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Characterization of Oil Well Cement–Formation Sheath Bond Strength

Musaed N. J. AlAwad * and Khalid A. Fattah

Petroleum and Natural Gas Engineering Department, College of Engineering, King Saud University, Riyadh 11451, Saudi Arabia; kelshreef@ksu.edu.sa
* Correspondence: malawwad@ksu.edu.sa

Abstract: The aim of this study is to develop a simple and reliable laboratory testing procedure for evaluating the bond strength of cement–formation sheaths that considers cement slurry composition and contamination as well as formation strength and formation surface conditions (roughness and contamination). Additionally, a simple and practical empirical correlation is developed for predicting cement–rock bond strength based on the routine mechanical properties of hard-set cement and formation rock. Cement slurries composed of Yamama cement type 1 and 25% local Saudi sand, in addition to 40% fresh water, are used for all investigations in this study. Oil well cementing is a crucial and essential operation in the drilling and completion of oil and gas wells. Cement is used to protect casing strings, isolate zones for production purposes, and address various hole problems. To effectively perform the cementing process, the cement slurry must be carefully engineered to meet the specific requirements of the reservoir conditions. In oil well cementing, the cement sheath is a crucial component of the wellbore system, responsible for maintaining structural integrity and preventing leakage. Shear bond strength refers to the force required to initiate the movement of cement from the rock formation or movement of the steel casing pipe from the cement sheath. Cement–formation sheath bond strength is a critical issue in the field of petroleum engineering and well cementing. Cement plays a crucial role in sealing the annulus (the space between the casing and the formation) and ensuring the structural integrity of the well. The bond strength between the cement and the surrounding geological formation is key to preventing issues such as fluid migration, gas leaks, and wellbore instability. To achieve the study objectives, sandstone and sandstone–cement composite samples are tested using conventional standard mechanical tests, and the results are used to predict cement–formation sheath bond strength. The utilized tests include uniaxial compression, direct tensile, and indirect tensile (Brazilian) tests. The predicted cement–rock sheath bond strength is compared to the conventional laboratory direct cement–formation sheath strength test outcomes. The results obtained from this study show that the modified uniaxial compression test, when used to evaluate cement–formation shear bond strength using cement–rock composite samples, provides reliable predictions for cement–formation sheath bond strength with an average error of less than 5%. Therefore, modified uniaxial compression testing using cement–rock composite samples can be standardized as a practical laboratory method for evaluating cement–formation sheath bond strength. Alternatively, for a simpler and more reliable prediction of cement–formation sheath bond strength (with an average error of less than 5%), the empirical correlation developed in this study using the standard compressive strength value of hard-set cement and the standard compressive strength value of the formation rock can be employed separately. For the standardization of this methodology, more generalized research should be conducted using other types of oil well cement and formation rocks.

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1. Introduction

Drilling a well is the primary method for extracting hydrocarbons from underground reservoirs. One of the key components of a well is the cement sheath, which bonds the casing to the formation.

The integrity of a primary cementing job is crucial, as successful completion heavily relies on it. The failure of primary cementing operations incurs significant costs for the oil and gas industry, with approximately USD 450 million spent annually on remedial cementing operations due to the failure of around 15% of primary cementing to serve its intended purpose [1].

The main goal of primary cementing is to provide full zonal isolation in the petroleum well to ensure safety and avoid environmental complications while the well is operating economically. Other important functions of the well cement sheath in a petroleum well include the following:

1. Carrying the dead weight of the casing string and supporting it in place.
2. Isolating the casing string from formation-corrosive fluids.
3. Preventing wellbore collapse and providing a reasonable mud weigh window.
4. Restricting fluid movement between permeable formations (zones).
5. Protecting freshwater aquifers.

The required short-term properties of oil well cement are summarized below:

1. The stability of cement slurry (a mixture of Portland cement, water, and additives)—non-settling under dynamic and static conditions.
2. Minimal filtration loss.
3. Static gel strength development.
4. Low permeability.
5. Minimal shrinkage during the transition period from slurry to final set.

In industry, attention has typically been paid to short-term rather than long-term properties [2]. Maintaining zonal isolation for the lifetime of oil and gas wells is critical. Leakage behind casing can reduce the cost effectiveness of the well and cause health and safety risks from pressure buildup and contaminated aquifers. During the completion and production phases of the well, variations in temperature and pressure can induce stresses at the cement–formation interface [3].

Portland cement is produced by partially fusing powdered blends composed of limestone with materials such as clays, shales, blast-furnace slag, siliceous sands, iron ores, and pyrite cinders. The basic components of cement are tricalcium silicate 3CaOSiO2 (50%), which has the fastest hydration and is used as an early strengthener to protect against sulfate attack, and dicalcium silicate $2CaOSiO_2$ (25%), a slow-reacting component responsible for a gradual increase in strength. API and ASTM classes of Portland cement are shown in Tables 1 and 2, respectively [4].

Table 1. API classes and properties of oil well cement [4].

API Class	Description	Depth Range, ft	Temperature Range, °F
A		Up to 6000 feet	80–170
B	High sulfate resistance	Up to 6000 feet	111–200
C	High temperature and sulfate resistance	Up to 6000 feet	80–170
D	Moderate to high sulfate resistance, high pressure resistance, and high hydration heat	6000–10,000	80–290
E	Moderate to high sulfate resistance, high pressure resistance, and high hydration heat	10,000–14,000	200–290
F	Can withstand the highest pressure and temperatures	Up to 10,000	160–320
G	Used with additives, called accelerators and retarders, to either shorten or lengthen setting times	Up to 8000	111–230
H	Coarser than Class G cement	Up to 8000	80–350
J	Class J cement is used in deep, high-temperature wells where conventional cements may not be suitable	Up to 16,000	Up to 400

Table 2. ASTM classes and properties of Portland cement [4].

ASTM Type		Applications
I	Ordinary cement	Used at low pressure, temperature, and depth
II	Modified cement	Used for low-shrinkage applications
III	Fast-setting cement	Used in high early setting applications
IV	Low-heat-hydration cement	Used in deep thermal applications
V	Highly sulfate-resistant cement	Used in corrosive environments

In drilling operations for oil and gas, well cementing is defined as the process of isolating the well casing pipe from the rock and underground corrosive fluids around it. There are two types of cementing in oil and gas operations: primary and secondary.

Primary cementing is more common and is part of the casing and cementing stage in oil well drilling. Once the wellbore is drilled, steel pipes, normally called well casings, are lowered into it. To keep the casing pipe stable in place, cement is pumped through the drill string into the well and up the annulus between the well side and the casing, forced up by the pressure of its own weight.

Secondary cementing: Also called remedial cementing, secondary cementing is used to fix problems created during the primary cementing stage or problems that have emerged during the lifetime of the well. Secondary cementing is applied by one of two methods: squeeze cementing and plug cementing. Squeeze cementing involves pumping a certain amount of cement slurry down the wellbore at high pressure to fill all cavities that have been identified as problematic for the normal operation of the well. It is usually used for casing cracks or cracks and holes in the rock. Plug cementing, as the name suggests, involves making a plug out of cement to seal off a hole, normally to prevent the flow of water and other fluids into and from the wellbore. Plug cementing is also used in well abandonment, after the casing is cut at a certain depth. The well then must be sealed with a cement plug to prevent the random release of any hydrocarbons remaining in the ground [4]. By applying secondary cementing techniques, operators can extend the life of their wells, maintain integrity, and ensure safe operation.

In order for the cement to fulfil its main utilization purposes mentioned above, it is necessary to develop the following properties in a satisfactory manner [5]:

1. Thickening time. The time taken to thicken the cement slurry must be long enough for the well annuls to be filled. The thickening time determines the length of time the slurry can be pumped or the time necessary for the consistency to reach 100 poises under stimulated bottom hole pressure and temperature. The thickening time is measured in a laboratory using an API cement consistometer apparatus.
2. Density. To minimize the risk of blowouts or lost circulation, the cement slurry density should be slightly higher than the drilling mud density.
3. Filtration loss. The cement slurry filtration loss should be low to avoid the filtration of cement water into the formation, resulting in incomplete cement hydration. Filtration can be measured in the laboratory under room-temperature conditions and HT-HP conditions using the API HT-HP Filter Press.
4. Permeability of the hard-set cement. The permeability of hard-set cement should be as low as possible. Bentonite cements are known to be very permeable. A high water/cement ratio increases the set cement permeability, while downhole high pressure and confinement due to their compacting effects decrease the set cement permeability.
5. Perforating quality. When ordinary cements are completely hardened, they fracture excessively when perforated. Low-strength cements are usually less brittle and have less tendency to shatter upon perforating.
6. Compressive and tensile strength of the set cement. The cement in oil wells is exposed to static and dynamic stresses. Static stress is induced by the dead weight of the casing pipe; compressive stresses are generated due to the action of fluid and formations; and dynamic stresses are induced by drilling operations, particularly the vibration of the drill string. To withstand these stresses, a cement compressive strength of 500 psi after a period of 24 h is necessary [6]. High-early-strength cement has a strength higher than ordinary-strength cement in the first 30 h. Density reduction additives decrease the cement strength, while retarders reduce both early and late strength. Fine sand increases the final hard-set cement strength and mitigates the effects of temperature.
7. Corrosion resistance. Hard-set cement can be penetrated by formation-corrosive fluids, especially those containing CO_3 or SO_4 irons. Cement corrosion decreases the final compressive strength of hard-set cement and increases its permeability. A reduction in the wait-on-cement (hardening) time improves the cement's resistance to corrosion.
8. Bond requirements. For clean surfaces (rock or casing), the bond increases with time and under moderate temperatures. Mud cake and dirty casing surfaces significantly reduce the bond between casing or rock and cement.

Since oil and gas well cementing processes and the evaluation of cement properties are conducted on a routine basis, the oil industry has set several standards to be followed. Oil well cement equipment has also been developed continuously in an advanced manner.

In 1952, six classes of cements used in oil and gas well cementing operations were introduced into the national API committee standards. The first tentative standard in 1953, designated API 10A, was entitled API Specification for Oil-Well Cements [6]. The petroleum industry mostly utilizes cements manufactured in accordance with API classifications. These specifications are reviewed annually and revised according to the needs of the oil industry. While the specifications do not cover all of the properties of cements over broad ranges of depth and pressure, they do embody a realistic method of classifying Portland cement for use in wells by specifying the required properties. Acoustic logs (CBL) provide the primary means for evaluating the mechanical integrity and quality of the cement sheath from the casing to the formation bond [6].

In API RP 10B-2 [6], a correlation is recommended for the prediction of the cement to casing shear bond strength (MPa) using cement uniaxial compressive strength (MPa) and is given by

$$(\tau_b)_{C\text{-}R} = 0.69 * (UCS_C)^{0.5} \quad (1)$$

The above empirical correlation neglects the formation rock's strength and its surface contamination; therefore, it is only applied for cement–casing shear bond strength evaluation (see Figure 1).

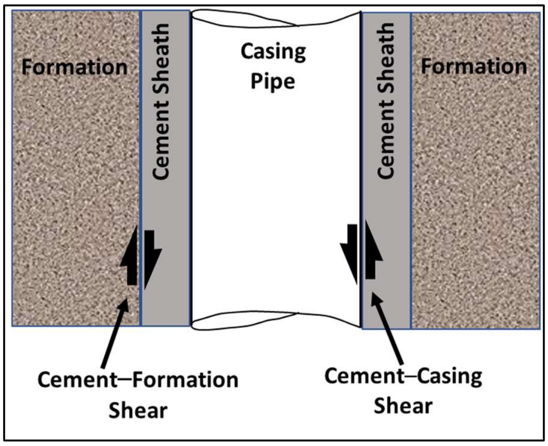

Figure 1. Cemented casing configuration.

Several factors influence the quality and strength of the bond between the cement and the rock formation:

1. Surface roughness of the formation: The roughness of the rock surface plays a significant role in the bond strength. A rough surface provides better mechanical interlocking between the cement and the formation, enhancing the bond strength.
2. Formation type: The type of rock surrounding the wellbore (e.g., sandstone, limestone, and shale) affects how well the cement adheres to the formation. Sandstone and carbonate rocks may form better bonds with cement due to their rougher texture and higher porosity compared to more impermeable rocks such as shale.
3. Cement composition: The composition and the quantity and type of added water have a crucial effect on the cement's properties and strength.
4. Contamination of the formation face: Contamination during the cementing process significantly impacts the cement–rock bond strength and, consequently, the integrity and long-term stability of the wellbore. Drilling mud, oil, gas, and other contaminants can interfere with cement hydration, alter formation surface properties, and introduce gas pockets or voids within the cement sheath. To mitigate these effects, proper wellbore cleaning, the use of contamination-resistant cement, pre-cementing treatments, and thorough monitoring are essential to ensuring a strong and reliable cement–rock bond. Addressing contamination effectively is key to maintaining well integrity and preventing gas migration, fluid leakage, and well failure [7].

The bond strength of the cement sheath is a critical factor in the integrity of oil and gas wells. Problems with cementing quality or the complex stresses from downhole operations can cause the cement sheath to yield or become damaged, which undermines its ability to seal effectively and exposes the casing to corrosion. The condition of the cement sheath is directly tied to the safe extraction of oil and gas from the wellbore and the protection of the environment. As such, assessing the integrity of the cement sheath is essential. To determine the shear strength of the cement-to-rock bond and the effects of drilling mud exposure, several researchers have utilized the pushout test. This method involves filling a hollow rock plug with cement, allowing it to set, and then applying force to push the cement out while measuring the amount of force required for this action. However, particularly for brittle rocks, pushing out the cement—which is often stiffer than the surrounding rock—can lead to rock fractures, resulting in inaccurate bond strength measurements. To address this issue, the reverse pushout test was developed to prevent rock breakage. In this method, a rock plug is surrounded by a cement cast in a mold, and instead of applying pressure to the cement, the force is applied to the rock. The results have shown that bond strength is significantly diminished if drilling fluid or mud cake is not thoroughly cleaned away before the cement hardens. This approach allows for the testing and ranking of different cement formulations based on their ductility and deformation characteristics before they are used in the field [8].

2. Objectives of This Study

Previous studies only characterized the factors affecting the cement–rock bond; thus, there is a lack of research on practical predictive empirical correlations and new testing techniques. Therefore, there is a need for standardized laboratory testing procedures and effective predictive correlations for the characterization of cement–formation sheath bond strength.

The main objectives of this study are as follows:

1. To review the fundamental principles of oil and gas well cementing procedures.
2. To develop simple and reliable laboratory testing methods for evaluating the cement–formation sheath bond strength.
3. To explore potential reliable correlations for predicting the cement–formation sheath bond strength using the conventional mechanical properties of rock and cement, such as tensile and compressive strength.

3. Raw Materials

3.1. Cement Powder

Yamama ordinary Portland cement (Type I) was used throughout this study (Table 3 and Figure 2). This cement is manufactured by Yamama Saudi Cement Company based in Riyadh, Saudi Arabia. This cement is an ordinary Portland cement that hardens into solid form when mixed with the proper amount of water. The chemical components are presented in Table 3 [9].

Table 3. Yamama ordinary Portland cement chemical composition.

Chemical Component		Weight %
1	Lime (CaO)	60–67
2	Silica (SiO_2)	17–25
3	Alumina (Al_2O_3)	3–8
4	Iron oxide (Fe_2O_3)	0.5–6
5	Magnesia (MgO)	0.1–4
6	Sulfur trioxide (SO_3)	1–3
7	Soda and/or Potash (Na_2O + K_2O)	0.5–1.3

Figure 2. Yamama ordinary Portland cement (Type I) [9].

3.2. Local Saudi Sand Mixture

Local Saudi sand obtained commercially was used throughout this work. The sieving (granulometric) analysis of the sand is shown in Figure 3.

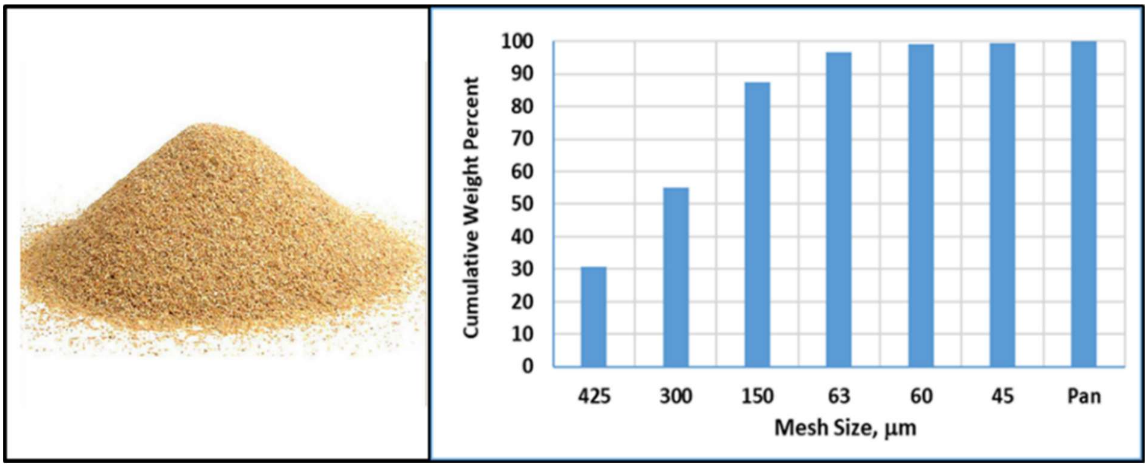

Figure 3. Granulometric analysis of the utilized local Saudi sand.

3.3. Cement Curing Conditions

Tap water was used as a mixing water throughout this study. The cement slurry was prepared according to the required composition (cement + sand + water). The mixture was mixed thoroughly for a minimum of 10 min using an electric mixer. At this stage, water was poured into the mixing container, and then, sand and cement were added slowly into the water under low-speed mixing. After finishing all slurry components, the mixer was run at full speed for a minimum of 10 min. After the mixing process was completed, the slurry was poured into molds suitable for the required test. The cement was left to cure on a bench under laboratory conditions for 48 h. Following this, the hard-set cement samples were extracted from the molds and soaked in the curing fresh water in an air-tight container. Then, the samples were extracted from the soaking ware and left on a bench to dry for 24 h, after which the test was performed.

3.4. Test Sample Dimensions

Cylindrical samples 1.5 inches in diameter and with a length-to-diameter (L/D) ratio equal to 2.0 were used for the uniaxial compressive strength (UCS) tests. For the direct tensile strength (pull) tests, standard dumbbell copper molds were utilized. Disk-shaped cement samples 1.5 inches in diameter with a thickness-to-diameter equal to 0.5 were used for the indirect (Brazilian) tensile strength test. These samples were prepared according to the ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007–2014 [10].

For the direct cement–rock sheath bond strength test, a core sample 3.54 inches in length and 1.5 inches diameter was used. Three sandstone rock samples cored from outcrops in Saudi Arabia were used throughout this study.

4. Testing Methodologies

4.1. Simulated Cement–Formation Sheath

In this test, a 1.5-inch-diameter core sample was cemented inside a 4-inch plastic mold, as shown in Figure 4A. The test set-up was placed in the compression machine, as shown in Figure 4B, and then, the axial load on the core sample (simulating the formation) was increased until the bond between the core and the cement was broken. An ELE ADR 2000 stiff compression frame was used to generate the required compression stress. The axial load at core–cement sheath bond failure was recorded from the machine's digital display, and the cement–formation sheath bond strength (τ_b) was calculated using the following equation:

$$\tau_b = \frac{\text{Axial load at failure}}{\text{Cement contact surface area}} \quad (2)$$

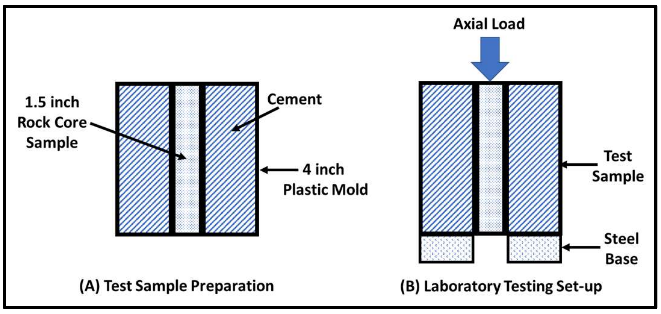

Figure 4. Cement–formation bond strength testing set-up.

4.2. Adaption of Conventional Rock Mechanical Tests

The direct tensile test (pull test), the indirect tensile test (Brazilian test), and the uniaxial compression test (UCS) are well-known tests that can be performed easily and rapidly. These tests have been modified for the use of measuring cement–formation sheath bond strength, as shown in Figure 5.

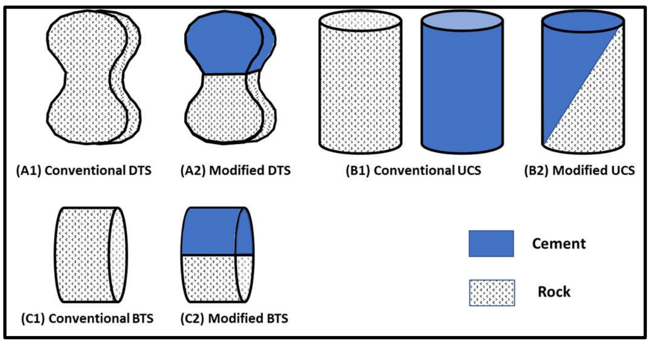

Figure 5. Adaption of conventional rock mechanical tests.

4.3. Testing Equipment, Test Sample Preparation, and Test Replication

- Loading frame: An ELE ADR 2000 stiff compression machine (ELE International, Milton Keynes, UK) was used with a pace rate of 2.5 kN/s. Accuracy and repeatability conformed to BS EN ISO 7500-1 [11]; ASTM E4-10 [12].

- Compression test samples: Samples were prepared according to the ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007–2014 [10]. The samples measured 1.5 inches in diameter with a length-to-diameter ratio equal to 2.0.
- Indirect tensile test (Brazilian) samples: Samples were prepared according to the ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007–2014 [10]. The samples measured 1.5 inches in diameter with a thickness-to-diameter ratio equal to 0.5.
- Direct tensile (Pull) test samples: An automated MATEST tensile tester (MATEST, Treviolo, Italy) was used with tensile briquette molds (1.0 inch × 1.0 inch × 1.7 inches × 2.5 inches) according to ASTM specification C307 [13].
- Cement–rock shear bond strength test samples: Designed by the authors—4.0 inches × 4.7 inches plastic pipe + 1.5 inches × 3.5 inches rock sample.
- Test repeatability: At least two replications per test.

5. Testing Results and Discussion

According to API Specification 10A (2002) [6], oil well cement compressive strength is defined as the capability to restrain the forces that come from either the formation or the casing. The minimum allowable compressive strength for oil well cement is 500 psi (3.447 MPa). Further, the shear bond strength for oil well cement is defined as the capability to restrain the forces from the weight of the casing. The minimum allowable shear bond strength for oil well cement is 100 psi (0.689 MPa) [6].

Cement slurries composed of Yamama cement type 1, 25% local Saudi sand, and 40% fresh water were used for all investigations in this study. In the simulated cement–formation sheath test, a cylindrical core sample was placed in the center of a 4-inch mold full of cement slurry, as shown in Figure 6. After 48 h of curing, the test set-up was placed in a compression machine. Then, the axial load on the rock sample (simulating well walls) was increased until the bond between the rock sample and the cement was broken. The axial load at failure was recorded from the machine's digital display, and the cement–formation bond strength was calculated using Equation (2).

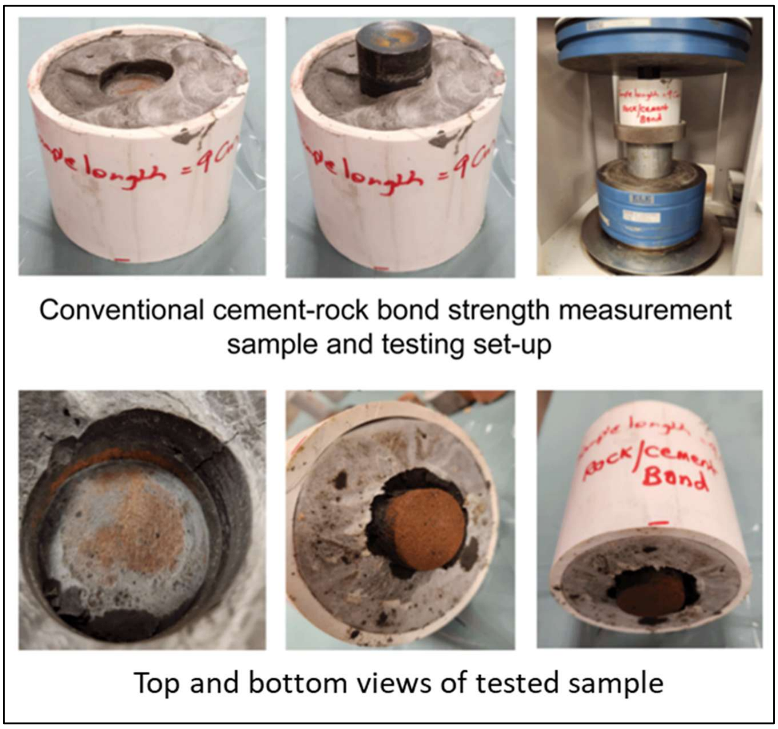

Figure 6. Simulated cement–rock sheath bond strength measurement.

The cement–formation bond strength was predicted indirectly using rock–cement disk samples, cylindrical samples, and dumbbell samples, as shown in Figure 7. All samples were tested using the procedures mentioned earlier.

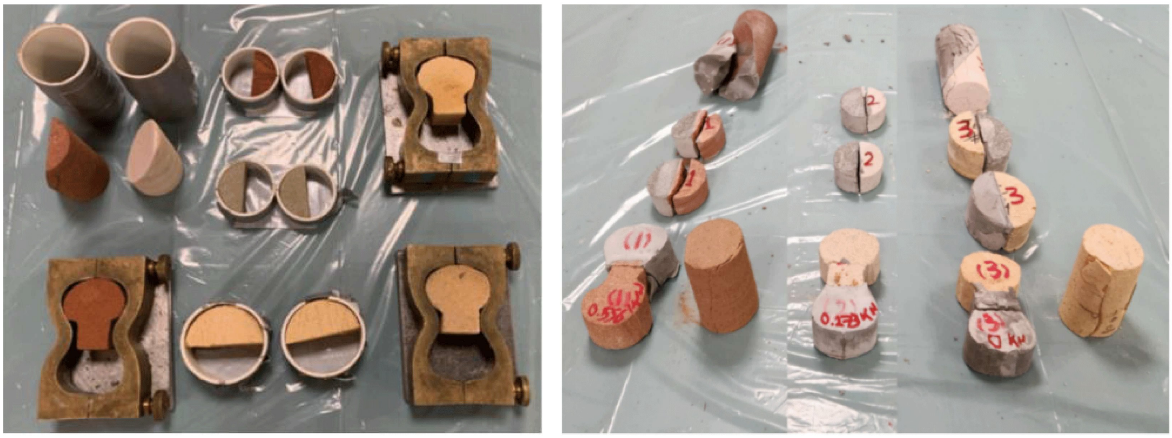

Figure 7. Unconventional method for cement–rock sheath bond strength measurement.

Direct and indirect tensile strength and uniaxial compressive strength were calculated using the following equations:

$$\text{Brazilian Indirect Tensile Strength} = \frac{2 * \text{Axial Compression Load at Failure}}{\pi * \text{Diameter} * \text{Thickness}} \quad (3)$$

$$\text{Direct Tensile Strength} = \frac{\text{Axial Tensile Load at Failure}}{\text{Cross Sectional Area}} \quad (4)$$

$$\text{Uniaxial Compressive Strength} = \frac{\text{Axial Compression Load at Failure}}{\text{Cross Sectional Area}} \quad (5)$$

The results of all laboratory tests conducted in this study are summarized in Table 4 and represented in Figure 8.

Table 4. Results for conventional and unconventional cement–rock sheath bond strength.

Rock Properties			Cement–Rock Bond Strength Evaluation Methods			
			Conventional	Unconventional		
Sandstone Rock Type	**(Cement + 40% Fresh Water + 25% Sand) Measured Cement Uniaxial Compressive Strength, MPa**	**Measured Rock Uniaxial Compressive Strength, MPa**	**Cement–Rock Shear Bond Strength, MPa**	**Uniaxial Compressive Strength of Cement–Rock Composite Sample, MPa**	**Brazilian Tensile Strength of Cement–Rock Composite Sample, MPa**	**Direct Pull Tensile Strength of Cement–Rock Composite Sample, MPa**
	UCS_C	UCS_R	$(\tau_b)_{C\text{-}R}$	$UCS_{C\text{-}R}$	$BTS_{C\text{-}R}$	$DTS_{C\text{-}R}$
Pink	30.40	4.40	1.15	6.72	1.40	0.43
Red	30.40	15.0	1.76	11.58	2.33	0.86
Yellow	30.40	23.25	2.58	16.32	2.72	1.90
Average Values			1.830	11.54	2.15	1.063
Cement–Rock Contact Area, in^2			16.7	5.0	1.25	1.0

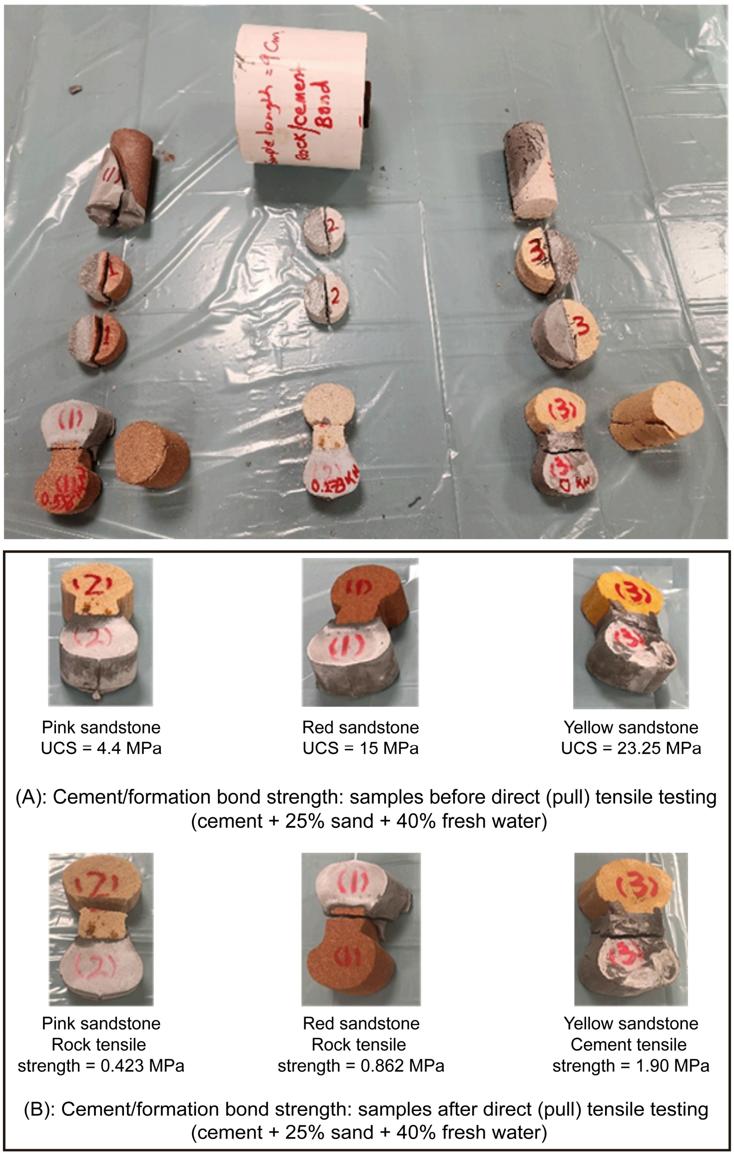

Figure 8. Test samples used to measure cement–rock sheath bond strength.

From Table 4, based on the test of cement–rock bond strength for three different rocks, three correlations can be obtained, as shown in Equations (6)–(8).

$$(\tau_b)_{C\text{-}R} = \frac{1.83}{11.54} * UCS_{C\text{-}R} = 0.159 * UCS_{C\text{-}R} \quad (6)$$

$$(\tau_b)_{C\text{-}R} = \frac{1.83}{2.15} * BTS_{C\text{-}R} = 0.851 * BTS_{C\text{-}R} \quad (7)$$

$$(\tau_b)_{C\text{-}R} = \frac{1.83}{1.063} * DTS_{C\text{-}R} = 1.722 * DTS_{C\text{-}R} \quad (8)$$

These correlations can be used to predict cement–rock shear bond strength based on the modified rock mechanics tests, including uniaxial compression, direct tensile, and indirect tensile strength tests. The measured and predicted cement–formation sheath bond strengths are shown in Table 5.

Table 5. Measured and predicted cement–rock sheath bond strengths.

Rock Type	Cement–Rock Bond Strength Evaluation Methods						
	Measured τ_b, MPa (Conventional Test, Figure 7)	Predicted $(\tau_b)_{C\text{-}R}$, MPa (Cement–Rock Composite Samples, Figure 8)					
		$UCS_{C\text{-}R}$ Using Equation (6)		$BTS_{C\text{-}R}$ Using Equation (7)		$DTS_{C\text{-}R}$ Using Equation (8)	
		Value	Error, %	Value	Error, %	Value	Absolute Error, %
Pink Sandstone	1.15	1.069	7.04	1.191	3.56	0.741	35.57
Red Sandstone	1.76	1.841	4.60	1.982	12.61	1.481	15.85
Yellow Sandstone	2.58	2.595	0.58	2.315	10.27	3.272	26.82
Average Error, %	-	-	4.1	-	8.8	-	26.1

The modified uniaxial compression test was selected among the direct and indirect tensile tests to develop a universal correlation for the prediction of cement–rock sheath bond strength due to the following reasons:

1. It is clear that the modified uniaxial compression test, using a cylindrical sample composed of identical halves of cement and rock, provided the best prediction values compared to the modified direct and indirect tensile strength methods, as shown in Table 4.
2. The cylindrical rock or cement samples used in the standard conventional uniaxial compression tests are much easier to prepare than those used in the direct and indirect tensile strength tests.
3. In this method, the acting effective shear stress is similar to the real situation in an oil well (see Figure 1), while tensile stress is dominant in the other two methods.
4. It is clear that the sandstone rock uniaxial compressive strength is directly proportional to the cement–rock sheath bond strength for the given cement slurry, as shown in Figure 9.

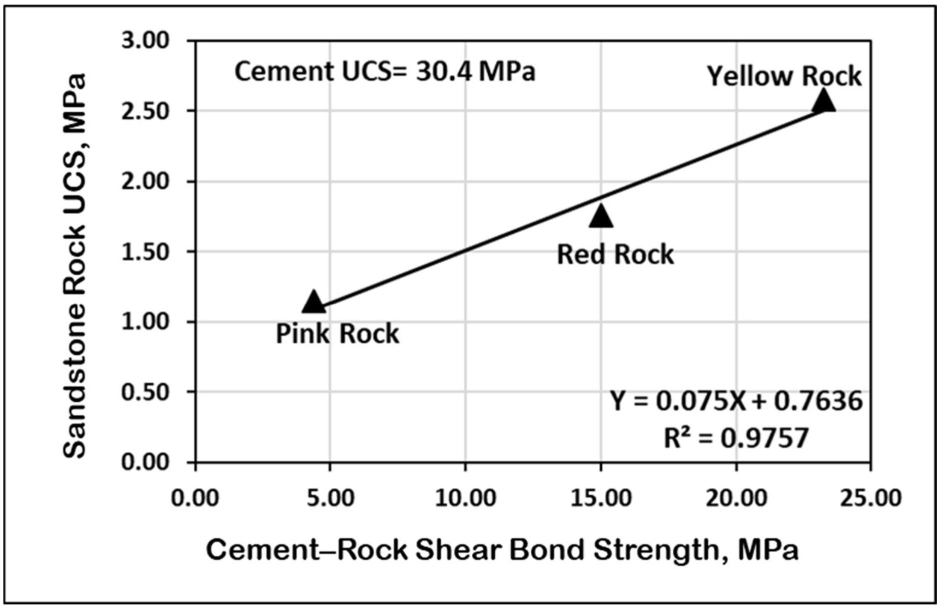

Figure 9. Relationship between rock UCS and cement–rock sheath bond strength.

Using a multiple regression analysis, an empirical correlation (Equation (9)) between the formation rock conventional uniaxial compressive strength, the hard-set cement conventional uniaxial compressive strength, and the conventional cement–rock sheath bond strength was developed using the experimental data shown in Table 6.

$$(\tau_b)_{C\text{-}R} = (0.075403 * UCS_R) + (0.025074 * UCS_C)$$
$$R^2 = 0.997761 \text{ Standard Error} = 0.157461 \text{ Multiple R} = 0.99888 \quad (9)$$

Table 6. Measured and predicted cement–rock sheath bond strength.

Sandstone Rock Type	Measured at Laboratory			Predicted Using Equation (9)	Absolute Error, %
	UCS Rock, MPa UCS_R	UCS Cement, MPa UCS_C	Cement–Rock Bond Strength, MPa $UCS_{C\text{-}R}$	Cement–Rock Bond Strength, MPa $UCS_{C\text{-}R}$	
Pink	4.4	30.4	1.15	1.104	4.0
Red	15.0	30.4	1.76	1.893	7.6
Yellow	23.25	30.4	2.58	2.515	2.52

The utilization of the cement–rock sheath bond strength empirical correlation (Equation (9) is considered a promising standard method over the tedious conventional cement–rock bond strength test for the reasons shown in Table 7.

Table 7. Advantages and disadvantages of cement–rock sheath bond strength evaluation methods.

Test Type	Methodology	Advantages and Disadvantages
Conventional cement–rock shear bond strength test (Figures 4 and 6)	Provides direct evaluation of cement–rock sheath bond strength using critically tedious laboratory testing set-up	• Time-consuming, especially for long-term testing conditions • Sample preparation is challenging • Field conditions such as temperature cannot be replicated • Unstandardized test
Uniaxial compressive strength test using cement–rock composite samples (Equation (6))	Provides indirect evaluation of cement–rock sheath bond strength using the evaluation of the laboratory modified uniaxial compressive strength using cement–rock composite samples	• Sample preparation is challenging
Predicted cement–rock shear bond strength using the developed empirical correlation (Equation (10))	Provides indirect evaluation of cement–rock sheath bond strength using the evaluation of the laboratory conventional uniaxial compressive strength for cement and for formation rock separately	• Simple and cost-effective test • Standardized test ensures consistency and comparability • Predictable and uses well petrophysical logging data and/or well-established published correlations • Downhole temperature, pressure, and stresses can be replicated within the uniaxial compression test [14–16]

The above empirical correlation (Equation (9)) was developed based on laboratory experiments with a 100% clean rock face and with no cement slurry contamination. This is because the bond between the cement and the formation strongly depends on the characteristics of the interface (permeability, porosity, roughness, and contamination) [17].

This is why cement–sandstone and cement–carbonate develop stronger bonds compared to shale [18,19]. When a well is drilled, the borehole wall is not very smooth and will have edges and breakouts. These breakouts and edges are very important for the shear strength between the rock and cement. The rougher and cleaner the rock surface, the better the bonding will be between the cement and non-porous rock such as shale [20]. The magnitude of cement–formation rock sheath bond strength is highly affected by the cement quality (slurry contamination magnitude and strength) and formation rock face quality (strength, roughness, and contamination).

Firstly, cement strength is highly affected by the degree of contamination with hydrocarbons, formation water, or drilling fluid components. The quality of contaminated cement slurry is directly measured using the uniaxial compressive strength of the hard-set cement (UCS_C). It is well documented that contamination decreases cement uniaxial compressive strength [21] and, hence, decreases the formation–cement sheath bond strength.

Understanding the downhole cementing conditions is crucial for executing a successful cementing job. Portland cement systems are subjected to extreme thermal conditions in wells, ranging from permafrost to high temperatures. Both shallow and deep wells expose cement to significant pressure variations. Additionally, the composition of formation fluids and the strength of the surrounding rock also influence the performance of the cement in the well. Cement additives are used to tailor the cement properties to suit specific downhole conditions, which can vary from well to well. Certain additives, such as silica fume, nano silica, and others, can enhance the uniaxial compressive strength of oil well cement, improving its overall performance in demanding environments [22–25].

Secondly, formation rock face (f_c) quality is controlled by permeability, porosity, natural fractures, mud invasion, and mud cake thickness. To achieve a proper cementing job, the drilling fluid should be completely displaced by the cement slurry and the mud cake scratched and/or flushed. However, this is hard to achieve in practice, and some mud is usually left on the wellbore, which ends up contaminating the cement slurry and the formation rock surface, as shown in Figure 10 [26,27].

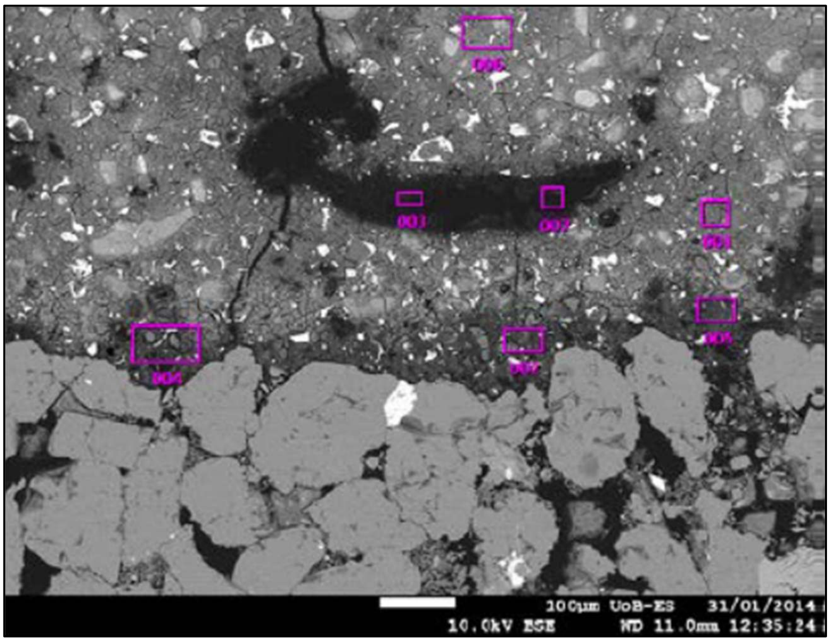

Figure 10. SEM image showing the presence of mud at the cement–rock interface (top: cement, bottom: rock) [26].

Therefore, the correlation developed in this study (Equation (9)) can be modified to account for the rock surface contamination factor (f_c), as follows (Equation (10)):

$$(\tau_b)_{C\text{-}R} = f_c * \{(0.075403 * UCS_R) + (0.025074 * UCS_C)\} \quad (10)$$

where the contamination factor (f_c) is equal to 1.0 for a 100% clean rock surface or 0% contamination, as in this study. The evaluation of rock surface contamination values has been investigated by many researchers [28] and is still a strong direction for future research. In their experimental study, Jun Gu et al. [29] found that the declining rate of shearing strength at the cement–formation interface reaches 83.4% to 99.9% when the mud cake thickness is 5 mm. This means that the contamination factor (f_c) reaches between 0.17 and 0.001. To verify the above correlation (Equation (10)), data from the literature [30,31] and the experimental results of this study were used to predict cement–rock shear bond strength, as shown in Table 8.

Table 8. Measured and predicted cement–rock sheath bond strength.

Test Specimen	Laboratory–Measured		f_c	Predicted Cement–Rock Shear Bond Strength Using Equation (10), MPa		Ref.
	UCS, MPa	Cement–Rock Bond Shear Strength, MPa		$(\tau_b)_{C\text{-}R}$	Absolute Error, %	
Class H Cement	20	-	-	-	-	[30]
Mancos Shale	10	-	-	-	-	
Cement–Shale	-	1.71	1.0	1.73	1.2	
Portland Cement	50	-	-	-	-	[31]
Cement–Berea	58	-	-	-	-	
Cement–Berea	-	5.1	1.0	4.71	7.7	
Portland Cement	30.4	-	-	-	-	This Study
Pink Sandstone	4.4	-	-	-	-	
Cement–Pink Sandstone	-	1.15	1.0	1.104	4.0	
Portland Cement	30.4	-	-	-	-	This Study
Red Sandstone	15	-	-	-	-	
Cement–Red Sandstone	-	1.76	1.0	1.893	7.6	
Portland Cement	30.4	-	-	-	-	This Study
Yellow Sandstone	23.5	-	-	-	-	
Cement–Yellow Sandstone	-	2.58	1.0	2.515	2.52	
Overall Average Absolute Error					4.6%	

Therefore, it is now easier to predict cement–rock sheath bond strength using the correlation developed in this study (Equation (10)), by measuring the uniaxial compressive strength for a rock specimen (UCS_R) and for a cement specimen (UCS_C) separately without the need for the tedious laboratory testing on rock–cement composite specimens. The method exhibits an acceptable and comparable error to that of the empirical correlation documented in API RP 10-B-2 (Equation (1)), as shown in Table 8 and Figure 11.

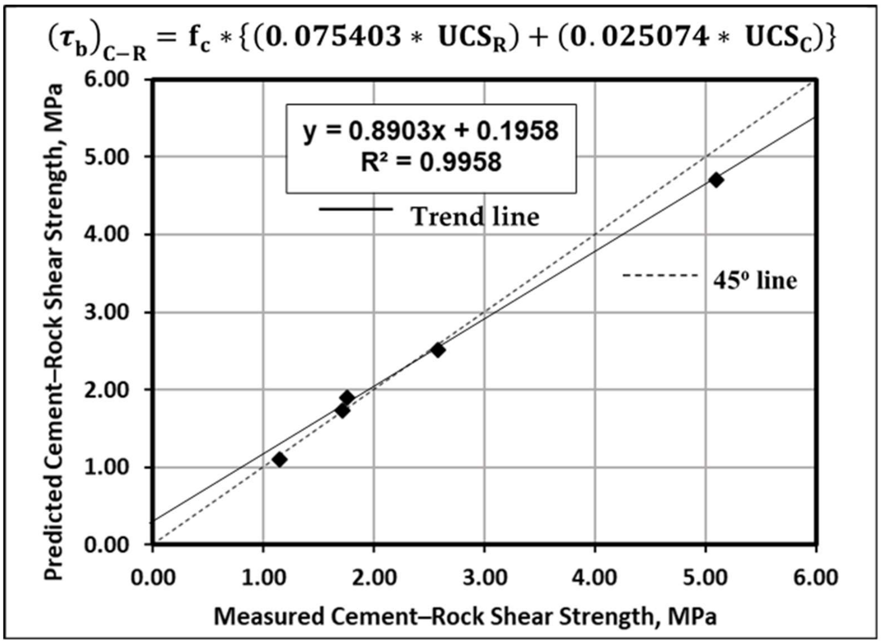

Figure 11. Measured and predicted cement–rock shear bond strength.

Table 9 represents the full sensitivity of the developed empirical correlation (Equation (10)). It can be seen that formation rock strength has a significant effect on cement–rock sheath bond strength compared to the cement strength. This effect is in agreement with the experiences of the oil and gas industry and the API RP 10 B-2 standard [6] that states that a cement uniaxial compressive strength of 500 psi after a period of 24 h is adequate in most cases. Conversely, cement and rock surface contamination has a considerable influence on the magnitude of cement strength and cement–formation rock bond sheath strength.

Table 9. Sensitivity analysis of the developed empirical correlation (Equation (10)).

Parameters	Name	Description	Sensitivity
f_c	Formation rock surface contamination factor	1. Mud cake thickness	Increase f_c and decrease $(\tau_b)_{C\text{-}R}$
		2. Degree of mud invasion into the formation rock	Increase f_c and decrease $(\tau_b)_{C\text{-}R}$
		3. Formation rock porosity, permeability, and natural fracture existence	Decrease f_c and increase $(\tau_b)_{C\text{-}R}$
UCS_R	Formation rock uniaxial compressive strength	1. Natural intrinsic parameter of the formation rock	Constant
		2. Rock uniaxial compressive strength values depends on rock type and may be affected by mud filtrate invasion	Decrease UCS_R and decrease $(\tau_b)_{C\text{-}R}$
UCS_C	Cement rock uniaxial compressive strength	1. Cement type (good quality)	Increase UCS_C and increase $(\tau_b)_{C\text{-}R}$
		2. Cement additives	Variable
		3. Cement/water ratio	Optimum cement/water ratio provides optimum strength for cement and for sheath bond strength
		4. Downhole temperature	Decrease UCS_R and decrease $(\tau_b)_{C\text{-}R}$
		5. Downhole pressure	Increase UCS_R and increase $(\tau_b)_{C\text{-}R}$
		6. Curing time (wait-on-cement time)	Increase UCS_R and increase $(\tau_b)_{C\text{-}R}$
		7. Cement contamination	Decrease UCS_R and decrease $(\tau_b)_{C\text{-}R}$

The limitations of this study are the use of one type of Portland cement and three sandstone rock types. Therefore, this study can be expanded in future using different rock types and cement classes to improve and standardize the developed empirical correlation (Equation (10)). Additionally, temperature, which has a considerable effect on cement's curing time and properties, should be included in any future study. Laboratory-based destructive core testing data provide the most accurate information about static formation uniaxial compressive values, which are not always available. Alternatively, several empirical relationships have been established based on petrophysical logs and core calibration. The flowchart in Figure 12 represents a summary of this work.

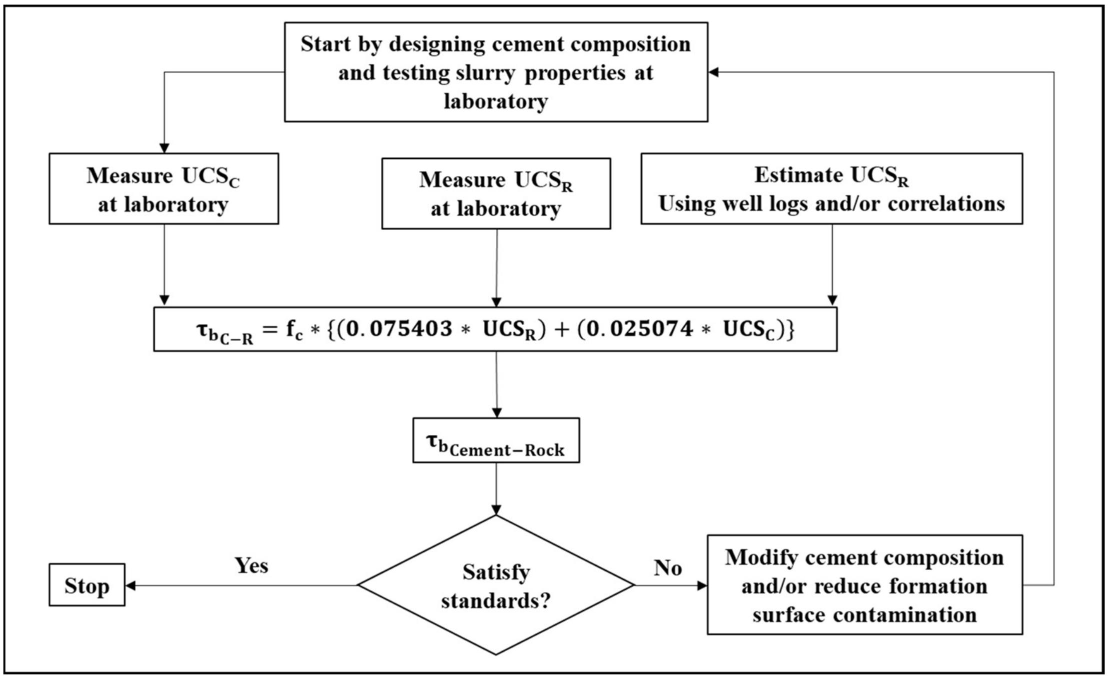

Figure 12. Cement–formation shear bond strength prediction process.

This study provides an initial practical laboratory testing technique plus an empirical correlation that would be of benefit in the field of oil cementing.

6. Conclusions

This study involved the use of Portland cement and three local sandstone rock samples to develop a new reliable laboratory testing procedure and a predictive empirical correlation for cement–rock sheath bond strength. The following conclusions are drawn:

1. The use of the modified uniaxial compression test to evaluate cement–formation shear bond strength using rock–cement composite specimens provided excellent predictions with an average error of less than 5%.
2. The experimental results showed that there is a direct and strong relationship between cement uniaxial compressive strength and cement–formation sheath bond strength.
3. The empirical correlation developed in this study can be used for the simple and reliable prediction of cement–rock sheath bond strength (with an average error of 5%) using cement and rock conventional uniaxial compressive strength values.
4. The modified uniaxial compression test using cement–rock composite samples can be standardized for cement–rock sheath bond strength laboratory tests after further extensive studies have been conducted using other types of cement, additives, and rocks.

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Nomenclature

UCS_C	hard-set cement conventional uniaxial compressive strength, MPa
UCS_R	formation rock conventional uniaxial compressive strength, MPa
τ_b	cement–rock sheath bond strength using conventional test, MPa
$(\tau_b)_{C\text{-}R}$	cement–rock sheath bond strength for composite samples, MPa
$UCS_{C\text{-}R}$	cement–rock uniaxial compressive strength for composite samples, MPa
$BTS_{C\text{-}R}$	cement–rock Brazilian tensile strength for composite samples, MPa
$DTS_{C\text{-}R}$	cement–rock direct pull tensile strength for composite samples, MPa
f_c	rock surface contamination factor, fraction between 0 and 1.0

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