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A Laboratory Study of Factors Affecting Primary Cement Sheath Strength

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Abstract. An investigation of factors affecting cement sheath strength has been carried out.. This study performed on hardened (cured for seven days) cement specimens. These specimens were prepared by mixing 35% fresh water by weight of dry Portland cement (class A according to API classification or C 150 type 1 according to ASTM classification) plus various percentages of Thumama sand (5-40% by weight of dry cement). The relationship between cement tensile and compressive strengths as well as cement direct and indirect tensile strenghs have been established. Factors affecting cement-casing and cement-formation shear bond strength were studied. Cement compressive and tensile strength were correlated to each other as well as to the cement shear bond strength. It was found that casing surface roughness, casing surface cleaning and casing centralization have enhanced the strength of cement-casing shear bond, whereas the deposition of mud cake on the wall of the simulated borehole has reduced the strength of cement-formation shear bond.

Nomenclature

A = Cross-sectional area
BWOC = By weight of cement
D = Diameter of test specimen
DF = Drilling fluid
D_c = Casing outside diameter
D_h = Hole size
C_1 = Constant of cement supporting capability
h = Casing length

L	=	Casing dead weight
L1	=	Compressional load
L2	=	Tensile force
R_Z	=	Average surface roughness
r	=	Radius of test specimen
t	=	Thickness of test specimen
σ_c	=	Uniaxial tensile strength
σ_{t2}, σ_{t1}	=	Direct and indict tensile strength respectively
τ_b	=	Shear bond strength

Introduction

Obtaining a successful cement job will remain one of the most important factors that determine the productive life of any well. Oil well cementing is the process of mixing cement with water and pumping the resultant slurry down the hole through the casing and up the annulus. Cementing procedures may be classified into primary and secondary phases. Primary cementing is performed immediately after the casing is run into the hole. Secondary cementing includes plug-back to another producing zone, plugging a dry hole and formation squeeze cementing. The main goals of cementing operations are [1,2]:

i) To restrict fluid movement between formations and the surface.
ii) To provide support for the casing string.
iii) To prevent pollution of fresh water formations.
iv) To prevent casing corrosion.
v) To support the borehole especially through productive intervals.

To achieve the above goals, the cement should reach downhole with the same properties planned in the laboratory. Failure to surround the casing with continuous and strong cement sheath can lead to such problems as annular imigration of formation fluids, casing corrosion or collapse, loss of well control and high remedial cementing costs [3,4].

Objectives

Several researchers [1-4] have investigated factors affecting primary cement sheath strength, such as cement composition, contamination and displacement rate, pipe rotation, spacer fluid composition, etc. In this study the following factors which affect the cement sheath strength were investigated:

i) Interrelationships among cement mechanical properties, such as compressive strength, direct and indirect tensile strengths and cement-casing and cement-formation shear bond strengths.
ii) The effect of casing surface contamination and the deposition of cake on the wall of

a simulated borehole on cement-casing and cement-formation shear bond strength.

iii) The effect of casing surface roughness and casing surface contamination on cement-casing shear bond strength.

iv) The effect of casing centralization on cement-casing shear bond strength.

The fulfilment of the above objectives is very important to maintain stability for the casing string against static stresses encountered due to the dead weight of the casing string as well as against the dynamic stress resulting from the drilling operations, especially drillstring vibration.

Testing Materials

A series of laboratory tests has been carried out to investigate how cement mechanical properties, casing offset from the hole centre and surface contamination and degree of roughness can affect the stability of the casing in the oil and gas wells.

Cement: Locally produced Portland cement (class A according to API classification or C 150 type 1 according to ASTM classification) was used in this study. This cement has been proven to be suitable for cementing deep oil and gas wells [5].

Sand: Local sand from Thumama area near Riyadh was used to enhance cement strength. The chemical and x-ray diffraction analysis of this sand have shown that it is mainly composed of Quartz and Feldspar as well as little quantities of Appetite, Zircon, Pyroxene, Amphibole and Anatase. The sieving analysis of this sand is shown in Fig. 1, whereas the effect of sand addition on cement uniaxial compressive strength is presented in Fig. 2.

Simulated borehole: Thick-walled cylinders cored from local sandstone have been used as simulated boreholes as shown in Fig. 3. The ratio of sample inner to outer diameter was 0.25.

Casing roughness: Resin-sand coats of different roughness were used to provide various degrees of pipe roughness. A sensitive linear differential variable transducer connected to a chart recorder was used to measure the average casing surface roughness.

Drilling fluids: Two types of drilling fluids were used in this study to produce a contaminated pipe surface including: water-base drilling fluid consisting of 20% Wyoming bentonite by weight of fresh water, and oil-based drilling fluid consisting of 100% crude oil of 32°API.

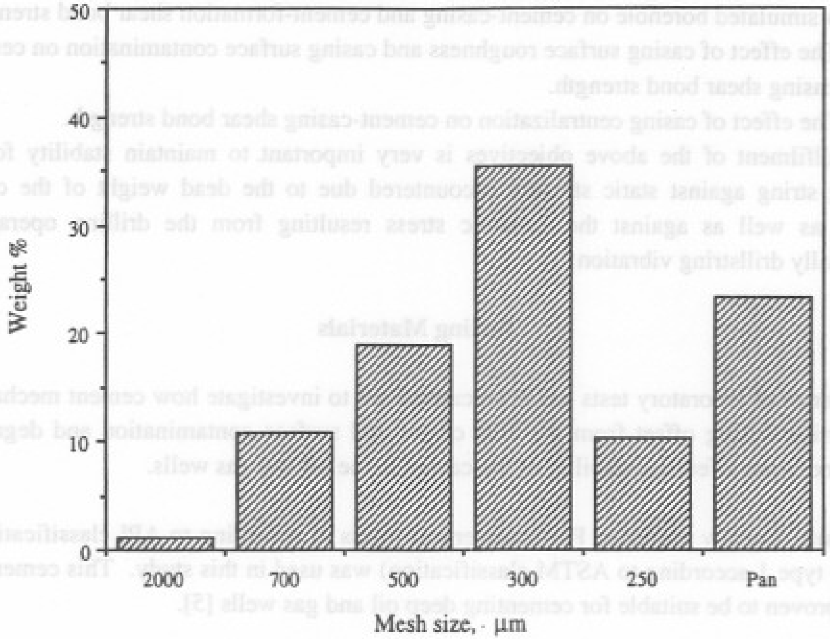


Fig. 1. Granulometric analysis of Thumama sand.

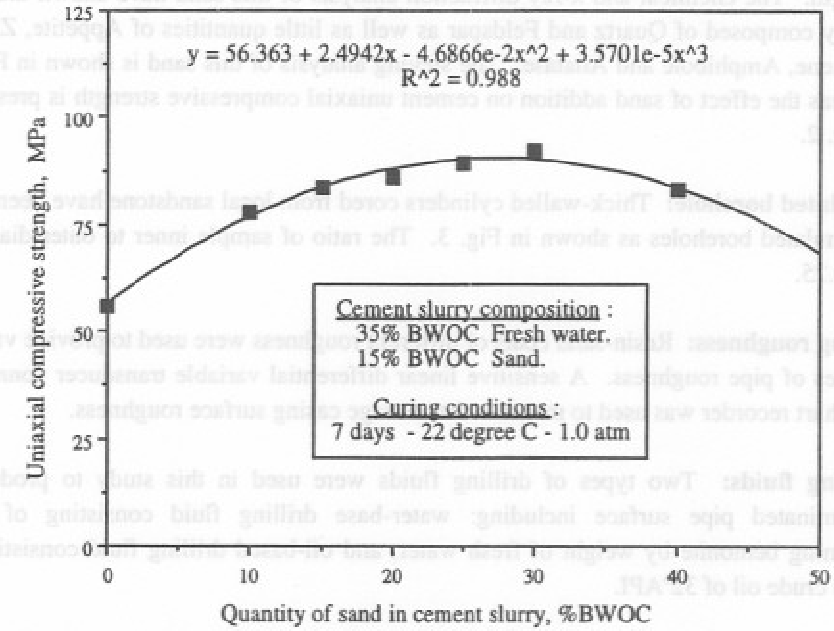


Fig. 2. Effect of sand addition on cement compressive strength.

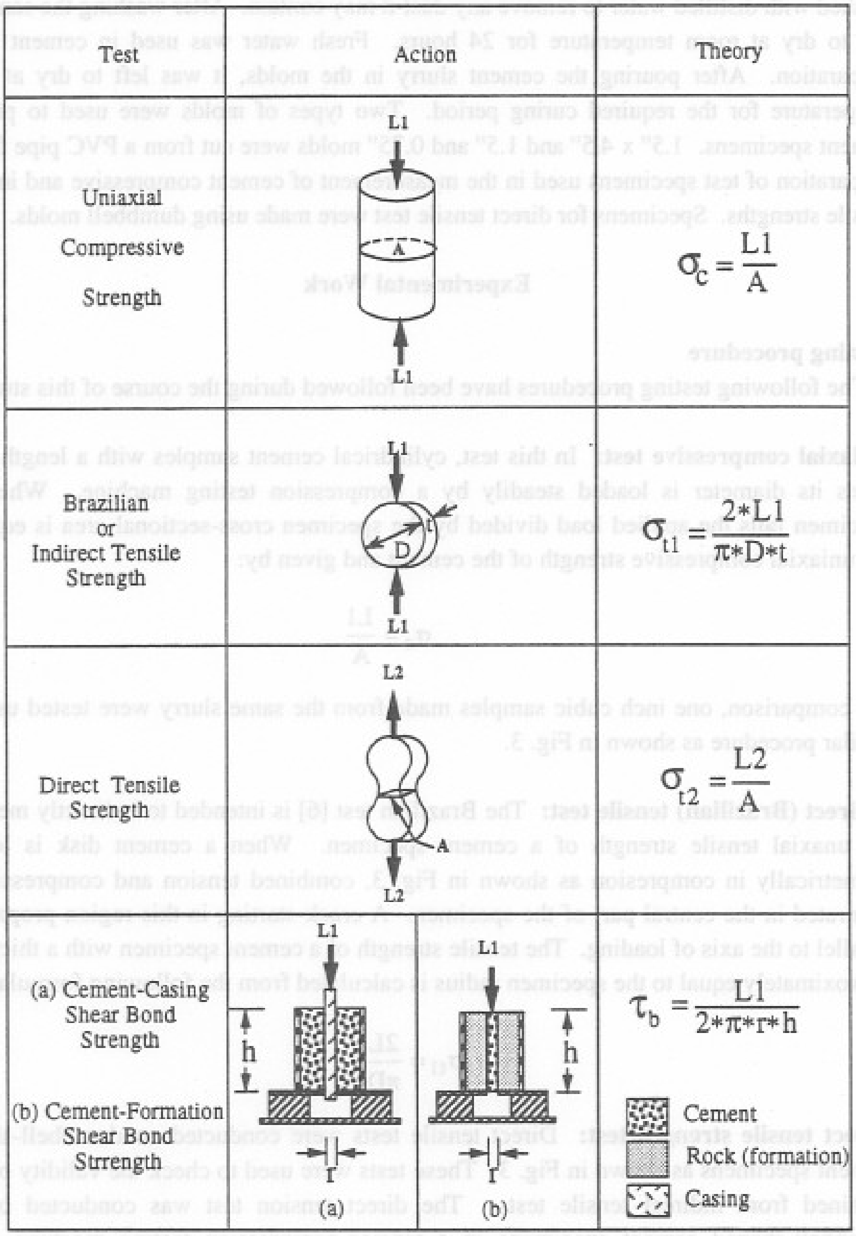


Fig. 3. Tests conducted to estimate cement mechanical and bonding strengths.

Sample preparation: Thumama sand was sieved to remove any contaminants, then was washed with distilled water to remove any dust it may contain. After washing the sand was left to dry at room temperature for 24 hours. Fresh water was used in cement slurry preparation. After pouring the cement slurry in the molds, it was left to dry at room temperature for the required curing period. Two types of molds were used to prepare cement specimens. 1.5" x 4.5" and 1.5" and 0.75" molds were cut from a PVC pipe for the preparation of test specimens used in the measurement of cement compressive and indirect tensile strengths. Specimens for direct tensile test were made using dumbbell molds.

Experimental Work

Testing procedure

The following testing procedures have been followed during the course of this study:

Uniaxial compressive test: In this test, cylindrical cement samples with a length three times its diameter is loaded steadily by a compression testing machine. When the specimen fails the applied load divided by the specimen cross-sectional area is equal to the uniaxial compressive strength of the cement and given by:

$$\sigma_c = \frac{L1}{A} \tag{1}$$

For comparison, one inch cubic samples made from the same slurry were tested using a similar procedure as shown in Fig. 3.

Indirect (Brazilian) tensile test: The Brazilian test [6] is intended to indirectly measure the unaxial tensile strength of a cement specimen. When a cement disk is loaded diametrically in compression as shown in Fig. 3, combined tension and compression is generated in the central part of the specimen. A crack starting in this region propagates parallel to the axis of loading. The tensile strength of a cement specimen with a thickness approximately equal to the specimen radius is calculated from the following formula [7]:

$$\sigma_{t1} = \frac{2L1}{\pi D t} \tag{2}$$

Direct tensile strength test: Direct tensile tests were conducted on dumbbell-shaped cement specimens as shown in Fig. 3. These tests were used to check the validity of data obtained from indirect tensile tests. The direct tension test was conducted on the dumbbell-shaped cement specimens in a tension-compression testing machine. The middle third of the specimen was subjected to tension by attaching metal hooks to the top and bottom third of, the specimen (with enlarged sections) and pulling the sections outward. In all cases, failure occurred at the middle of the middle third of the specimen. The following load on the specimen at failure is recorded and the direct tensile strength is calculated from the followingformula [7].

$$\sigma_{t2} = \frac{L2}{A} \tag{3}$$

Shear bond tests: Shear-bond strength was measured for both cement-casing and cement-formation cases. Test arrangements for both cases are shown in Fig. 3. The shear bond of a cement sheath can be determined from the following formula [8, 9].

$$\tau_b = \frac{L1}{2\pi rh} \tag{4}$$

Whereas the support capability of cement sheath can be determined from the following formula [10, 11].

$$L = C_1 D \sigma_c h \tag{5}$$

Therefore, a theoretical length of casing can be calculated based on the laboratory measured strength properties of cement under consideration.

Tests repeatability: To avoid erroneous results due to odd samples, i.e. samples containing micro-fractures or irregularly distributed composition, each test was repeated three times using three different samples and an average value of the three tests was used to establish the required relationships.

Results and Discussions

Figure 4 shows that the cement compressive strength increases with time. The rate of increase in compressive strength starts to stabilize after one week. 24 MPa (3481 psi) compressive strength was recorded after 24 hours curing time. Based on the above finding, seven days curing time was kept for all remaining tests. Fig. 5 shows a cross-plot between direct and indirect tensile strength of the tested cement. It can be seen that both tests provided comparable results. Indirect tensile test, therefore can be used to measure the cement tensile strength due to the simplicity in sample preparation and in testing.

Tensile strength was found to be directly proportional to the compressive strength as shown in Fig. 6. It is clear that the compressive strength is 10 to 12 times greater than the tensile strength, which is in full agreement with the findings of other researchers [6,7].

Shear bond between "casing and cement" and "cement and formation" increases with increasing cement compressive strength. A similar effect has been noticed for the tensile

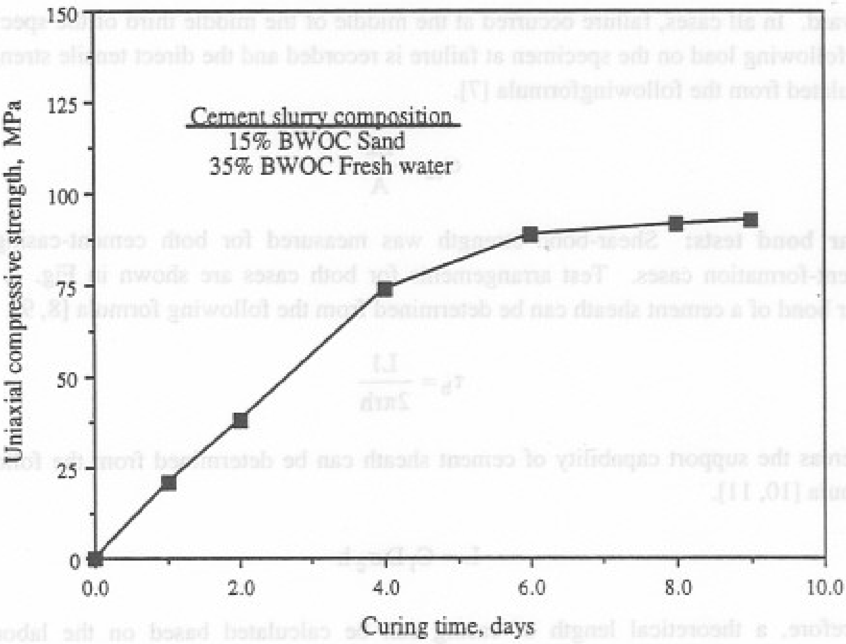


Fig. 4. Effect of curing time on the uniaxial copressive strength of hardened cement.

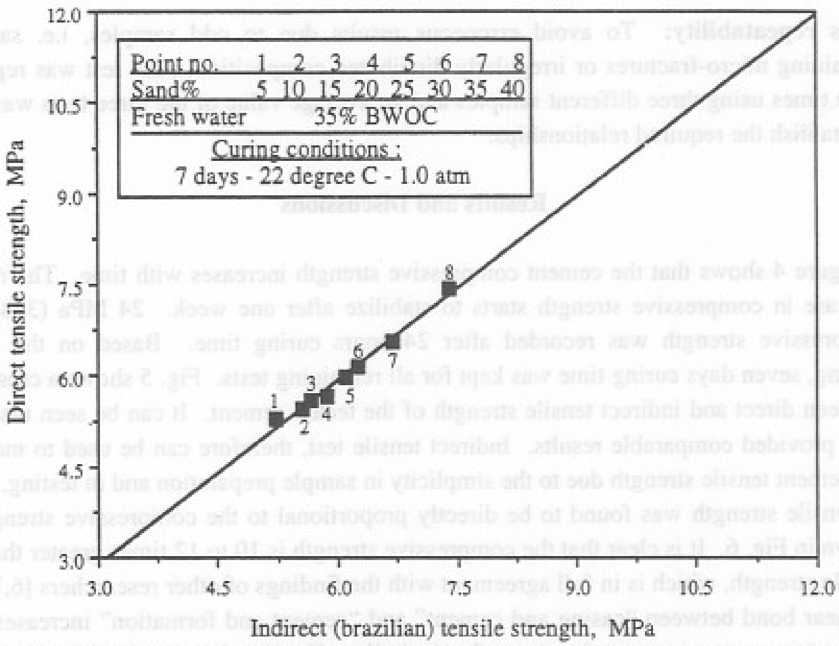


Fig. 5. Relationship between direct and indirect tensile strengths of various cement compositions.

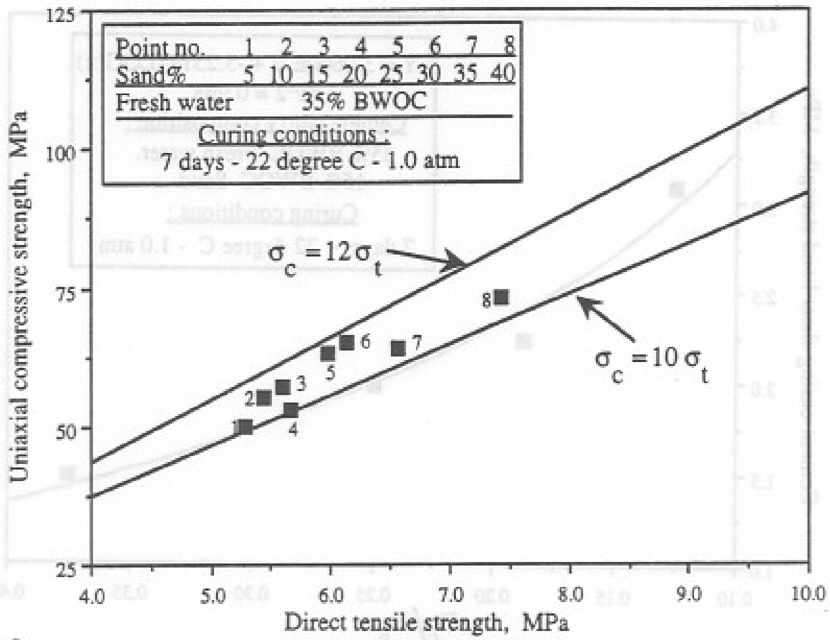


Fig. 6. Relationship between direct tensile strength and uniaxial compressive strength of various compositions of cement slurries.

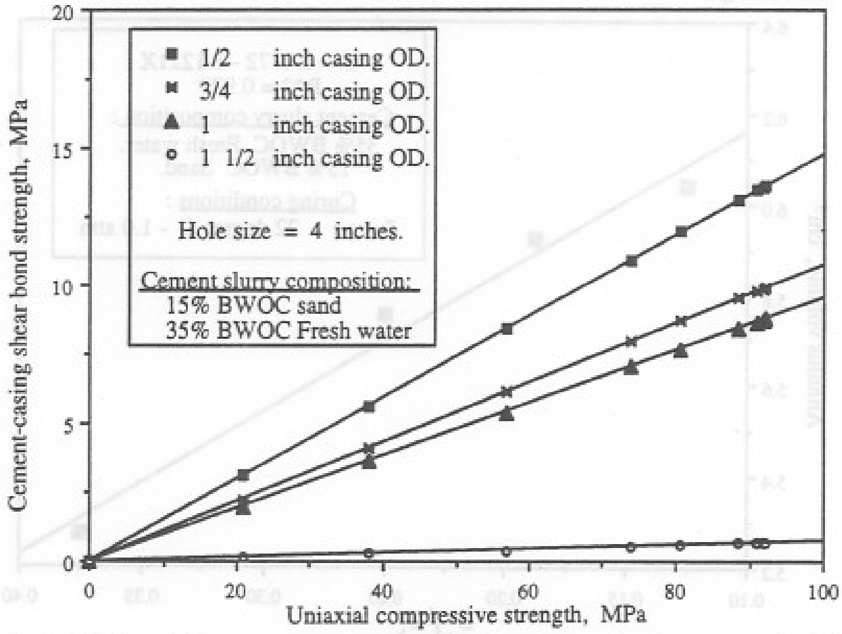


Fig. 7. Relationship between cement-casing shear bond strength and cement uniaxial compressive strength for various casing diameters at different curing periods.

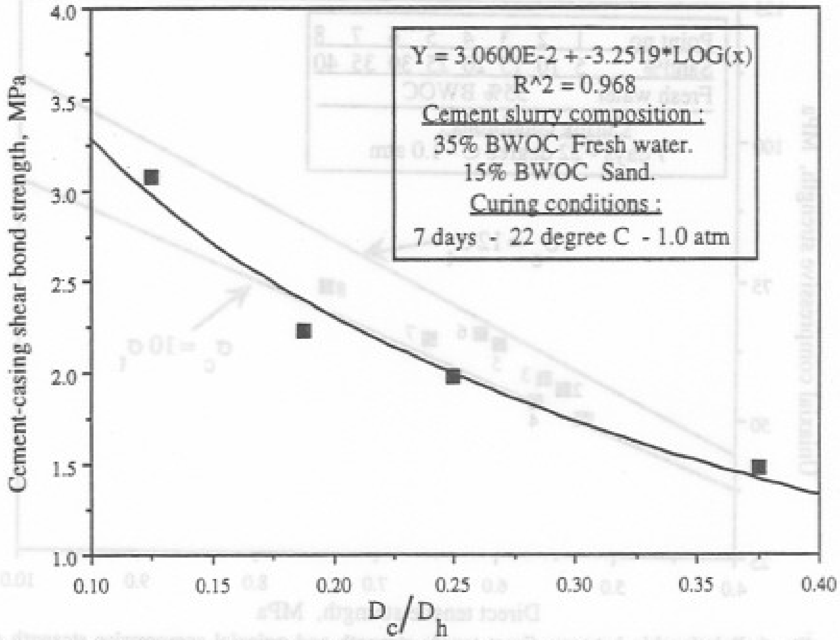


Fig. 8. Effect of casing diameter (D_c) to hole diameter (D_r) ratio on cement-casing shear bond strength.

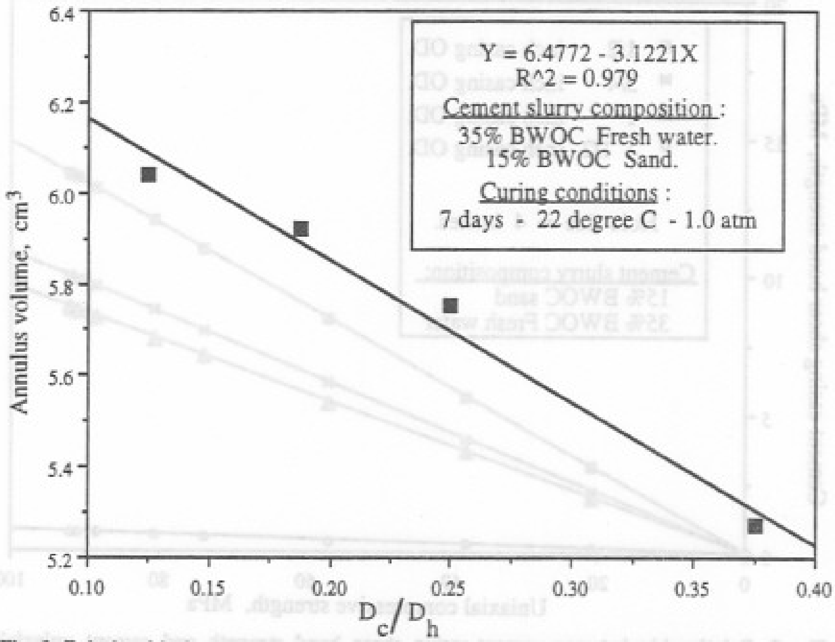


Fig. 9. Relationship between casing diameter (Dc) to hole diameter (Dh) ratio on annular volume.

strength. Casing size (outside diameter) to hole size ratio has shown a great effect on cement-casing shear bond strength. Cement-casing shear bond decreases as the casing size increases as shown in Figs. 7 and 8. This might be due to the reduction in the annular space provided for cement slurry, which in turn reduces the amount of cement sheath around the casing as shown in Fig. 9.

Bond strength between cement and formation depends on the degree of contact between cement and formation. When a mud cake was present between the cement and formation, bond strength was greatly reduced. When cement was squeezed against dry core, bond strength approached formation compressive strength as shown in the following table. This is because the mud cake prevents cement sheath from bonding to the formation and hence minimizing the stability of the casing string.

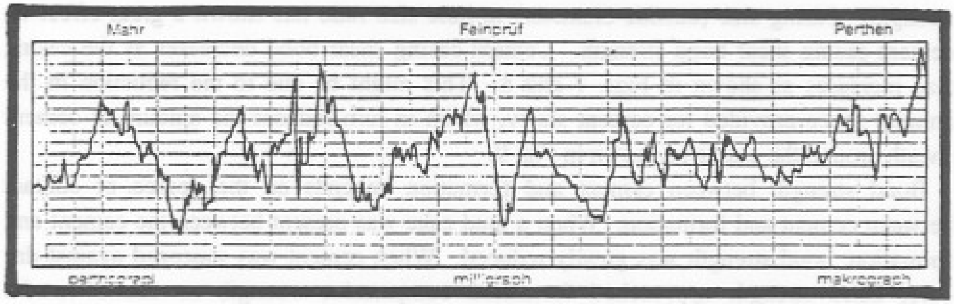
Cement-casing shear bond strength increases as casing roughness increases as shown in Fig. 10. This is because high surface roughness provides high friction forces between cement and casing which increases cement-casing shear bond strength. The casing contamination by the formulated drilling fluids decreased the cement-casing shear bond strength by isolating the cement sheath and the casing surface. This may results in a contaminated cement (with a lower strength) near the casing, which reduces cement-casing shear bond strength as shown in Fig. 11.

Cased hole stability can be enhanced if casing offset from the centre of the hole is minimized (i.e. centralizing the casing) as shown in Fig. 12. Uncentralized casing results in non-uniform distribution of cement sheath around the casing, which results in a reduction in cement-casing shear bond strength.

Figure 13 shows the effect of cement compressive strength as well as casing size to hole size ratio on the capability of the cement sheath to carry heavy casing grades shown

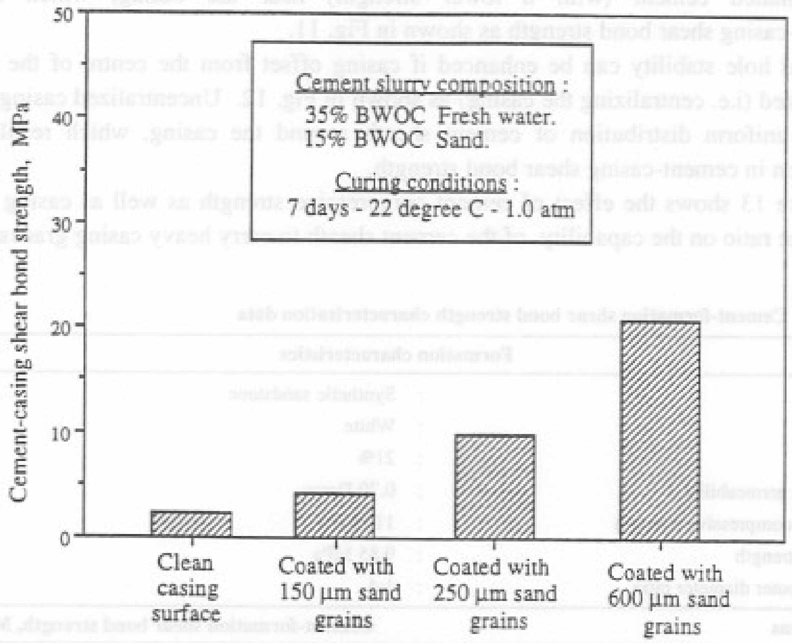
Table 1. Cement-formation shear bond strength characterization data

Formation characteristics	
Type	Synthetic sandstone
Color	White
Porosity	21%
Absolute permeability	0.70 Darcy
Uniaxial compressive strength	113 MPa
Tensile strength	9.85 MPa
Inner to outer diameter ratio	1:4
Conditions	**Cement-formation shear bond strength, MPa**
Clean formation	107
Mud cake from 20% by weight Wyoming bentonite in fresh water	75
Mud cake from 32° API crude oil	56



Average roughness (R_z)	=	8.05
Maximum roughness	=	8.7
Vertical scale	=	1 mm = 0.333 µm
Horizontal magnification	=	40 : 1

(a) Surface roughness graph for clean casing.



(b) Casing roughness-shear bond strength relationship.

Fig. 10. Effect of sand coats on casing-cement shear bond strength.

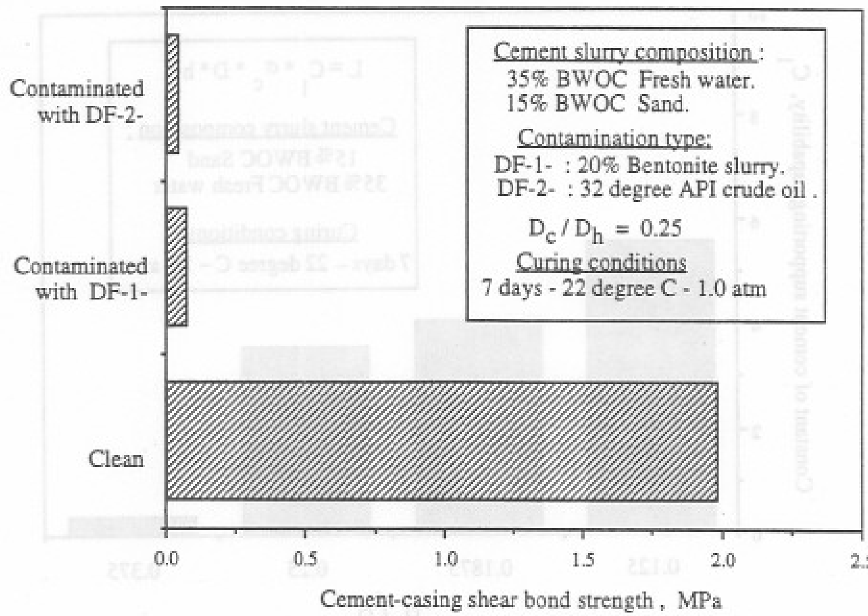


Fig. 11. Effect of casing surface contamination on cement-casing shear bond strength.

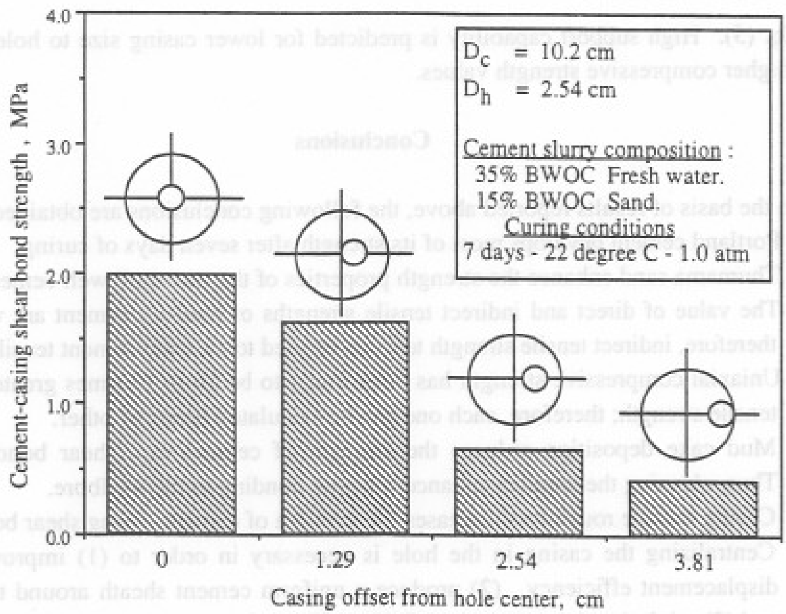


Fig. 12. Effect of casing offset from hole center on cement-casing shear bond strength.

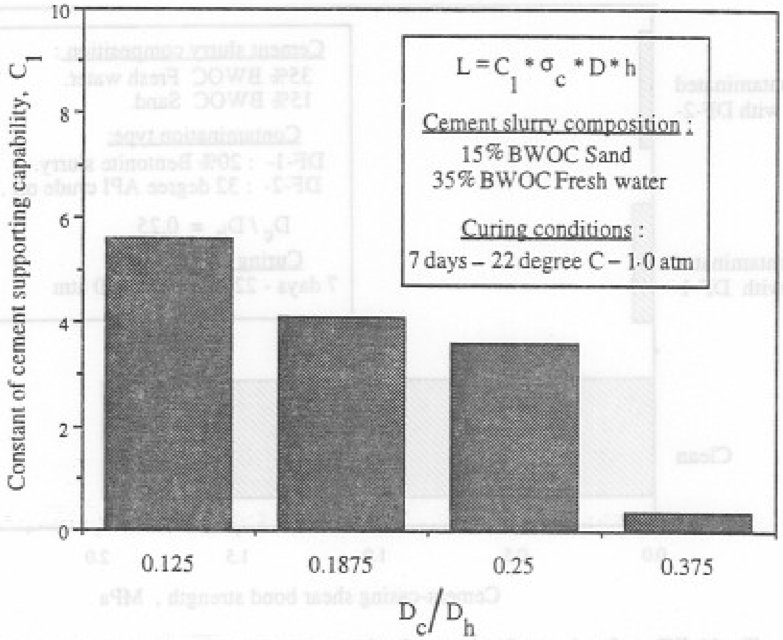


Fig. 13. Effect of cement sheath strength and casing size to hole size ratio on cement supporting capability.

by Eq. (5). High support capability is predicted for lower casing size to hole size ratio and higher compressive strength values.

Conclusions

On the basis of results reported above, the following conclusions are obtained:

i) Portland cement develops most of its strength after seven days of curing.

ii) Thumama sand enhance the strength properties of the tested oil well cement.

iii) The value of direct and indirect tensile strengths of hard-set cement are very close; therefore, indirect tensile strength test can be used to measure cement tensile strength.

iv) Uniaxial compressive strength has been found to be 10 to 12 times greater than the tensile strength; therefore, each one can be calculated from the other.

v) Mud cake deposition reduces the strength of cement-rock shear bond strength. Thus, cleaning the annulus enhances cement bonding to the wellbore.

vi) Casing surface roughness increases the strength of cement-casing shear bond.

vii) Centralizing the casing in the hole is necessary in order to (1) improve cement displacement efficiency, (2) produce a uniform cement sheath around the casing, and (3) minimize the occurrence of channelling of cement.

viii) Strengthening of the cement in the annular space is very important in order to withstand the resulting stresses during perforation of the producing zone. This can be achieved by mixing the cement with strength-enhancing materials or by using high-strength cement.

ix) Casing surface contamination by the drilling fluids may severely reduce the development of a strong cement-casing bond.

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دراسة معملية للعوامل المؤثرة على قوة الربط في عمليات السمنتة الأولية

مساعد ناصر جاسم العواد

قسم هندسة النفط، كلية الهندسة، جامعة الملك سعود، ص. ب ٨٠٠،

الرياض ١١٤٢١، المملكة العربية السعودية

(استلم في ١١/١١/١٩٩٥م؛ قبل للنشر في ٢١/٥/١٩٩٦م)

ملخص البحث. تمت دراسة العوامل المؤثرة على قوة الربط للاسمنت. استخدمت عينات اسمنتية متصلبة بعد ٧ أيام من الصب. جهزت العينات الاسمنتية بخلط ماء عذب بنسبة ٥٣,٠٪ من وزن الاسمنت البورتلاندي الجاف (نوع A حسب مقاييس API أو نوع C105 رقم ١ حسب مقاييس ASTM مع نسب متعددة من رمل الثمامة (٥-٤٠٪ من وزن الاسمنت البورتلاندي الجاف). وتمت دراسة العوامل المؤثرة على قوة الربط بين الاسمنت وأنابيب التبطين والاسمنت وصخور جدار البئر ومن ثم أوجدت العلاقة بين قوة الشد وقوة الانضغاط غير المحصور للاسمنت مع قوة الربط بين الاسمنت وأنابيب التبطين. ووجد أن خشونة ونظافة السطح الخارجي لأنابيب التبطين وكذلك توسيطها في البئر قد حسنت من ثباتية تلك الأنابيب. بينما وجد أن ترسيب كعكة سائل الحفر على جدار البئر قد قللت من قوة الربط بين أنابيب التبطين وجدار البئر.

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