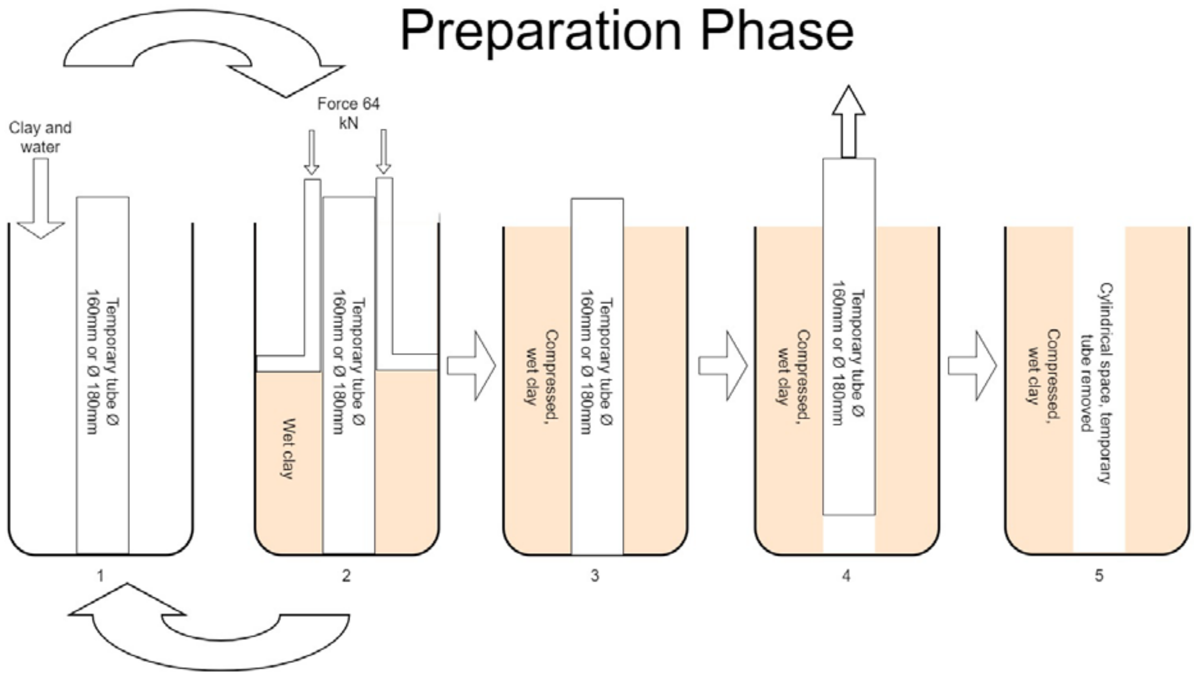

Fig. 12. Stages of filling the tank with clays mixture.

The tests can be divided into preparation phase and test phase. In the preparation phase, the tank was gradually filled with clays mixtures and water with tubular space left free. Mixture of clays has been obtained by mixing commercially available “OCMA Drilling Bentonite” + “Wertonit swelling Mix” in equal proportions. Detailed composition of the clays mixture is shown in Table 5.

Table 5. Mineralogical composition of obtained clay mixture

Smectite	Kaolinite	Illite	Rest – No Clay
42.5%	17.5%	25%	15%

Between each stage of filling the container, clays were compressed with 8 MPa (64kN considering the cylinders specification) load. When the tank was filled, the inner tube was pulled out leaving the hole imitating the real borehole environment with swollen clays, with smaller diameter than tested tool (Figure 12). The test phase (Figure 13) followed the preparation phase. The tested tool was connected to a casing pipe and the drilling mud circulation system was also connected and engaged. The hydraulic system was turned on and the trolley began to push the tool down the hole. The mud flow, pressure driving the cylinders and linear displacement were measured throughout the test. Once the tool reached the bottom of the tank, it was pulled out. The tested tool was dismantled and images of the simulated wellbore were taken from fixed position above its entrance. The drilling mud was separated from bigger clay cuttings which were photographed.. The preparation and testing procedures were repeated for each of the three cases specified in Table 7.

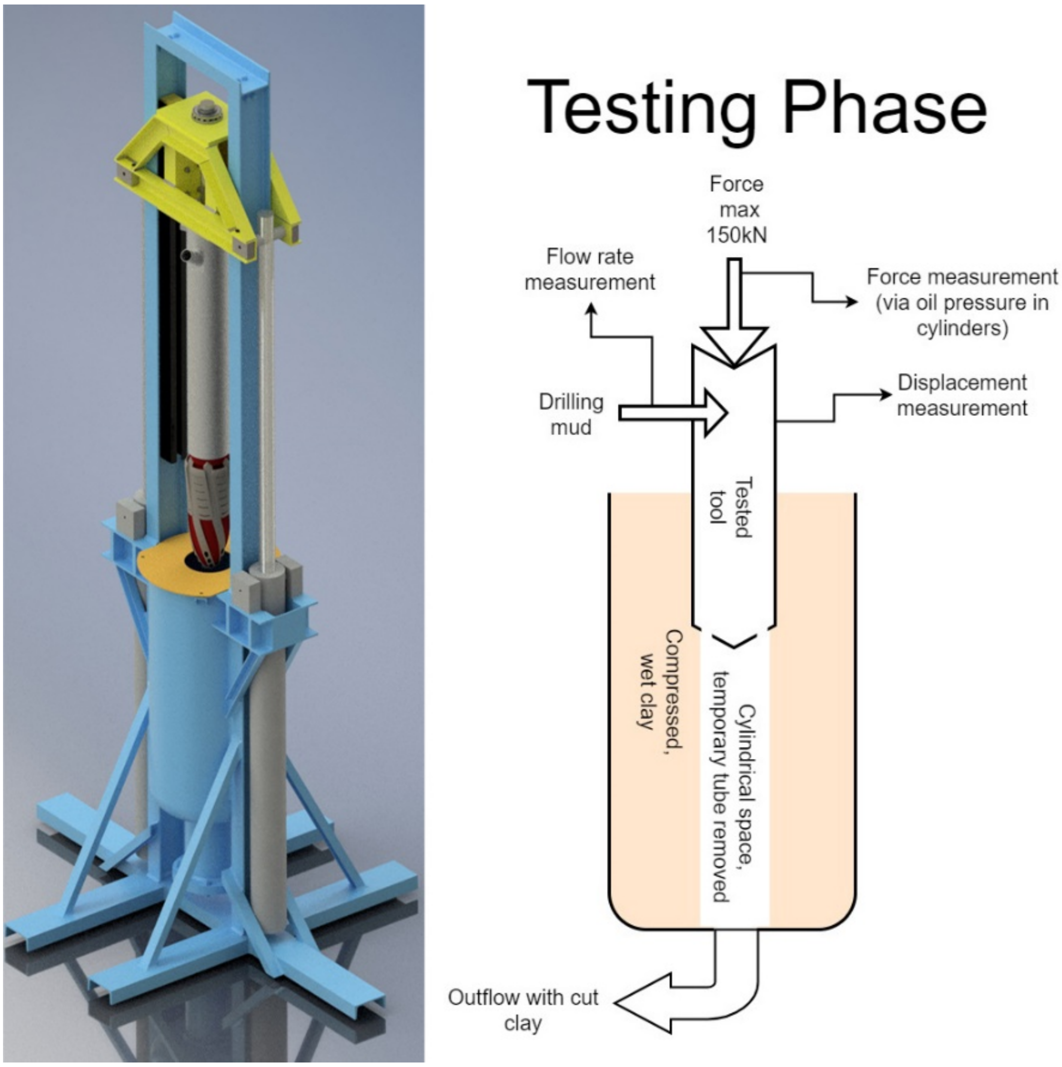

Fig. 13. Testing principle and measurements.

4. RESULTS AND DISCUSSION

4.1. Cementing tests results

Computed Tomography (CT) 3D scans were analysed to determine the influence of well narrowings and well closures (Figure 10) on the quality of cement sheath and problems such as channelling and the lack of bonding between cement and casing. These3D images of annular sections below and above each obstacle were used to determine the poor cement volumes. Comparing the outcome with annular space volume yielded the percentage of poor cement within each section. Poor cement percentage was also calculated for control specimen taken from unobstructed annular space. The poor cement volume increase in relation to control specimen was calculated for each section. The poor cement volume increase between the section below the obstacle and the one above it was calculated for each obstacle. The numbers mentioned above are summarised in Table 8.

Table 8. Cement sheath quality of the investigated sections.

	Below obstacle			Above obstacle			
	void/poor cement volume [mm^3]	void/poor cement percentage	increase normal/ obstacle	void/poor cement volume [mm^3]	void/poor cement percentage	increase normal/obstacle	increase before/after obstacle
without obstacle	25616	6.29%	0%				
closing							
50%	28000	6.87%	9.3%	40705	10.0%	58.9%	45.4%
75%	79966	19.62%	212.2%	91542	22.5%	257.4%	14.5%
90%	45142	11.08%	76.2%	64731	15.9%	152.7%	43.4%
narrowing							
25%	39047	9.58%	52.4%	70819	17.4%	176.5%	81.4%
50%	41076	10.08%	60.4%	36121	8.9%	41.0%	-12.1%
75%	151546	37.19%	491.6%	107740	26.4%	320.6%	-28.9%

In all closure cases and 25% narrowing case the imperfection volume was larger above the obstacle than below it. It is intuitive and consistent with CFD simulations of viscous fluids. The flow velocity near the wall is higher before the necking than after it. The space directly behind the obstacle is shielded from the flow[53] . This is where the gelled drilling mud accumulates and corrupts the cement sheath. In 50% and 75 % narrowing cases, the imperfection volume above the obstacle decreased in comparison with the volume below the obstacle due to the fact that accumulated gelled drilling mud was unable to pass the obstacle. In all the cases, the imperfection volume was larger than imperfection volume for annulus without obstacle. In most severe case the obstacle caused 5-fold increase of imperfections volume. In the best case, the increase was between 5-10%.

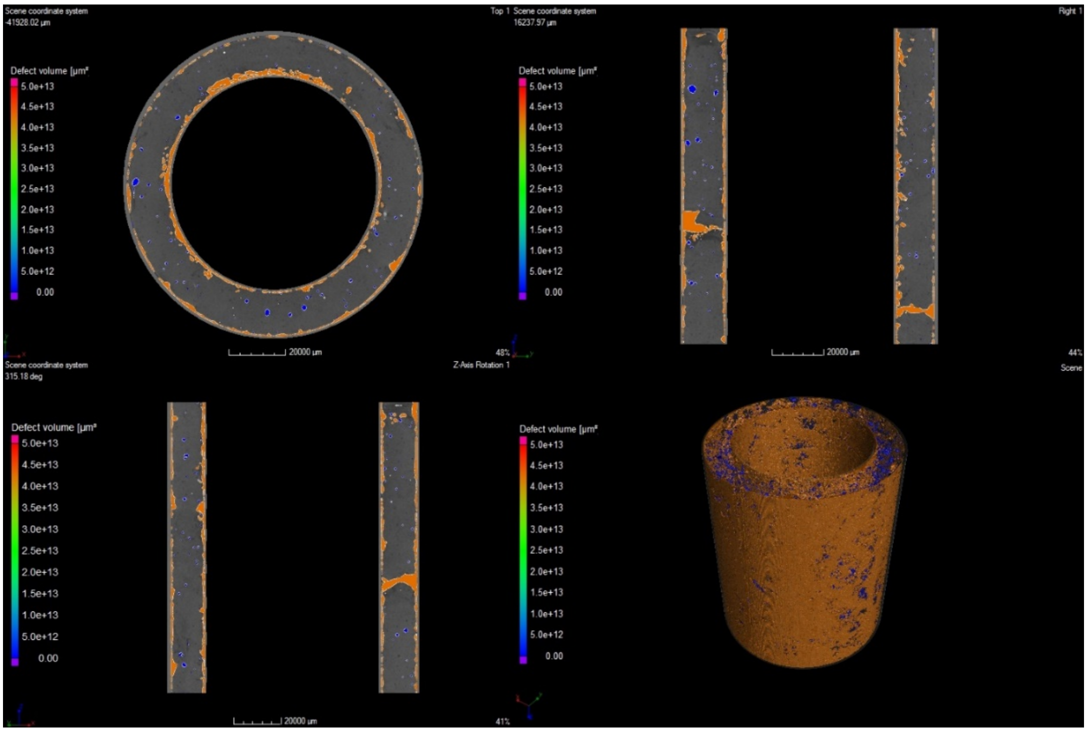

Fig. 14. Computed Tomography results for specimen with obstacle 50% closure – section A – below obstacle. The warmer the colour, the bigger the volume of non-cement area.

Figure 14 presents a number of failures in cement sheath. Two most important types of defects have been recognized: failures parallel to a casing in which gas migration can occur and large failures in cross section which allow contact of the casing with aggressive corrosion agents present in borehole environment.

These results are in good correlation with other researchers' works[31], [54] that show negative influence of annulus geometry imperfections on drilling mud displacement and, therefore, poor cement sheath quality.

4.2.Run in hole tests results

After running the tests all the measurements were plotted and aligned with respect to linear displacement, rather than time, for more clarity. As shown in Figure 15, the use of the Protector reduced force needed to push it through swollen clay in comparison to standard cementing shoe. Also, there is little force difference between 180mm and 160mm hole cases in which Protector was used. Moreover, at the end of run the difference in oil pressure (force exerted to push the tool through) for the same diameter was almost 2-fold (3.68/1.97 MPa) for shoe.

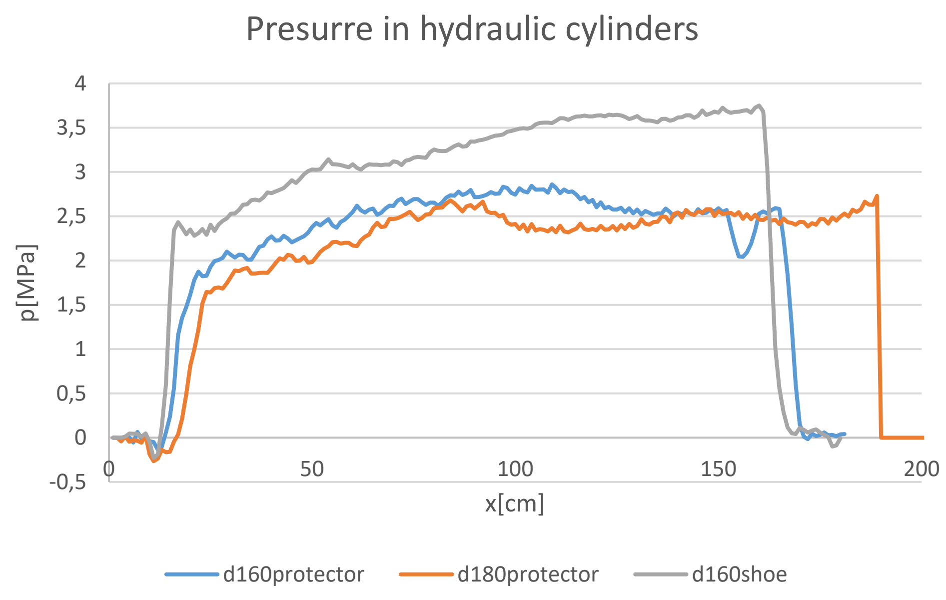

Fig. 15. The results of Protector tests compared to standard cementing shoe. Protector was tested in 160mm and 180mm diameter holes in clay. The plot shows the pressure in the hydraulic cylinders needed to push the tool through the hole, as a function of depth reached by the tool. Pressure of 1 MPa in hydraulic cylinders translates into 8kN of force exerted on the tool.

Drilling mud flow rate (Fig. 16) shows that standard cementing shoe gets clogged easily, mud flow stops and the excessive clay cannot be removed from the hole. Using Protector ensured mud flow during whole test .The cuttings were easily removed with the drilling mud flowing out of the wellbore.

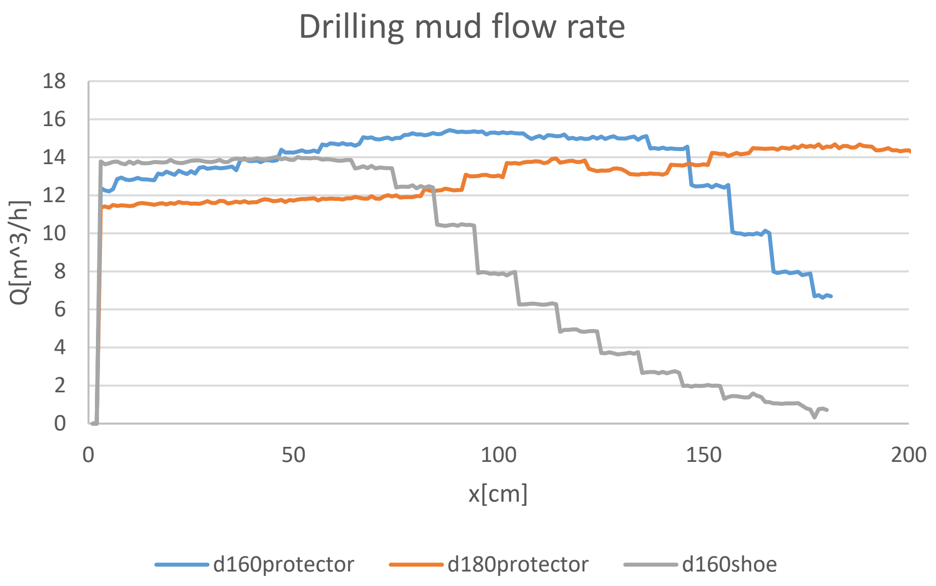

Fig. 16. The results of prototype tests - the drilling mud flow rate during the test as a function of depth reached by the tool. The mud flow decreases, when the tool gets clogged. When the mud flow drops, the cuttings are not properly flushed from the wellbore.

Entrance to the hole was photographed before and after the experiment, along with clay cuttings filtered out of drilling mud (Figure 17).

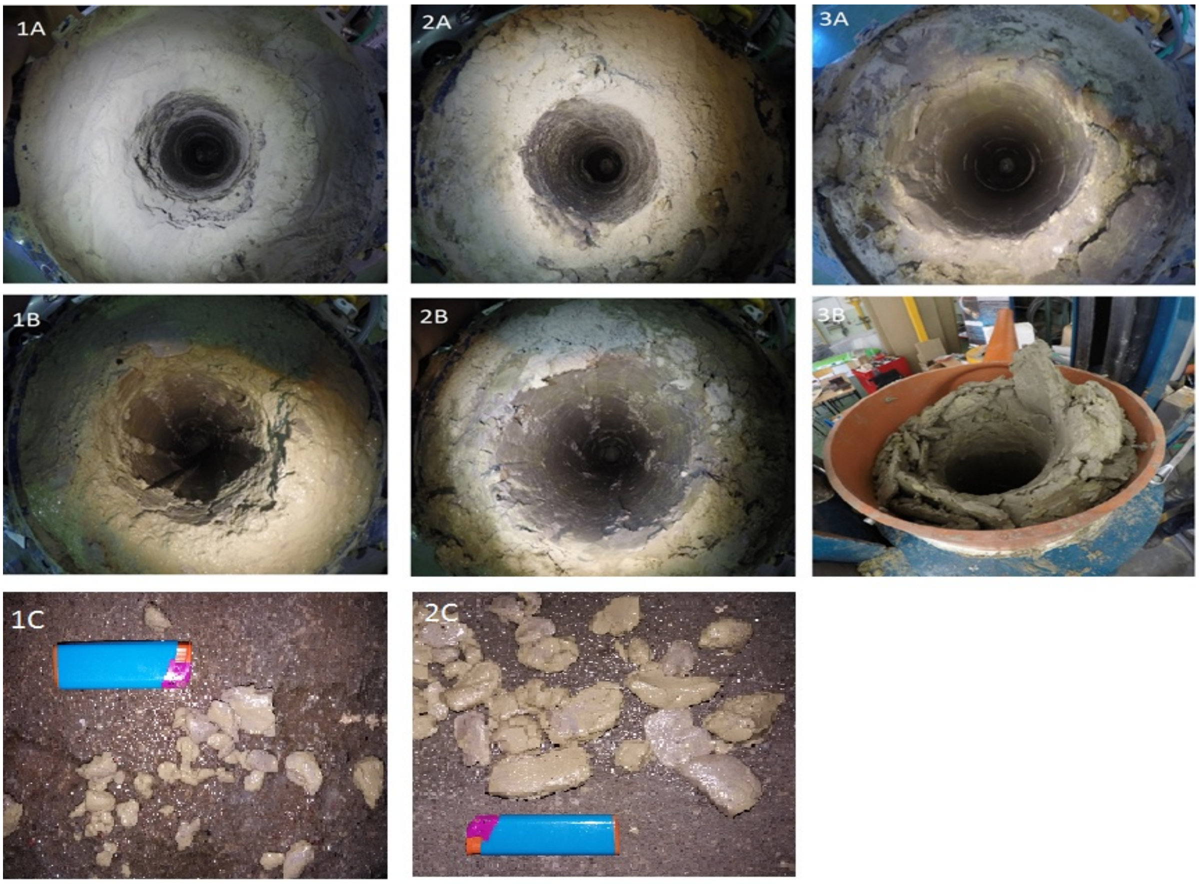

Fig. 17. Photographs of holes A – Before. B – After Test 1-Ø 180 protector; 2- Ø160 protector; 3- Ø160 cementing shoe; 1C and 2C – Clay Cuttings removed from the well with drilling fluid during protector tests.

When using Protector on Ø 180 and Ø 160mm holes there was no visible pushed-out-clay accumulation in the entrance of the hole (Fig17 1,2B) and the clay cuttings were present in drilling fluid that circulated through the tool out of the hole. This observation proves that the size of clay cuttings was sufficiently small for them to get carried with the drilling fluid flow and, thus, to be removed from the hole. It is worth to mention that the removal of excess material from the hole is essential for the process[55], since it reduces the risk of plugging the hole. In case of the cementing shoe, the clay accumulated in the entrance of the hole (Fig 17 3B) and no clay cuttings were found in the drilling mud. This observation is consistent with mud flow measurement indicating lost circulation.

The usage of reamer shoes is highly recommended to increase cement quality and reduce risks associated with leaks, like the one in the Gulf of Mexico[56]. Our research proved Protector to be an efficient reamer shoe that does not need casing rotation to work efficiently which is not the case for standard reamer shoes.

5. CONCLUSIONS.

The problem of poor cementing due to swelling clays is common in the drilling industry. A test stand imitating a wellbore section with annular space was constructed. Cemented sections were scanned and analysed with 3D tomography in search for imperfections. According to presented data, even relatively small well geometry deviation due to swelling clays adversely influences cementing quality. 3D scans with the results from defect analysis present a clear view that phenomena like channelling and lack of bonding between cement and casing occur in obstructed annular space. The study confirmed that bigger deviations directly translate into elevated level of corruption of the cement sheath. .

The research performed on the cementing test stand confirmed that any annular space deviations should be removed before cementing. This problem can be addressed with the innovative downhole tool that was designed to cut swollen clay from wellbore walls – the Protector Against Swelling Clays. The tool fragments the clay and allows it to circulate to the surface with the drilling fluid. AProtector prototype has been tested and compared with standard cementing shoe. The results acquired using run in hole test stand confirm that the usage of Protector tool against swelling clay is justified because it effectively cuts the swollen clay minerals and the clay cuttings are lifted to the surface successfully.

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