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Review

A Review of Recent Research on Contamination of Oil Well Cement with Oil-based Drilling Fluid and the Need of New and Accurate Correlations

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Received: 19 February 2020; Accepted: 11 April 2020; Published: 14 April 2020

Abstract: Drilling fluids and oil well cement are important well barriers. Their compatibility affects the long-term integrity of the well. The mixing of drilling fluid with the oil well cement causes contamination of oil well cement. If the contamination is due to diesel/oil-based drilling fluid (OBF) it adversely affects the rheological and mechanical properties of oil well cement—in other words, the long-term integrity of the well. An initial study on OBF contamination of oil well cement was carried out two decades ago. In recent years, several research projects were carried out on the same topic to understand the reason for changes in the properties of oil well cement with OBF contamination. This literature review shows that using OBF eliminates several drilling problems, as the long-term integrity of the well depends on the amount of OBF contamination in the cement slurry. This paper compares the experiments performed, results and conclusions drawn from selected research studies on OBF contamination of oil well cement. Their shortcomings and a way forward are discussed in detail. A critical review of these research studies highlights the need for new and accurate correlations for OBF-contaminated oil well cement to predict the long-term integrity of wells.

Keywords: contaminated cement slurries; oil well cement; diesel-based mud; oil-based mud (OBM)

1. Introduction

The use of a specific type of drilling fluid for a well depends on various factors such as the geological formation to be drilled, the temperature, pressure, depth and formation evaluation procedure to be used, the environmental and ecological impact, costs, etc. Similarly, the type of oil well cement used depends on the depth range, rheological properties required, wellbore conditions, costs and so on. Oil-based drilling fluid (OBF) consists of oil/diesel in the continuous phase with a percentage of water in the dispersed phase. Additives are added to achieve the desired drilling fluid properties. The base of the OBF is usually diesel or mineral oil, with the former being more toxic than mineral oil systems. The toxicity of OBF is reduced by lowering the aromatics in diesel/mineral oil. Emulsifiers help in maintaining a stable water-in-oil emulsion under downhole conditions. Using OBF instead of water-based drilling mud (WBM) has several pros and cons associated with it [1–3].

Case histories [4–11] justify the use of OBF instead of WBM and helps to eliminate several drilling problems. The productivity index of long, horizontal open-hole gravel packed wells in West Africa improved three times when drilled with OBF compared to those drilled with WBM [4]. A multilateral well was drilled in the Aasgard field (a high-temperature reservoir in Norway) using low-solid OBF which saved 37 days of budget time [5]. Special OBF was designed and used for drilling exploration and appraisal wells for a major operator in the North Sea, where the expected reservoir pressure and temperature were 1700 psi and 400 °F respectively. The designed mud system provided the required thermal stability, consistency in properties and compatibility with the wireline programs [6]. Laboratory experiments on shale oil core samples from the Eagle Ford field were carried out to understand the effect of OBF and WBM on shale oil properties and the swelling properties of the formation [7]. Laboratory and field results (Gudrun Field) shows OBF can be used as a cost-effective and less-damaging perforation fluid for fields with High Pressure and High Temperature (HPHT) conditions [8]. Severe drilling problems, like lost circulation into weak zones and wellbore stability issues, can be eliminated by using OBF and Managed Pressure Drilling techniques [9]. The case history of Southeast Kuwait fields shows a successful application of OBF with a 60:40 oil–water ratio reduces the environmental impact compared to previously drilled wells with 80:20 oil–water ratio OBF [10]. An economic analysis of large fields (approx. 500 wells) using the holistic approach [11] proves that using OBF is better than using WBM.

The success of any drilling project depends on the compatibility of drilling fluid with the spacer and oil well cement [3,12–17]. Due to the oil-wetting characteristics of OBF, displacing OBF becomes a critical operation before cementing. The spacer must be uniquely designed to displace the drilling fluid from the annulus and leave it water-wet [14]. It is highly recommended to test the compatibility of the drilling fluid with the spacer and oil well cement before field application. It helps to overcome the challenges and prevent remedial cementing operations [15–17]. It is difficult to displace 100% mud from the annulus using the spacer. The drilling fluid left behind mixes with the cement and contaminates it.

The effects of oil-based mud have been investigated in the past, especially to understand how the composition and chemistry of OBF affect cement performance [18]. One of the most common pieces of equipment used for cement mechanical properties is the Ultrasonic Cement Analyzer (UCA), which is a great instrument for describing the cement strength evolution [19–24]. For example, in 1993, Harder et al. [18] carried out laboratory experiments on 17 ppg density Class H Portland cement consisting of fluid loss additives and friction reducers designed for 200 °F. The cement slurry was contaminated (10%, 20%, 30%) with four different types of OBF, which were prepared in the lab with combinations of two base oils (diesel and mineral oil) and two emulsifiers (standard fatty acid and alkanolamide) as shown in Table 1.

Table 1. Composition of oil-based drilling fluids (OBFs) used in laboratory investigation by Harder et al., 1993.

OBF	Base Oil	Primary Emulsifier
Mud 1	Mineral Oil	Alkanolamide
Mud 2	Mineral Oil	Standard Fatty Acid
Mud 3	Diesel Oil	Alkanolamide
Mud 4	Diesel Oil	Standard Fatty Acid

Figure 1 shows the one-day compressive strength results obtained by performing a non-destructive test on the contaminated cement samples measured using the Ultrasonic Cement Analyzer (UCA).

Figure 2 shows the development of compressive strength for 20% contamination of cement slurry with Muds 3 and 4.

Based on the two base oils used in the study, diesel oil had a more adverse effect on the compressive strength compared to mineral oil. On comparing the two-primary emulsifiers, the presence of alkanolamide showed better strength development compared to standard fatty acid (calcium soap) [18].

It is evident that the contamination of oil well cement with OBF causes well integrity issues and there is a need to better understand the effect of this contamination. Research studies [25–30] have been carried out in recent years to evaluate and quantify the effect of OBF contamination of oil well cement on the long-term integrity of the well. A summary of these recent studies is presented in the following sections, followed by critical analyses and discussions of the same. This paper aims to highlight the results of these studies and to point towards new and better investigations into cement contamination with oil-based mud.

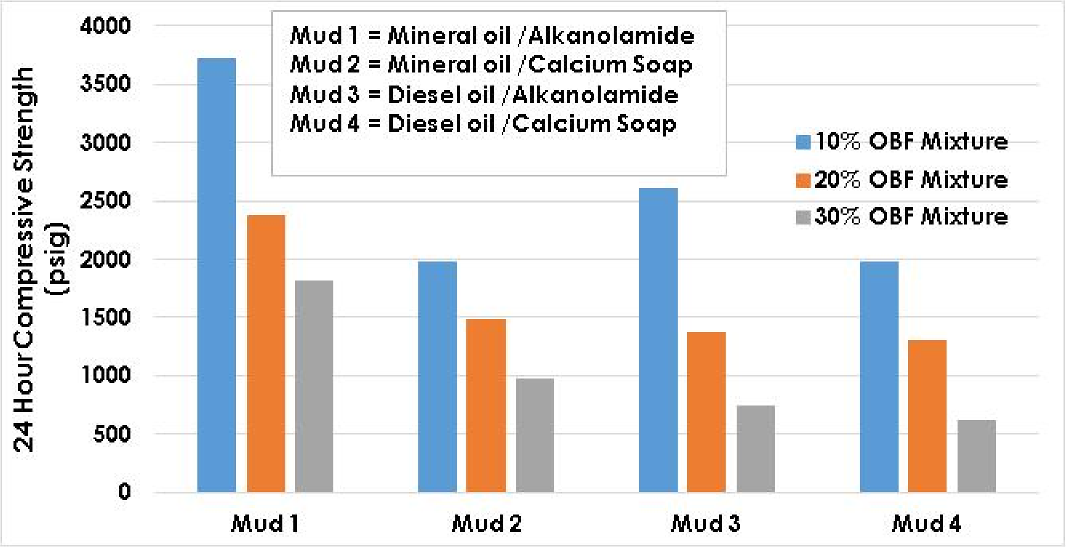

Figure 1. Effect of OBF chemistry on compressive strength of oil well cement adapted from Harder et al., 1993.

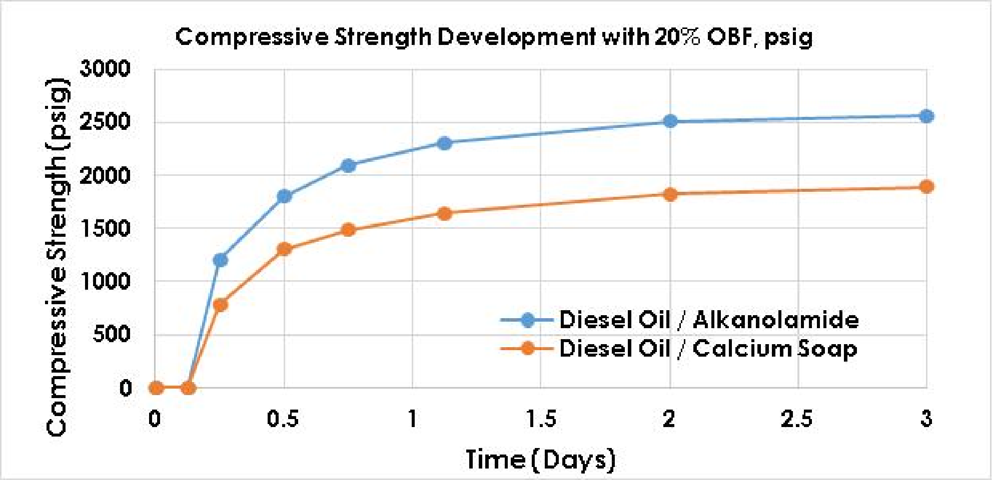

Figure 2. Development of compressive strength with 20% contamination (Muds 3 and 4) adapted from Harder et al., 1993.

The paper will describe in the Materials and Methods chapter all of the found case studies (in historical order) about cement contamination, which will later be used for discussions and data dissemination.

2. Material and Methods

2.1. Contamination of Oil Well Cement with OBF

In recent years, research was carried out to discover the mechanism behind changes in mechanical and rheological properties of OBF-contaminated oil well cement. Modern research methodologies and equipment have allowed scientists to look in great detail at the OBF and cement interaction. A decade ago, research was mainly focused on optimizing the spacer fluid program to reduce the OBF contamination and/or look for additives to improve the compatibility between OBF and oil well cement. This section summarizes selected experimental studies performed in recent years to understand the phenomenon of contamination of oil well cement with OBF. A summary of the case studies considered in this paper will later presented in form of a table.

2.2. Case Study 1

The objective of study carried out by Aughenbaugh et al. [25] was to quantify the effects of contamination of various cement slurries with synthetic-based mud (SBM) and look for additives to reduce the effect of contamination. This research was/is divided into multiple phases and these were the objectives of the first phase. API RP 10A standard recommendations [31] were followed for preparing and mixing cement slurries in this study. The composition of cement slurries tested in this study are shown in Table 2.

Table 2. Composition of cement slurries tested by Aughenbaugh et al., 2014.

Slurry Name	Composition
H-1	API Class H-1 and tap water
H-2	API Class H-2 and tap water
C-1	API Class C and tap water
L-1	Lightweight cement and tap water
S-1	Blast furnace slag and alkaline activating solution
DW-H-2	API Class H-2 and Tap water and Additives

The above cement slurries were contaminated (5%, 10% and 15% by volume) by replacing part of the cement slurries with field SBM (11.6 ppg; 70/30 invert emulsion–oil/$CaCl_2$), laboratory-formulated SBM (Lab-SBM) and silica sand. Slurries were contaminated with silica sand to test the effect of a reduction in cement contents. A drill press and a paint stirrer were used to mix the contaminants and the cement slurries. Samples were cured for 48 h and destructive as well as non-destructive tests (UCA) were performed to obtain the compressive strength values (curing at 170 °F and 3000 psi).

Figure 3 shows the percentage reduction in compressive strength of field SBM-contaminated cement slurries with respect to neat cement slurries and the 48 h compressive strength of silica sand contaminated cement slurries (0% to 15%). The results obtained from silica sand contamination tests proved that the decrease in compressive strength due to contamination with field SBM is because of chemical interaction and not due to the dilution of cement content.

It was noted that the time required for strength development was constant, irrespective of the percentage of contamination.

Lab-SBMs were prepared (in the laboratory) in two different ways to detect which component was responsible for the decrease in compressive strength of contaminated cement slurries: Lab-SBM with the same composition as the field SBM and Lab-SBM (no brine) where brine was replaced with an equal volume of freshwater. Lab-SBM and field SBM showed similar results of compressive strength, which were less than the Lab-SBM (no brine) compressive strength values. This test proved that brine affects the compressive strength negatively and the reason for lower compressive strength values for SBM-contaminated cement slurries could be due to the osmosis of the water from cement slurries to SBM.

Compressive strength values obtained for the slag-based cement slurry contaminated with SBM were least affected compared to other cement slurries tested in this study, see Figure 4. Several additives were added to SBM-contaminated cement slurries to compensate for the reduction in strength. The only additive that improved the strength was alkali when added at 10% of the weight of SBM. These were the findings from Aughenbaugh et al., 2014.

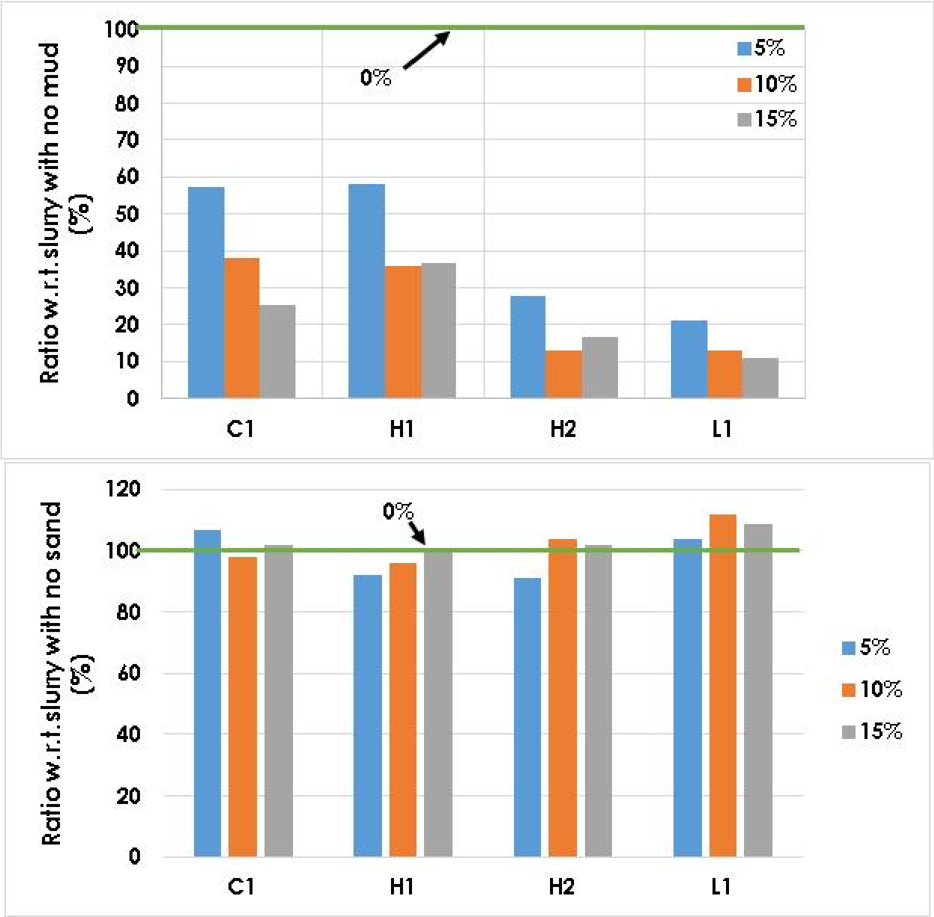

Figure 3. (**Top**) 48 h compressive strength of field synthetic-based mud (SBM) contaminated cement slurries (0% to 15%); (**bottom**) 48 h compressive strength of neat cement slurries contaminated with inert silica sand (0% to 15%); adapted from Aughenbaugh et al., 2014.

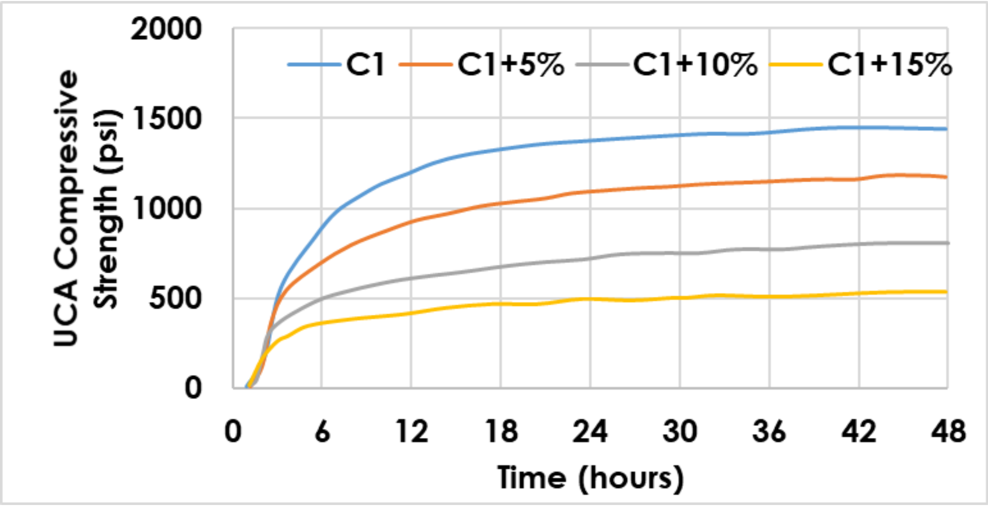

Figure 4. *Cont.*

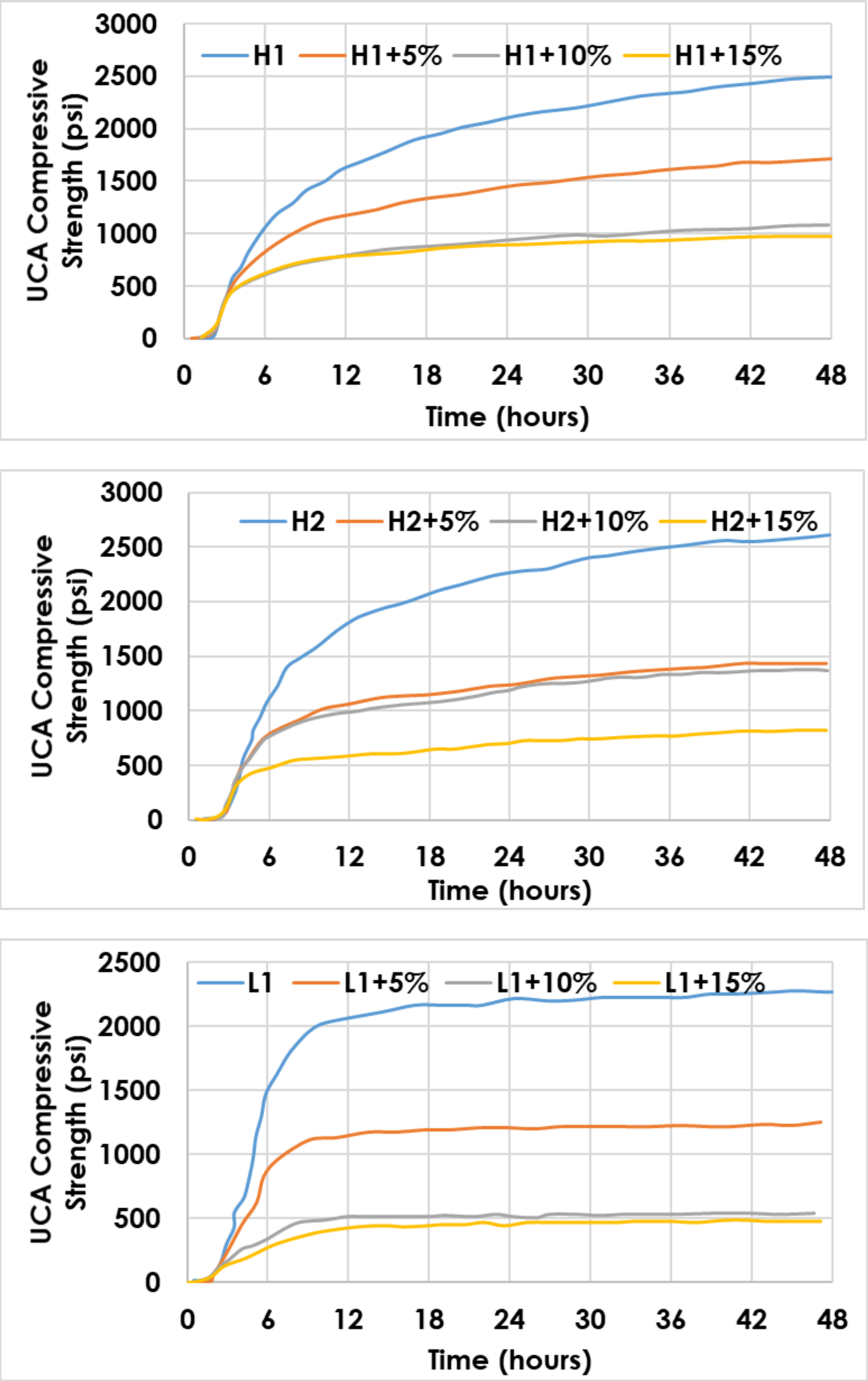

Figure 4. UCA results for field SBM-contaminated (0% to 15%) cement slurries adapted after Aughenbaugh et al., 2014.

2.3. Case Study 2

Vipulanandan et al.'s [26] study tried to find out the correlation between the piezoelectric properties, rheological properties and mechanical properties of modified API Class H cement. The sensing properties of cement slurries were improved by adding conductive fillers (0.1% by the weight of cement). The modified cement slurries were contaminated (0.1%, 1% and 3% by the weight of cement) with vegetable oil-based drilling fluid (75/25 invert emulsion). Cylindrical samples (2″ diameter and 4″ height) with two conductive wires 5 cm apart were cured for 28 days at room temperature. The densities of the modified cement slurries were measured using a standard mud balance cup; rheological properties were tested using the rotational viscometer (ambient pressure and temperature for a rotational range from 3 to 600 rpm); a standard API Resistive meter was used to measure the electrical resistivity and destructive test for measurements of compressive strength, which were performed using a hydraulic compression machine for 1, 7 and 28 days cured samples.

The author proposed a hyperbole model to predict the shear strain rate vs. shear stress. This proposed model was fitted with laboratory results and produced better results compared to Herschel–Bulkley model and Bingham plastic model. It was also observed (Figure 5) that the initial electrical resistivity of the modified cement slurries increased with the increase in contamination. The waiting on cement time could be calculated by monitoring the changes in the electrical resistivity of the cement slurries.

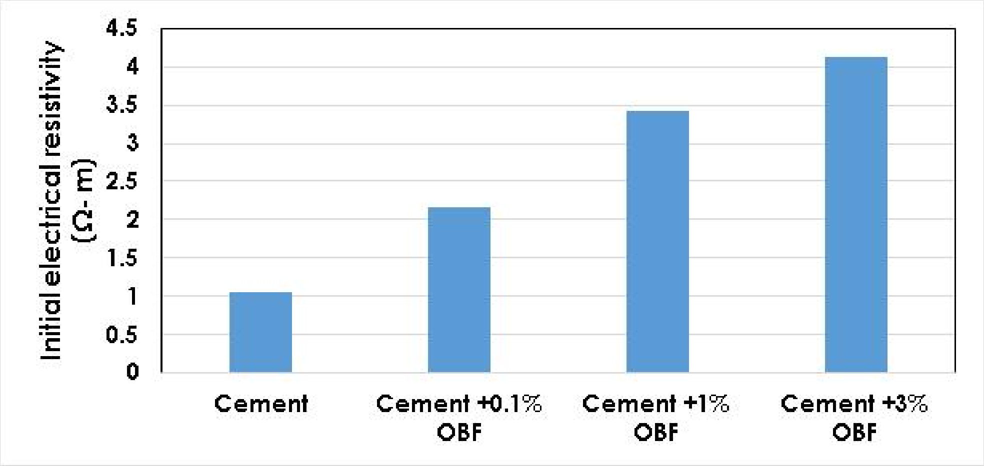

Figure 5. Initial electrical resistivity of cement samples (adapted after Vipulanandan et al., 2014).

The compressive strength (Figure 6) of the samples tested in this study showed a similar trend of decreases in strength with increases in contamination.

The correlation between the electrical resistivity and compressive strength of samples tested in this study for different curing ages was found to be linear in nature.

2.4. Case Study 3

An extensive study was carried out by Li et al. [28] at the microscopic level to understand the mechanism of OBF contamination of oil well cement. The hydration process of contaminated cement slurries was studied using X-ray diffraction (XRD), Scanning Electron Microscope (SEM), Environmental Scanning Electron Microscope (ESEM), Thermogravimetry (TG) and Energy Dispersive Spectrometer (EDS). The changes in rheological properties and mechanical properties of contaminated cement slurries were quantified first and then the mechanisms behind them were studied.

The cement slurries used in this study were mixed based on API recommendations, which consist of API Class G cement, free water control additives, water, dispersant, etc. These slurries were contaminated (0%, 5%, 25% and 50% by weight or volume of cement) with UDM-2 system diesel-based drilling fluid (85/15 invert emulsion). Compressive strength was measured by performing destructive tests on contaminated cement slurries cured in a water bath at 93 °C for 1, 3 and 7 days. Microstructure analyses of 5% and 25% contaminated cement slurries were discussed in the paper.

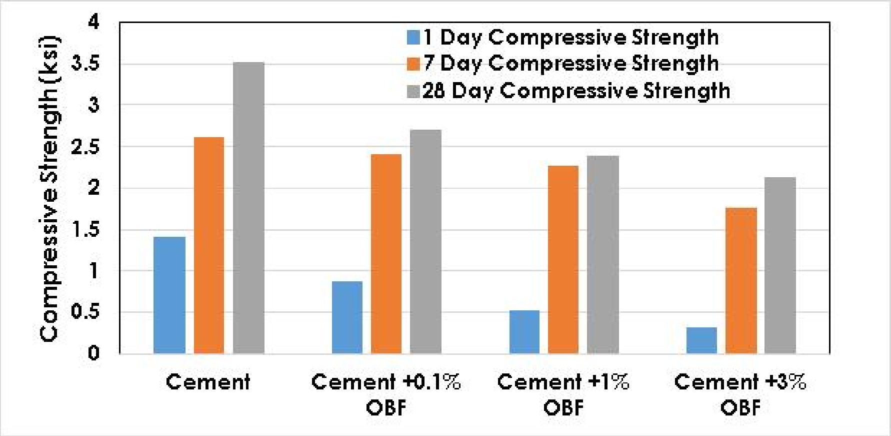

Figure 6. Development of compressive strength of samples tested in study by Vipulanandan et al., 2014.

The results obtained for the compressive strength and bonding strength for different contaminations (Figure 7) showed a 100% reduction in strength when the contamination was 50%.

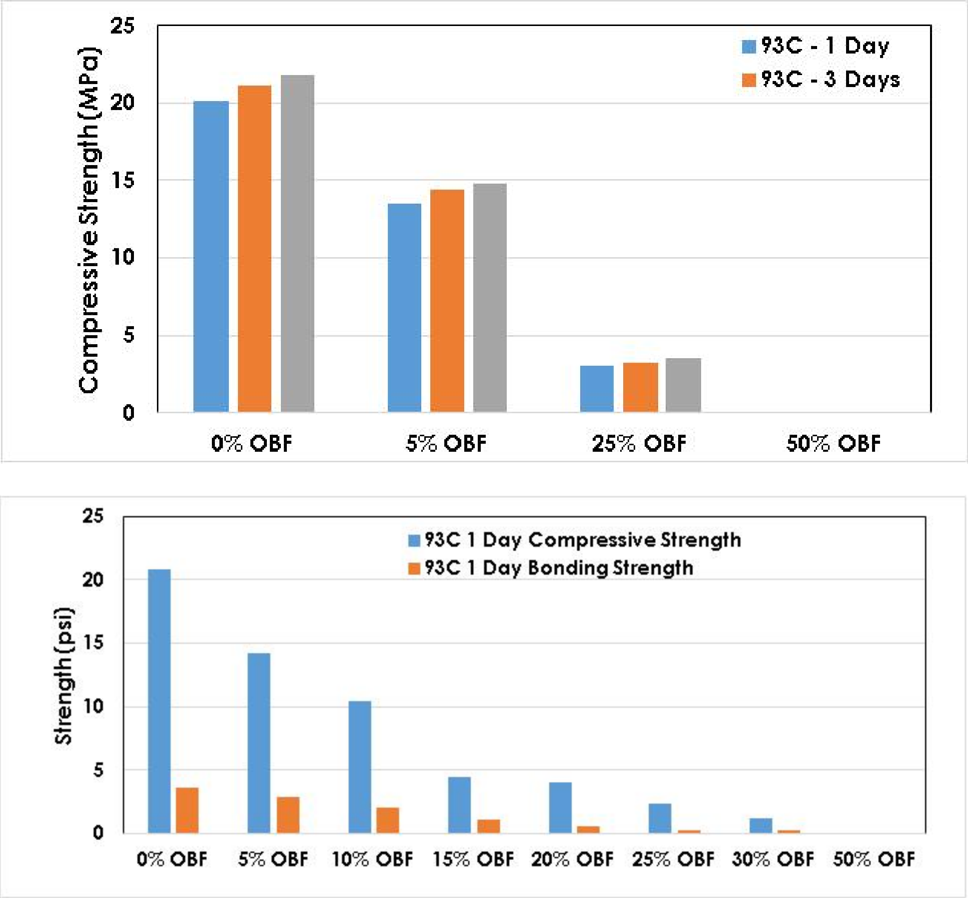

Figure 7. Compressive strength and bonding strength results of contaminated cement sample (after Li et al., 2015).

XRD test results confirmed the reason for the decrease in strength. OBF hinders the hydration reaction without interacting chemically. Incomplete hydration of the contaminated samples leads to the formation of a honeycomb structure. Figure 8 shows the general process of hydration of contaminated cement slurries.

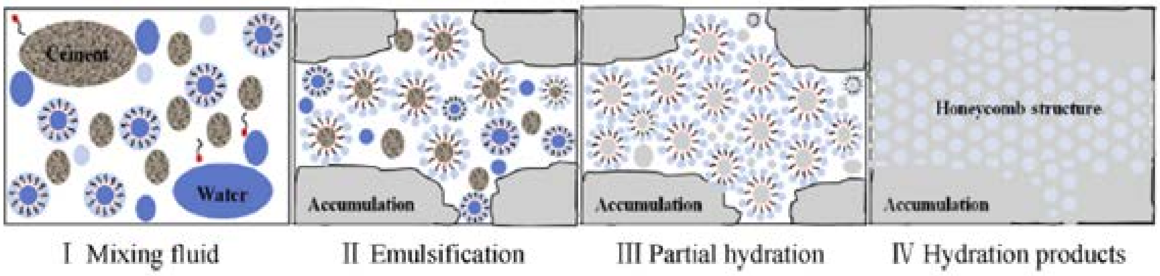

Figure 8. Hydration process for contaminated cement slurries (Li et al., 2015).

Demulsification and osmotic pressure changed the rheological properties of contaminated cement slurries. Figure 9 shows the process of water migration in OBF-contaminated cement slurries.

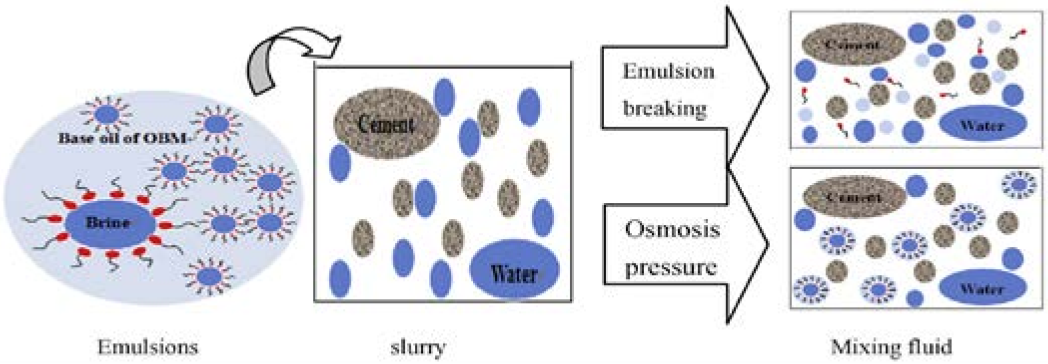

Figure 9. Water migration process in contaminated cement slurries (Li et al., 2015).

This study also proved that the addition of surfactants to contaminated cement slurries improves the mechanical and rheological properties.

2.5. Case Study 4

An extensive study was performed by Li et al. [29] to find out the effect of OBF and its components on the rheological properties, mechanical properties, porosity and permeability of cement slurries. An Ultrasonic Cement Analyzer (UCA), X-ray diffraction (XRD), Thermogravimetry (TG), a Scanning Electronic Microscope (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) were used in this study.

The cement slurry used in this study consisted of API Class G cement, 2% anti-gas migration agent, 25% silica powder, 5% filtrate reducer, 1% dispersant, 2% retarder and 0.2% defoaming agent. The above cement slurry was contaminated (0%, 5%, 25% and 50% by weight or volume of cement) with diesel-based drilling fluid. The cement samples were cured for 2 days at 135 °C and 20.7 MPa. With the increase in contamination, the compressive strength and bonding strength decreased, while porosity and permeability increased (Table 3). An increase in porosity and permeability was confirmed by SEM tests (Figure 10).

Table 3. Test Results from Li et al., 2016.

% Contamination	Compressive Strength (MPa)	Bonding Strength (MPa)	Porosity %	Permeability (mD)
0	17.2	3.4	11.2	0.04
5	13.5	2.2	16.8	0.19
25	4.1	0.7	32.1	0.41
50	0	0	-	-

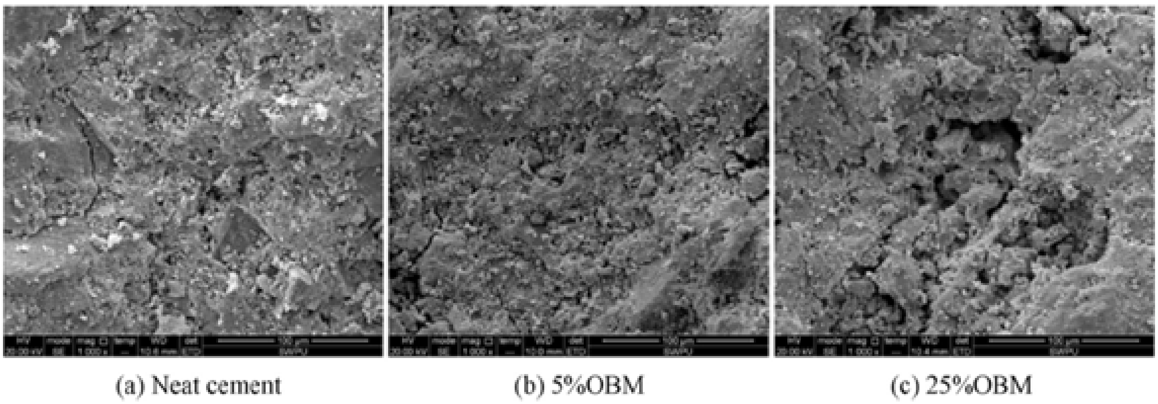

Figure 10. SEM test results (Li et al., 2016).

Furthermore, the effects of contamination of cement slurry with different components of OBF was also studied. The compressive strength was reduced to zero when cement slurries were contaminated with 50% emulsion and 50% diesel, respectively. The reduction in compressive strength values for different contaminations of primary emulsifier, secondary emulsifier, and organic clay was much less compared to the effect seen with diesel and emulsion contaminations.

Li et al. [29] also contradicted their previous work [28] and concluded that OBF does not hinder the hydration process of contaminated cement slurries. An increase in contamination of OBF causes an increase in lubrication and porosity of the contaminated cement slurries, thereby decreasing the strength of the hydrated samples.

2.6. Case Study 5

Soares et al. [27] conducted a study on contaminated cement samples to determine the rheological properties, mechanical properties and slurry sedimentation testing, and evaluated the hydrated samples using XRD and SEM. The reference cement slurry (RS) consists of API Class G cement, water, antifoam, dispersant, fluid loss control and retarder which weighed 15 ppg. Two different OBFs (10 ppg, 63/37 invert emulsion) were formulated—one with a wetting agent (DF) and another without a wetting agent (DF *). The sample names and their corresponding contaminations are presented in Table 4. The samples were cured for 24 h at 52 °C. They were demolded 45 min earlier followed by 30 min cooling under flowing water and destructive tests were carried out to determine the compressive strength values.

Samples with 50% contamination were still in the slurry phase even after curing time of 24h, which is consistent with the values published in the previous literature. A reduction in compressive strength was more pronounced in the presence of the wetting agent compared to without the wetting agent, see Figure 11.

The yield point and plastic viscosity increased with the increase in contamination. Microcavities in the hydrated samples increased with an increase in OBF contamination, causing the compressive strength to decrease.

Table 4. Nomenclature of samples (Soares et al., 2017).

Sample Name	RS/DF (%)	Sample Name	RS/DF * (%)
S95/05	95/05	95/05 *	95/05
S75/25	75/25	75/25 *	75/25
S50/50	50/50	50/50 *	50/50
S25/75	25/75	25/75 *	25/75
S05/95	05/95	05/95 *	05/95

* samples marked are without wetting agent.

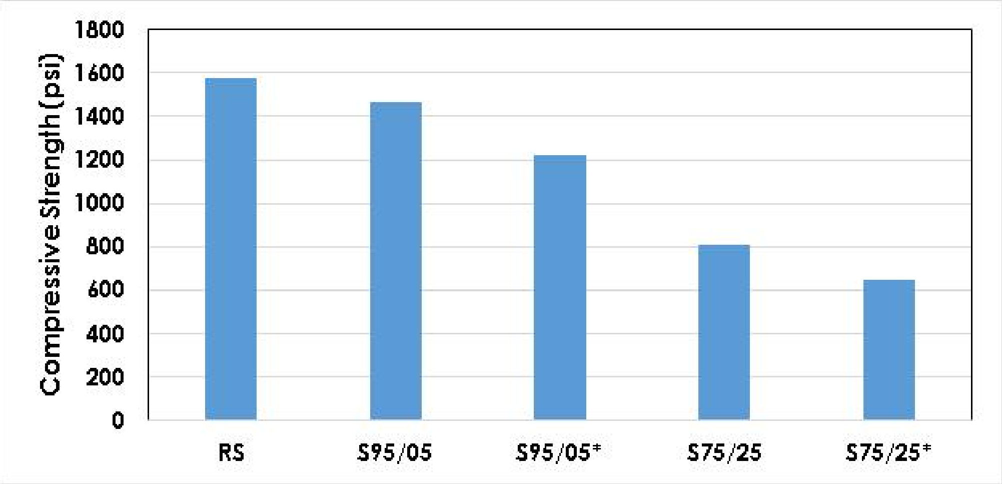

Figure 11. Compressive strength values for contaminated cement samples (after Soares et al., 2017).

2.7. Case Study 6

Performing the non-destructive tests to measure the compressive strength of cement has gained popularity in recent years. To simulate the poor-quality wellbore cleaning, cement slurries were contaminated with OBF and ultrasonic pulse velocity was measured. Olteanu et al.'s [30] study aimed to check the trustworthiness of ultrasonic measurements in the presence of OBF. API Class C cement was contaminated with 40 mL OBF and cured at room temperature (20 °C). The results obtained for over 200 tests are shown in Figure 12.

The contaminated cement slurries behave better than uncontaminated cement slurries during the initial hours of curing, as shown in Figure 13. This can mislead the engineer and consider the poor-quality cement job as a success.

The authors also presented the correlations of Unconfined Compressive Satrength (UCS) vs. Ultrasonic Pulse Velocity (UPV) for contaminated, uncontaminated and uncontaminated–thermal cycles, see Table 5. The thermal cycle tests were carried out in a pre-heated water bath at 60 °C for 8 h/day.

Table 5. Correlations obtained for Class C cement (Olteanu et al., 2020).

Correlation	Equation	R^2
UCS vs. UPV (uncontaminated)	$Y = 0.1392e^{0.0018\times}$	0.9115
UCS vs. UPV (contaminated)	$Y = 0.2094e^{0.0015\times}$	0.9758
UCS vs. UPV (uncontaminated–thermal cycles)	$Y = 0.2879e^{0.0016\times}$	0.9856

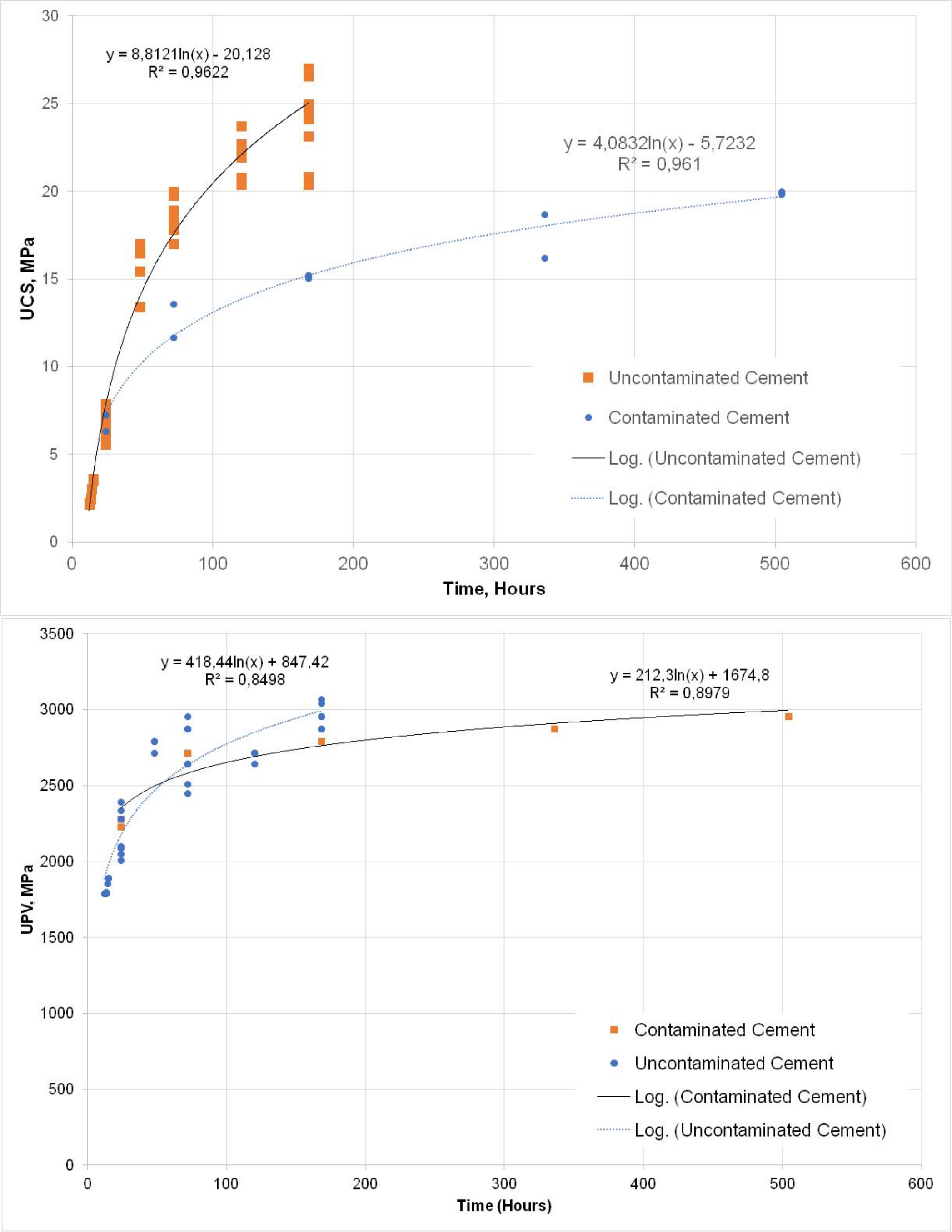

Figure 12. Unconfined Compressive Strength (UCS) vs. time and Ultrasonic Pulse Velocity (UPV) vs. time (Olteanu et al., 2020).

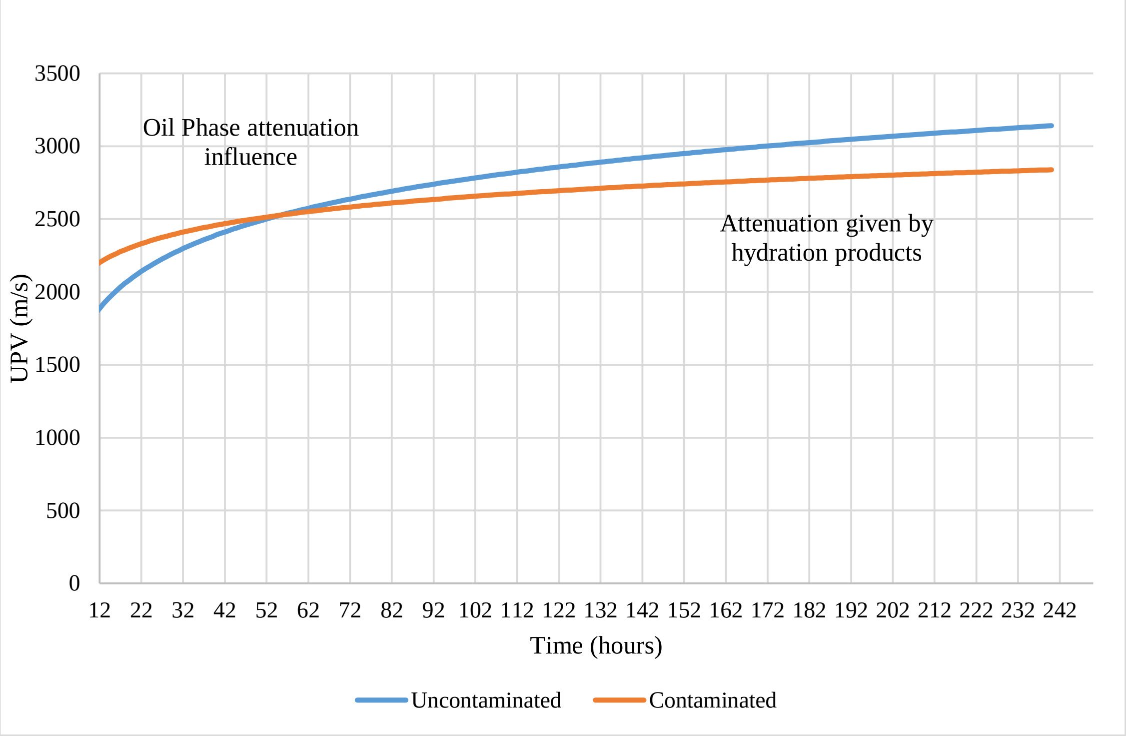

Figure 13. UPV vs. time for initial hours—early hydration (Olteanu et al., 2020).

Table 6 summarizes important details from the above case studies.

Table 6. Comparison of laboratory studies performed by several authors.

Authors	**Harder et al., 1993**	**Aughenbaugh et al., 2014**	**Vipulanandan et al., 2014**	**Li et al., 2015**	**Li et al., 2016**	**Soares et al., 2017**	**Olteanu et al., 2019**
Cement	API Class H (Slurry density—17 ppg)	• API Class H (H-1 and H-2) • API Class C • L-1 • S-1 • DW-H-2	API Class H	API Class G	API Class G	API Class G (Slurry Density—15 ppg)	API Class C (Slurry Density—14.77 ppg)
Additives	Fluid loss additive and friction reducers	• Alkaline activating solution for S-1 • Dispersant, bonding agent, anti-static agent, anti-foam agent and free water control additive for DW-H-2	0.1% (BWOC) conductive fillers	• Free water control additives • Water • Dispersant, etc	• 2% anti-gas migration agent • 25% silicon power • 5% filtrate reducer • 1% dispersant • 2% retarder • 0.2% defoaming agent	• Antifoam • Dispersant • Fluid loss control • Retarder	-
Contamination	Four types of OBF formulated with combinations of base oil (Diesel oil and Mineral oil) and primary emulsifier (Alkanolamide and Calcium Soap).	• Field SBM (11.6 ppg; 70/30 invert emulsion –Oil/CaCl2) • Lab-SBM (with brine) • Lab-SBM (without brine) • Silica sand	Vegetable oil-based mud (75/25 invert emulsion) with 1% chemical surfactant	UDM-2 system diesel-based drilling fluid (85/15 invert emulsion)	VERSACLEAN system diesel-based drilling fluid	• OBF and DF* • OBF and DF • 10 ppg, Oil/Water Invert Emulsion (63/37)	OBF
Amount of contaminant	• 10% • 20% • 30%	• 5% • 10% • 15% •	• 0.1% • 1% • 3% •	• 5% • 25% • 50% •	• 5% • 25% • 50% •	• 5% • 25% • 50% • 75% • 95%	40 mL
Curing Temp.	≈93 °C *	≈77 °C *	Room temperature	93 °C	135 °C	52 °C	• 20 °C • 60 °C thermal cycles 8 h/day

Table 6. *Cont.*

Authors	**Harder et al., 1993**	**Aughenbaugh et al., 2014**	**Vipulanandan et al., 2014**	**Li et al., 2015**	**Li et al., 2016**	**Soares et al., 2017**	**Olteanu et al., 2019**
Curing Press.	Atmospheric *	20.7 MPa *	Atmospheric	Atmospheric	20.7 MPa	Atmospheric	Atmospheric
Curing Time	• 1 day • 3 days	2 days	• 1 day • 7 days • 28 days • • 7 days • 28 days	• 1 day • 1 day • 3 days • 7 days • • 7 days	2 days	1 day	8 h to 50 days
Mechanical Properties	Diesel oil had a more adverse effects on the compressive strength compared to mineral oil. The presence of alkanolamide showed better strength development compared to standard fatty acid (calcium soap).	UCS reduction rate was 40% for C-1 and H-1 and for L-1 it was 80% at 5% contamination. While at 15% contamination reduction in C-1 was 25%, H-1 was 38% and L-1 was 90%. UCS remained same with 10% error margin for different contamination of silica. Brine affects the compressive strength negatively. For DW-H-2 at 5% contamination reduction is 5% while at 15% contamination reduction is 50%.	UCS reduction rate for 1 day of curing with 0.1% and 3% contamination is 40% and 75% respectively. Similarly, UCS reduction rate for 28 days of curing with 0.1% and 3% contamination is 25% and 35% respectively.	UCS reduction rate for 1, 3,7 days of curing with 5% contamination is 33.17%, 32.46% and 31.75% respectively. At 25% contamination it is 85.15%, 84.56% and 83.95% for 1,3,7 days of curing respectively reduced to 0 for 50% contamination.	UCS and bonding strength reduced by 76% and 79% for 25% contamination respectively; and reduced to 0 for 50% contamination.	For 5% and 25% contamination (comparing DF* vs. DF), UCS reduction was 15% and 25%. UCS reduced to 0 for 50% contamination.	50% reduction in UCS after curing for 14 days
Authors	**Harder et al., 1993**	**Aughenbaugh et al., 2014**	**Vipulanandan et al., 2014**	**Li et al., 2015**	**Li et al., 2016**	**Soares et al., 2017**	**Olteanu et al., 2019**
Rheological Properties	-	-	Proposed a Hyperbolic model over the Herschel–Bulkley and Bingham Models.	Bingham Plastic model used to characterize the mixtures at 25 °C and 93 °C.	Contamination increases initial consistency and decreases fluidity	Bingham and Power Law models used to characterize the mixtures.	-
Correlation	No	No	No	No	No	No	Yes *
Other findings	Addition of ethoxylated nonylphenol improves the strength of contaminated cement slurry.	Strength of contaminated samples was improved by addition of 10% (by weight of SBM) alkali. Mechanism behind the reduction in strength is osmotic dehydration.	Measurement of initial electrical resistivity of contaminated samples can help in understanding the amount of OBF contamination.	Demulsification and osmotic pressure change the rheological properties. Honeycomb structure is formed in the presence of OBF. Adding surfactant to contaminated slurry improves the rheological and mechanical properties.	At 25% contamination the porosity and permeability increased by 187% and 925% respectively. Out of all the components of OBF, emulsion and diesel had worst effects on rheological and mechanical properties compared to other OBF components.	Contamination in general increases plastic viscosity and yield point; decreases the max. pumpable consistency; formation of microcavities affect the UCS; Wetting agent modifies zeta potential values.	Up to 24 h both contaminated and uncontaminated samples have similar properties.

* this information is not clearly specified by the cited work, but is assumed.

3. Discussion

Our review study selected the abovementioned case studies since their objective was to understand the effect on the mechanical and rheological properties of cement slurries contaminated with OBF and/or to understand the mechanism behind the reduction in mechanical and rheological properties of cement slurries contaminated with OBF. Upon comparing these studies, differences in the sample preparation methods and testing procedure of the samples are evident. The type of API cement, additives, type and amount of contamination, curing time, curing temperature and pressure differs from one group to another.

Inadequate information on sample preparations is evident in the literature—many research groups have not mentioned whether the OBF contamination is by weight of cement or by volume of cement. Moreover, many groups have not mentioned if the OBF is added to standard cement slurry compositions or if OBF is replaced by equal volumes of cement slurry. Few groups follow the API 10D recommendations to prepare the 2″ × 2″ samples for measuring the UCS, others have not specified the dimensions of the samples. Also, many groups have not specified the number of samples prepared and tested to prove the accuracy of their UCS results.

It can be seen from studies carried out two decades ago that the OBF composition hinders the mechanical properties of cement slurries. Inadequate information about the OBF used in the study makes the results obtained from the study invalid for comparison. It is seen that the reduction in the mechanical properties depend on the testing temperature and pressure for a given class of cement and curing time. Differences in the composition of OBF used along with the differences in curing time, temperature and pressure makes it difficult to compare and validate the results obtained by different research groups.

In study performed by Aughenbaugh et al. [25], it is also seen that for the same class of cement (H-1 and H-2) under the same testing conditions and the same OBF contamination, different results were obtained and the reason for this is unclear. Furthermore, the long-term effect on the mechanical properties of contaminated slurries is examined by few research groups. The limitation with long-term tests is to maintain the same pressure and (elevated) temperature over a longer duration. Research has been done on the rheological properties, but due to inadequate information provided in the literature, it becomes difficult to draw conclusions.

Romanowski et al. [32] have presented destructive and non-destructive tests carried out to determine the relationship between the unconfined compressive strength (UCS) and the ultrasonic pulse velocity (UPV) in the presence of additives. Three cement compositions tested in this study were API Class G cement, API Class G cement and 4% Bentonite, and API Class G cement and 10% Bentonite. The prepared samples were cured at atmospheric pressure and temperature for 1, 3, 7, 21, 30, 40, 70 and 150 days. Figure 14 shows the results obtained in this study and Figure 15 shows the comparison of the correlations obtained in this study with the previous work done on the same topic. Similar to the findings of Olteanu et al. [30], Romanowski et al. [32] specifically indicated that additives may change the UPV vs. UCS response and, thus, if the correlation equation is not known, the results of various researchers cannot be compared accurately.

A lot of effort has been undertaken recently to understand the mechanism of changes in mechanical and rheological properties of OBF-contaminated cement slurries. Shortcomings like the lack of standardization in testing methods for OBF-contaminated cement slurries and inadequate information provided in the literature made it difficult to compare the results. It is evident that the mechanical properties of cement slurries decrease with an increase in contamination. However, the reduction in mechanical properties is different for the same classes of cement in similar conditions.

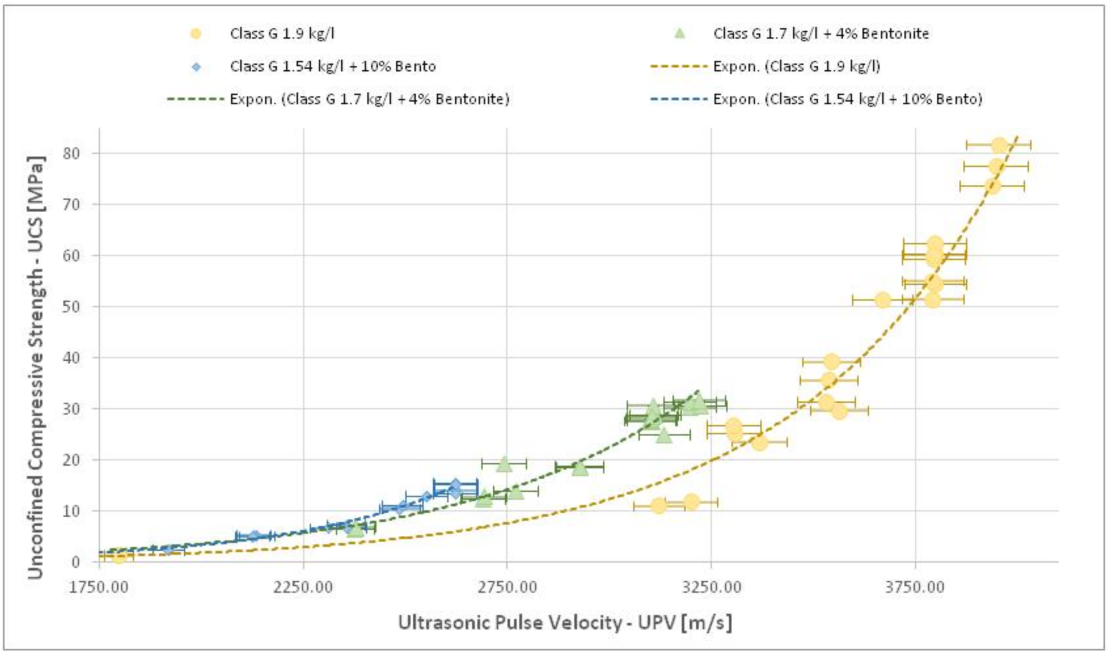

Figure 14. UCS vs. UPV (Romanowski et al., 2018).

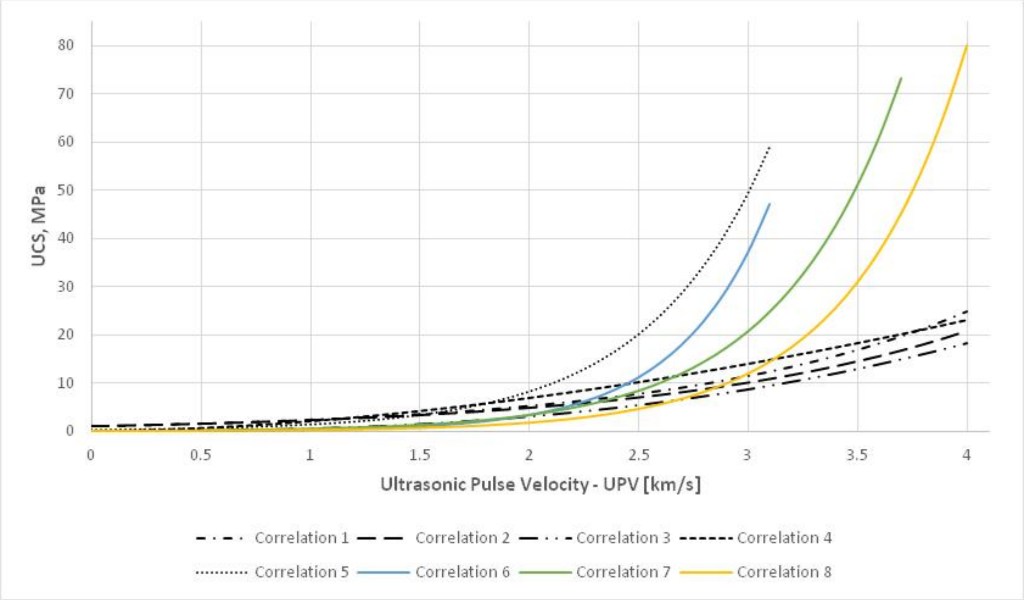

Figure 15. Graphic comparison of UCS vs. UPV correlations (Romanowski et al., 2018).

4. Conclusions

This paper reviewed the work done by several researchers and tried to compare their results.

The data found in the literature show that oil contamination may alter the cement mechanical properties by up to 50% if even a small amount of contaminant is trapped in the cement. This could have a catastrophic impact on well integrity. This paper shows that there is a large inconsistency in the way the data is reported and, in particular, the sample preparation. Reference values are hard to find among the studied references, which makes it difficult to accurately compare the results of various authors. Moreover, the curing time for which the mechanical properties have been reported varies largely from paper to paper, which also makes comparative studies more difficult. It can be concluded that laboratory testing at expected bottom hole conditions is necessary for approximation of the reduction in mechanical properties of OBF-contaminated cement slurries in order to understand OBF's effect on well cement integrity.

Author Contributions: Conceptualization: C.T., N.A.; Methodology: C.T., N.A.; Formal analysis, N.A., C.T.; Writing—original draft preparation, N.A.; Writing—review and editing, C.T.; Editing reviewer comments: N.A., C.T.; Supervision of experiments: C.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

API	American Petroleum Institute
BHST	Bottom hole static temperature
EDS	Energy Dispersive Spectrometer
ESEM	Environmental scanning electron microscope
FLA	Fluid loss additive
FR	Friction reducer
FTIR	Fourier Transform Infrared Spectroscopy
HPHT	High Pressure, High Temperature
OBF	Diesel/oil-based drilling fluid
OBM	Oil-based mud
RS	Reference cement slurry
SBM	Synthetic-based mud
SEM	Scanning electron microscope
TG	Thermogravimetry
UCA	Ultrasonic Cement Analyzer
UCS	Unconfined compressive strength
UPV	Ultrasonic pulse velocity
WBM	Water-based mud
XRD	X-ray diffraction

References

1. Bourgoyne, A.; Millheim, K.; Chenevert, M. *Applied Drilling Engineering*; Society of Petroleum Engineers: Dallas, TX, USA, 1984.
2. Rabia, H. *Well Engineering & Construction Hussain Rabia*; Entrac Consulting Publisher: USA, 2002; pp. 1–789.
3. Scott, P.; Broussard, P.; Freeman, M.; Growcock, F.; Bland, R. *Drilling Fluids Manual*, 12th ed.; 2015; ISBN 9780991509546.
4. Chambers, M.R.; International, M.; Services, D.; Hebert, D.B.; Shuchart, C.E. *SPE 58743 Successful Application of Oil-based Drilling Fluids in Subsea Horizontal, Gravel-Packed Wells in West Africa*; Society of Petroleum Engineers: Dallas, TX, USA, 2000.
5. Fossum, P.V.; Van Der Zwaag, C.; Taugbøl, K.; Mjaaland, S.; Sletfjerding, E.; Høgstøl, H.; Olsen, P.A.; M-I, S. SPE 107754 Design and Utilization of Low Solids OBM for Aasgard Reservoir Drilling and Completion. In Proceedings of the European Formation Damage Conference, Scheveningen, The Netherlands, 30 May–1 June 2007.
6. Kabanov, M.; Telford, E.; Gray, C.; Hughes, B. *Designing and Running a Special Oil-Based Mud for a North Sea HPHT Campaign Planning the Wells*; Society of Petroleum Engineers: Dallas, TX, USA, 2014.
7. Emadi, H.; Soliman, M.; Heinze, L.; Moghaddam, R.; Samuel, R. An Experimental Study of the Swelling Properties of Unconventional Shale-Oil Rock Samples Using both Water-Based and Oil-Based Muds and Effects of Invasion on Rock Mechanical Properties. In Proceedings of the SPE/IADC Drilling Conference and Exhibition, London, UK, 17–19 March 2015.
8. Fleming, N.; Karunakaran, M.; Hireche, S. *Qualification and Implementation of Oil-Based Mud as a Cost-Effective and Low-Damaging Perforation Fluid for Gudrun Case History*; Society of Petroleum Engineers: Dallas, TX, USA, 2019; pp. 7–9.

9. Harold, M.; Pe, E.I.I.I.; Partners, N.E. Case Study: Using Managed Pressure Drilling and Oil Based Mud to Efficiently Drill an Extremely Thick and Highly Fractured Carbonate Sequence Under an Extremely Thick and Highly Sensitive Laminated Shale. In Proceedings of the SPE/IADC Drilling Conference and Exhibition, London, UK, 17–19 March 2015.
10. Sheer, S.; Alotaibi, A.; Gadhiya, K.; Hughes, B.; Al-khaldy, M.; Abhijit, D.; Al-failkawi, K.; Al-saadi, D.; Al-saeedi, A.; Hamed, A.; et al. SPE-198582-MS The Dynamics of Drilling with Oil-Based Mud, 60:40 Oil-Water Ratio – Case History in South East Kuwait Fields. In Proceedings of the SPE Gas & Oil Technology Showcase and Conference, Dubai, UAE, 21–23 October 2019.
11. Sinha, P.; Kumar, V.; Prabhakaran, T.; Katre, A.; Patel, M.; Doodraj, S. A More Holistic Approach to Determine Economics of Using Synthetic Oil Based Mud over Water Based Mud System in Onshore Development Drilling Onshore drilling history in Rajasthan. In Proceedings of the SPE Oil and Gas India Conference and Exhibition, Mumbai, India, 4–6 April 2017.
12. Degni, C. *Drilling Practices*; IADC: Houston, TX, USA, 2012; pp. 1–497.
13. IADC. *IADC Drilling Manual*; IADC: Houston, TX, USA, 2000; pp. 1–1463.
14. Patel, A.D.; Wilson, J.M.; Loughridge, B.W.; Services, H.E. SPE 50726 Impact of Synthetic-Based Drilling Fluids on Oilwell Cementing Operations. In Proceedings of the SPE International Symposium on Oilfield Chemistry, Houston, TX, USA, 16–19 February 1999.
15. Design, G.C. Improved primary cement jobs with a unique spacer design. *J. Pet. Technol.* **1997**, *49*. [CrossRef]
16. Budiawan, A.; Farahani, H.S.; Anugrah, A.; Brandl, A. Innovative Cement Spacer Improves Well Cementing Integrity—60 Case. In Proceedings of the IADC/SPE Asia Pacific Drilling Technology Conference, Bangkok, Thailand, 25–27 August 2014; pp. 1–16.
17. Chan, A.F.; Bell, R.W.; Morrison, E. Improved Primary Cement Jobs Through the Use of Unique Spacer Design Technology: Gulf of Mexico Case History Study. Spe 36486. In Proceedings of the SPE Annual Technical Conference and Exhibition, Denver, Colorado, 6–9 October 1996; pp. 727–737.
18. Harder, C.A.; Carpenter, R.B.; Freeman, E.R.; Brookey, T.E.; Gandy, R.G. Optimization of oil-base mud chemistry for cementing. In Proceedings of the 1993 SPE International Symposium on Oilfield Chemistry, New Orleans, Louisiana, 2–5 March 1993; pp. 329–338.
19. Abdulrazzaq, W.; AlBuraikan, R.; Savari, S.; Whitfill, D.L. New methodology to evaluate the performance of chemical sealant loss circulation materials. In Proceedings of the SPE Kuwait Oil Gas Show Conference, Kuwait City, Kuwait, 15–18 October 2017.
20. Garnier, A.; Fraboulet, B.; Bois, A. OTC 18754 Characterization of Cement Systems to E nsure Cement Sheath Integrity. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 30 April–3 May 2007; pp. 1–11.
21. Goodwin, K.J. Guidelines for ultrasonic cement-sheath evaluation. *SPE Prod. Eng.* **1992**, *7*, 280–284. [CrossRef]
22. McDaniel, J.; Watters, L.; Shadravan, A. Cernent sheath durability: Increasing cement sheath integrity to reduce gas migration in the marcellus shale play. In Proceedings of the SPE Hydraulic Fracturing Technology Conference, The Woodlands, TX, USA, 4–6 February 2014; pp. 904–916.
23. Rao, P.P.; Sutton, D.L.; Childs, J.D.; Cunningham, W.C. Ultrasonic Device for Nondestructive Testing of Oilwell Cements At Elevated Temperatures and Pressures. *Jpt. J. Pet. Technol.* **1982**, *34*, 2611–2616. [CrossRef]
24. Reddy, B.R.; Santra, A.; McMechan, D.; Gray, D.; Brenneis, C.; Dunn, R. Cement mechanical property measurements under wellbore conditions. In Proceedings of the SPE Annual Technical Conference and Exhibition, Dallas, TX, USA, 9–12 October 2005; pp. 9–12.
25. Aughenbaugh, K.; Nair, S.; Cowan, M.; Van Oort, E. Contamination of deepwater well cementations by synthetic-based drilling fluids. In Proceedings of the SPE Deepwater Drilling and Completions Conference, Galveston, TX, USA, 10–11 September 2014; pp. 767–777.
26. Vipulanandan, C.; Heidari, M.; Qu, Q.; Farzam, H.; Pappas, J.M. Behavior of piezoresistive smart cement contaminated with oil based drilling mud. In Proceedings of the Annual Offshore Technology Conference, Houston, TX, USA, 5–8 May 2014; pp. 1360–1373.
27. Soares, A.A.; de Freitas, J.C.O.; de Melo, D.M.A.; Braga, R.M.; Amaral-Machado, L.; Silva Santos, P.H.; Soares, L.W.O. Cement slurry contamination with oil-based drilling fluids. *J. Pet. Sci. Eng.* **2017**, *158*, 433–440. [CrossRef]
28. Li, M.; Ou, H.; Li, Z.; Gu, T.; Liu, H.; Guo, X. Contamination of cement slurries with diesel-based drilling fluids in a shale gas well. *J. Nat. Gas Sci. Eng.* **2015**, *27*, 1312–1320. [CrossRef]

29. Li, Z.; Liu, H.; Guo, X.; Ou, H.; Gu, T. Contamination of cement slurries with oil based mud and its components in cementing operations. *J. Nat. Gas Sci. Eng.* **2016**, *29*, 160–168. [CrossRef]
30. Olteanu, A.; Teodoriu, C. Uncertainty in ultrasonic measurements of oil-based mud contaminated cement. *Mater. Today Commun.* **2020**, *22*, 100783. [CrossRef]
31. *Specification for Cements and Materials for Well Cementing API Specification 10A*; API: Houston, TX, USA, 2010.
32. Romanowski, N.; Ichim, A.; Teodoriu, C. Investigations on Oilwell Cement Strength Response to Ultrasonic Measurements in the Presence of Additives1. *J. Sol. Energy Eng. Trans. ASME* **2018**, *140*, 1–7. [CrossRef]