ARTICLE IN PRESS

Journal of King Saud University – Engineering Sciences xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of King Saud University – Engineering Sciences

journal homepage: www.sciencedirect.com

Original article

A new approach for understanding the mechanism of wellbore strengthening theory

Musaed N.J. AlAwad

Petroleum and Natural Gas Engineering Department, College of Engineering, King Saud University, Riyadh, Saudi Arabia

ARTICLE INFO

Article history:
Received 12 June 2020
Accepted 25 July 2020
Available online xxxx

Keywords:
Wellbore strengthening
Multi-stage triaxial compression test
Unconfined compression test
Brazilian indirect tensile test
Fracture seal materials
Oil well drilling
Confining pressure
Crushed dates palm seeds

ABSTRACT

To achieve fast, safe and economical drilling operations through formations containing natural fractures or vugs, all fractures and vugs must be perfectly sealed using proper fractures seal materials in a process called wellbore strengthening. Wellbore strengthening may elevate the overall tensile strength of the treated formation to a value approaches the intrinsic tensile strength of unfractured rock.

Numerous studies have been conducted for testing fractures seal materials suitability for wellbore strengthening application in various formations. However, there is no solid and simple theoretical explanation on how wellbore strengthening process can recover the tensile strength and hence the fracturing pressure of the treated naturally fractured formation.

In this study, test specimens cored from an artificial (building) sandstone bricks were used to measure the unconfined compressive strength (UCS), Brazilian indirect tensile strength (BTS), and establishing the multi-stage triaxial compression (MS-TCS) test. Core samples from the same sandstone were previously used for wellbore strengthening studies using crushed dates palm seeds. Crushed dates palm seeds succeeded to completely stop mud losses at a pressure equal to 6.9 MPa.

Data obtained from unconfined compression, multi-stage triaxial compression, Brazilian indirect tensile, and wellbore strengthening tests were collectively used to develop a clear theoretical understanding of the mechanism of tensile strength recovery caused by wellbore strengthening effect.

It was found that wellbore strengthening effect in sealing natural fractures and vugs is similar to the confining pressure effect in closing the induced shear fractures in the test specimen during a multi-stage triaxial compression test.

For the tested sandstone, using crushed dates palm seeds as a fracture seal material has improved wellbore strengthening from zero tensile strength (complete loss of mud circulation) to 2.56 MPa tensile strength at which there was a complete fracture seal (zero mud loss). The recovered tensile strength (2.56 MPa) is approaching the intrinsic tensile strength (BTS = 2.7 MPa) of the same sandstone in its initial unfractured state.

1. Introduction

Drilling is the first and the most expensive step in the oil and gas industry. Expenses for drilling represent 25% of the total oil field exploitation cost. Drilling fluids represent 15 to 18% of the total cost of petroleum well drilling operation.

The lost circulation in naturally fractured formations and vugs is one of the most complicated problems that have existed in drilling engineering for a long time. The key for solving the loss of drilling fluid circulation is to improve the fracturing pressure of the formation by sealing the existing natural fractures. This process is called wellbore strengthening.

As research on lost circulation has evolved, the solutions have gradually developed from simple plugging to a combination of plugging and prevention. Lost circulation prevention has been accepted widely, and a series of prevention technologies such as improving the narrow window of safe mud density in drilling fluid technology. On the other hand, wellbore strengthening technology has been developed to treat natural fractures and vugs. All these technologies are designed to improve the integrity of the wellbore

E-mail address: malawwad@ksu.edu.sa

Peer review under responsibility of King Saud University.

ELSEVIER Production and hosting by Elsevier

https://doi.org/10.1016/j.jksues.2020.07.015
1018-3639/© 2020 Production and hosting by Elsevier B.V. on behalf of King Saud University.

and improve the formation fracture pressure for safe and fast drilling operations (Biao et al., 2019).

This study is focusing on developing a simple and clear understanding of the mechanism of tensile strength recovery caused by wellbore strengthening process.

2. Literature review

Drilling mud lost circulation in formations containing natural fractures and/or vugs add more to the overall drilling expenses in terms of time, mud components and overall safety. Several other problems may happen as a side effect of lost circulation such as stuck pipe, wellbore instability, difficult cementing job, etc. The magnitude of drilling mud lost circulation problem can be divided into the following categories (Biao et al., 2019):

- Seepage: up to 10 barrels/hr.
- Partial loss: 10–50 barrels/hr.
- Severe loss: more than 50 barrels/hr.
- Total loss: 100%

There are several field practical methods normally used to overcome lost circulation while drilling oil and gas wells as follows:

- Applying blind drilling using water as a drilling fluid.
- Drilling with lightweight fluid (air, foam ... etc.).
- Applying wellbore strengthening by utilizing lost circulation materials LCM in conjunction with fracture seal material (FSM).

The most efficient and safe method applied for the treatment of naturally fractured formation is wellbore strengthening. Wellbore strengthening process has been studied extensively by two main approaches:

- Experimental studies searching for and/or testing new fracture plugging materials.
- Theoretical studies simulating wellbore strengthening process.

In the following sections, both of the above mentioned approaches will be discussed in details.

2.1. Experimental studies in wellbore strengthening

Sanders et al. (2008) and Contreras et al. (2014) experimentally studied the mechanisms of lost circulation materials (LCM) seal of induced fractures in thick-wall cylindrical cores. Knudsen et al. (2014) applied the first thermal activated resin as an unconventional LCM. The thermal activated resin is a particle free, multi-component polymer resin based liquid plugging material with a curing process activated by temperature. Kumar et al. (2011), developed a tapered slot to physically resembling a wedge shaped fracture for testing various types of LCM. Matthew et al. (2013), developed a low-volume, laboratory-scale apparatus with multiple configurations to better model lost circulation conditions encountered while drilling through vugular and fractured zones. The apparatus has a high working pressure and high pressure differentials can be used to test plugs formed by lost circulation materials. Chellappah et al. (2015), performed an attempt to simulate fractured formation by replacing the ceramic disc in the HT-HP filter press by slotted stainless steel. Amanullah (2016) used crushed palm date seeds as a lost circulation material (LCM) for sealing fractured formations simulated by using 2 mm slotted stainless steel discs fitted into 250 mm HT-HP filtration cell to test the possibility of fracture seal by a drilling fluid containing the crushed palm date seeds. The result was a perfect fracture seal indicating the possibility of utilizing this LCM in drilling oil and gas wells. Musaed and Fattah (2019) , developed a new approach for testing fracture seal materials. In their study they utilized rock cores with man-made fracture fitted into HT-HP filtration apparatus. Using their new experimental set-up, they found that crushed palm date seeds can plug open fractures perfectly under elevated pressure (6.9 MPa) and temperature (90 °C). Quanxin et al. (2014), conducted experimental tests to investigate the applicability and effectiveness of various wellbore strengthening materials. They concluded that particle size distributions of the lost circulation materials with respect to the open fracture aperture are critical in the sealing process. Yongcun and Gray (2017), provided an extensive summary of fundamental studies on lost circulation and wellbore strengthening reported in the literature 30 years. Additionally, they presented the strengths, limitations, and ambiguities of published experimental studies and mathematical models from a neutral perspective.

2.2. Theoretical studies in wellbore strengthening

Wang et al. (2007) used boundary element analysis to theoretically investigate the process of cracks sealing to strengthen the wellbore. They concluded that perfect sealing of cracks enhances wellbore stability. Donald and Whitfill (2003) recommended complete engineering approaches for controlling circulation loss during well drilling based on results obtained from new laboratory study on LCM test and compered to large scale laboratory data from Drilling Engineering Association (DEA). This approach including number of planning tools such as borehole stability analysis, hydraulics modeling to estimate the equivalent circulating density, and LCM material selection criteria. Test results indicated that LCM type, LCM concentration, and LCM particle size distribution are important factors for fractures seal. El-Sayed et al. (2007) have used "dual-action" LCM while drilling in the Miocene age (Qwassim and Sidi Salim) formations in the Nile Delta region of Egypt. The study was based on drilling history (3 wells drilling history). The total solution to this problem was based on understanding the lost circulation mode to enhance treatment design, and due to this, the "dual-action" LCM was able to cure losses. Mansour and Taleghani (2013) introduced a new smart lost circulation material made from anionic shape memory polymer that can be programmed to change in shape when stimulated by specific temperature. The smart LCMs was activated by the temperature of bottom hole and can seal the face and tip of fractures, the continuum model and discrete model have been made to find the relationship between fracture size, smart LCM particle size and its sealing efficiency. The concentration of particle required to seal the different fracture size and bring the fluid loss to less than 3 ml/min is measured as result the bridging and volumetric expansion property that the smart LCM has made effectively seal big fracture and minimize or prevent loss. Mark and Mclean (2004) developed a finite element model for studying the stress state during fracture plugging during wellbore strengthening process. The developed model yielded that the success of wellbore strengthening process is mainly dependent on the distribution of the additives relative to the fracture width. Hong et al. (2008) used boundary element numerical simulator to investigate wellbore strengthening by propping natural open fractures. He found that stress anisotropy has a large effect on the stability of the fractures after stress cage treatment.

Most of the above mentioned theoretical approaches used to understand the mechanism of wellbore strengthening are either mathematically complicated or based on numerical analysis and expensive simulation packages that required many assumptions which made it irrelevant for practical drilling engineering applications.

3. Study objective

The objective of this study is to develop a simple, practical and technically valid approach suitable for theoretical and experimental understanding and evaluating of wellbore strengthening process. To fulfil this objective, wellbore strengthening effect is clarified using the three main laboratory rock mechanic tests named the multi-stage triaxial compression test (MS-TCS), the unconfined (unconfined) compression test (UCS), and the Brazilian indirect tensile test (BTS) in conjunction with wellbore strengthening (WBS) test.

4. Theoretical background

In this study, the integration of the multi-stage triaxial compression test, the unconfined compression test, and Brazilian indirect tensile test will be used to provide a clear understanding on how wellbore strengthening can enhance tensile strength of the treated formation. The following sections outline the theoretical background of the wellbore strengthening process as well as the theoretical background and the experimental procedures required to perform the multi-stage triaxial compression test, the unconfined (unconfined) compression test, and the Brazilian indirect tensile test.

4.1. Wellbore strengthening mechanism

Wellbore Strengthening is the term generally used in drilling engineering to artificially increase the maximum pressure a wellbore can withstand without intolerable mud losses. This can be done by the sealing (plugging) of existing natural fractures and vugs as shown in Fig. 1.

With untreated natural fractures and vugs, tensile strength of the formation is considered equal to zero which means a condition of total loss of the drilling mud into the formation being drilled (i.e. zero fracturing pressure). By sealing these open fractures and vugs, the formation fracturing pressure will tremendously increase resulting in an increase in wellbore capability to withstand higher mud pressure without lost circulation.

Several fractures sealing materials for wellbore strengthening application have been proposed throughout the past years.

Among these materials are nanoparticles for sealing heavily fractured shales. For larger fractures prima seal, cellophane, walnut, rubber crumb, crushed dates palm seeds, fibers, saw dust, crushed carbonates, etc. (Biao et al, 2019).

4.2. Tensile strength measurement

As a standard test for measuring rock tensile strength indirectly, the Brazilian tensile test (unconfined) is widely used and recommended by the international society for rock mechanics and rock engineering, (ISRM, 2014). The Brazilian test is performed by applying diametrical compression stress (σ_1) to induce tensile stresses in a thin disc of rock at zero lateral confinement (i.e. σ_2 = σ_3 = zero). As shown in Fig. 2, a line load creates a uniform tensile stress across the loaded diameter accompanied with a vertical compressive stress.

This test was developed based on the assumptions that the test is done at zero confining pressure, the sample thickness is equal to its radius. Failure is assumed to start at the center under a state of stress and the tensile strength is calculated using the following expression:

$$\sigma_{Bt} = \frac{2P}{\pi Dt} \tag{1}$$

where

σ_{Bt} = The indirect tensile strength, MPa.
P = The applied diametrical load at failure, kN.
D = Test specimen (disc) diameter, m.
t = Test specimen (disc) thickness, m.

The common relationship between tensile strength and fracturing pressure is given in the following equation (Jaeger et al., 2007):

$$\sigma_{frac} = \left(\frac{\nu}{1-\nu}\right)\sigma_{ov} + \sigma_H + \sigma_t - P_p \tag{2}$$

Where

σ_{frac} = Formation fracturing pressure, MPa.
ν = Poisson's ratio, fraction.
σ_{ov} = Overburden in-situ stress, MPa.
σ_H = Maximum in-situ horizontal stress, MPa.
σ_t = Rock tensile strength (intrinsic or wellbore strengthening recovered), MPa.
P_p = Near wellbore formation pore fluid pressure, MPa.

For naturally fractured rocks, tensile strength is almost equal to zero. Therefore, when drilling through naturally fractured formations, it required to treat these open fractures using wellbore strengthening mechanism to enable drilling this formation with safe and economic drilling process.

4.3. Unconfined compressive strength measurement

The unconfined compression test (UCS) is performed by loading the sample axially at zero confining pressure till failure is reached. The unconfined compressive strength is calculated using the following equation:

$$UCS = \frac{L}{A} \tag{3}$$

where

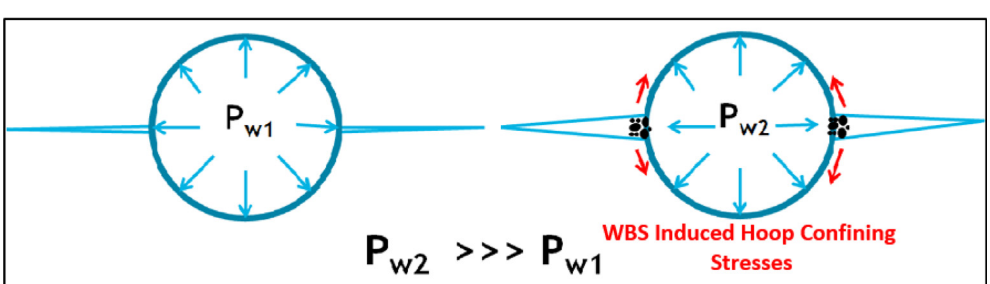


Fig. 1. The mechanism of wellbore strengthening process (Eric and Omid, 2014).

Please cite this article as: M. N. J. AlAwad, A new approach for understanding the mechanism of wellbore strengthening theory, Journal of King Saud University – Engineering Sciences, https://doi.org/10.1016/j.jksues.2020.07.015

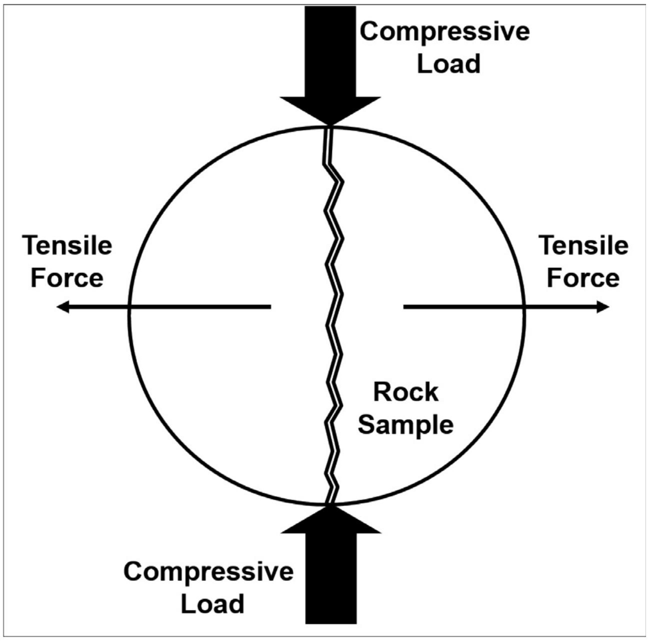


Fig. 2. Schematic diagram of the Brazilian tensile test.

UCS = The unconfined compressive strength, MPa.
L = Axial load at failure, kN.
A = Test specimen minimum cross sectional area, m^2.

The UCS test is very important for characterizing formations at a very shallow depth where the confining pressure role is minimal. The relationship between tensile strength and unconfined compressive strength (BTS/UCS) will be used in conjunction with the multi-stage triaxial compression test result to explain the mechanism of wellbore strengthening process.

4.4. Triaxial compressive strength measurement

The triaxial compression test (TCS) is utilized to establish rock failure criteria which identifies zones of safety and failure. Rock failure criteria can help in calculating the optimum drilling mud weights for application in overbalanced and underbalanced drilling (Musaed, 2016) critical production rate for sand production management (Musaed, 2001) and hydraulic fracturing and many other applications (Musaed, 1998). Triaxial compression test can be performed in two different procedures both of each provides the same output with acceptable error as shown in the following sections.

4.4.1. Discrete triaxial compression test

The procedure for conventional discrete triaxial compression test (D-TCS) requires several rock specimens to be tested individually up to failure under different confining pressures so that the failure criteria (failure envelope) can be established as shown in Fig. 3. Each data point in Fig. 3 represents a single discrete triaxial compression test using individual rock sample.

4.4.2. Multi-stage triaxial compression test

In some situations, there are insufficient core samples available for laboratory testing, therefore, an alternative triaxial compression procedure is applied to establish rock failure criteria called the multi-stage triaxial compression test (MS-TCS). In this test, a single rock specimen is axially loaded at several stages of compression at different confining pressures.

In other word, all of the data points shown in Fig. 4 are obtained by testing one rock sample using multi-stage triaxial compression test. The International Society for Rock Mechanics and Rock Engineering (ISRM, 2014) recommended testing procedure could be divided into sub-stages as shown in Fig. 4.

In the multi-stage triaxial compression test a rock cylindrical sample is loaded axially and the confining pressure should be increased until both of them reach the value of the confining pressure (CP1 greater than 0) of the first stage, bringing the specimen into hydrostatic condition. In the next phase of the test the axial load is then increased keeping confining pressure (CP1) constant until the corresponding failure point is observed in the axial stress – axial strain curve (Point A in Fig. 4). The axial load is being increased while the strain rate is kept constant (displacement controlled test).

The confining pressure is then increased to the next level in one step (CP2 > CP1) as shown in Fig. 4. This step is followed by an axial load increase using the procedure described above. The confining pressure will then be kept constant, while the axial loading is continued up to the failure of the specimen (Point B in Fig. 4). Similarly, the confining pressure is then increased to the next level in one step (CP3 > CP2) as shown in Fig. 4. Then the axial load is increased till the failure of the specimen (point C in Fig. 4). After the failure the axial load will fall back to its residual value (Point D, Fig. 4). The confining pressure is progressively reduced until the specimen is completely unloaded. Data obtained from the multi-stage triaxial compression test can are used to establish rock failure criteria as shown in Fig. 4.

5. Materials, methods and results

5.1. Wellbore strengthening test

Many researchers have been studied wellbore strengthening experimentally to test the potential suitability of various lost circulation additives for fractures sealing. In all these studies tremendous enhancements in wellbore fracturing were observed. Musaed and Fattah (2019) tested crushed dates palm seeds for potential fracture seal capability for wellbore strengthening applications. In their study they used core plugs with man-made fracture and modified HT-HP filtration cell as shown in Fig. 5.

In their study (Musaed and Fattah, 2019) a medium strength commercial building sandstone has been chosen with average properties as shown in Table 1. They found that the tested fracture seal material (crushed dates palm seeds) provided excellent wellbore strengthening at which the mud pressure can be raised up to 6.9 MPa. Without fracture seal, the mud was completely flow through the fracture in the test sample.

5.2. Unconfined compression and tensile tests (UCS and BTS)

Using ELE-ADR2000 stiff compression machine, the unconfined compressive strength and the indirect tensile strength were conducted using samples obtained from the same rock shown in Table 1. The test specimens have been prepared according the ISRM standards (ISRM, 2014). The estimated values of these two strength parameters are shown in Table 2.

5.3. Multi-stage triaxial compression test

The same sandstone used in the wellbore strengthening study, UCS and BTS experiments have been chosen for the multi-stage triaxial compression test. Test sample has been cored from a block of the selected sandstone. Test specimen has been prepared

Please cite this article as: M. N. J. AlAwad, A new approach for understanding the mechanism of wellbore strengthening theory, Journal of King Saud University – Engineering Sciences, https://doi.org/10.1016/j.jksues.2020.07.015

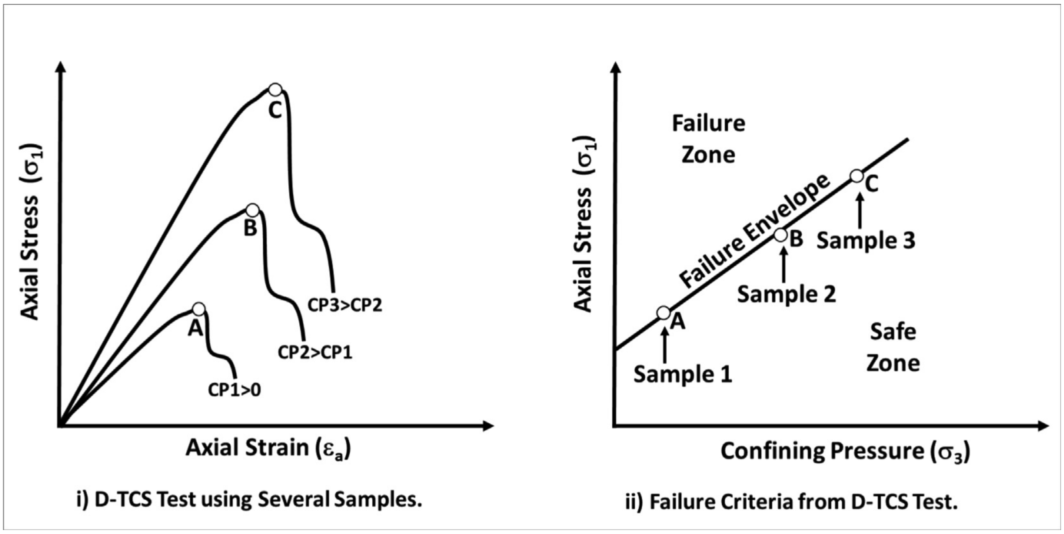


Fig. 3. Typical rock failure criteria based on the D-TCS test.

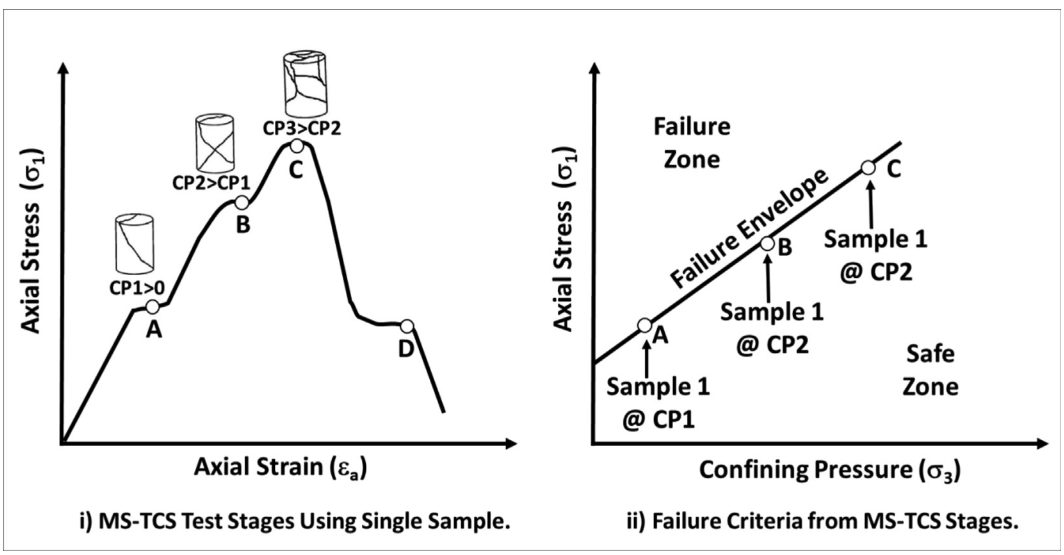


Fig. 4. Typical rock failure criteria based on the MS-TCS test.

according the ISRM standards. Experimentally measured data obtained from the multi-stage triaxial compression tests are tabulated in Table 3.

The multi-stage triaxial compression test in this study has been performed using ELE-ADR2000 stiff compression machine, constant confining pressure system, and 1.5-inch Hock cell.

In the first cycle of the multi-stage triaxial compression test (CP1 = 3.45 MPa), a single shear failure was initiated as shown in Table 3. To demonstrate the effect of wellbore strengthening, the confining pressure was increased (CP2 = 6.89 MPa) and this fracture was closed letting the sample to carry more axial load in the second cycle of the test. At the end of the second cycle of the multi-stage triaxial compression test, a second shear fracture was initiated as shown in Table 3.

Moreover, the confining pressure was increased (CP3 = 10.35 MPa) and these fractures are closed letting the sample regain its initial strength and become able to carry more axial load leading to the initiation of a multi fractures throughout the sample as shown in Table 3.

Fig. 6 represents the failure criteria of the tested sandstone using multi-stage triaxial compression test using one sample only. The UCS data point was inserted into Fig. 6 to prove that UCS value can be estimated from the multi-stage triaxial compression test. The measured UCS is equal to 14 MPa while the estimated UCS (for trend line in Fig. 6) is equal to 13.9 MPa. As shown in Fig. 6, the tested rock gets harder as the confining pressure is increased. In the second and third stages in the MS-TCS test, the adjusted confining pressure managed to hold the failed (fractured) test sample together and almost returned it to its initial intact state.

6. Discussion of results

Based on the previous laboratory results, the mechanism of wellbore strengthening is an analogue to the multi-stage triaxial compression test.

In the MS-TCS test, the series of confining pressure increase are aiding in closing the induced shear fractures in the test sample and recovering the initial strength of the sample which is demonstrat-

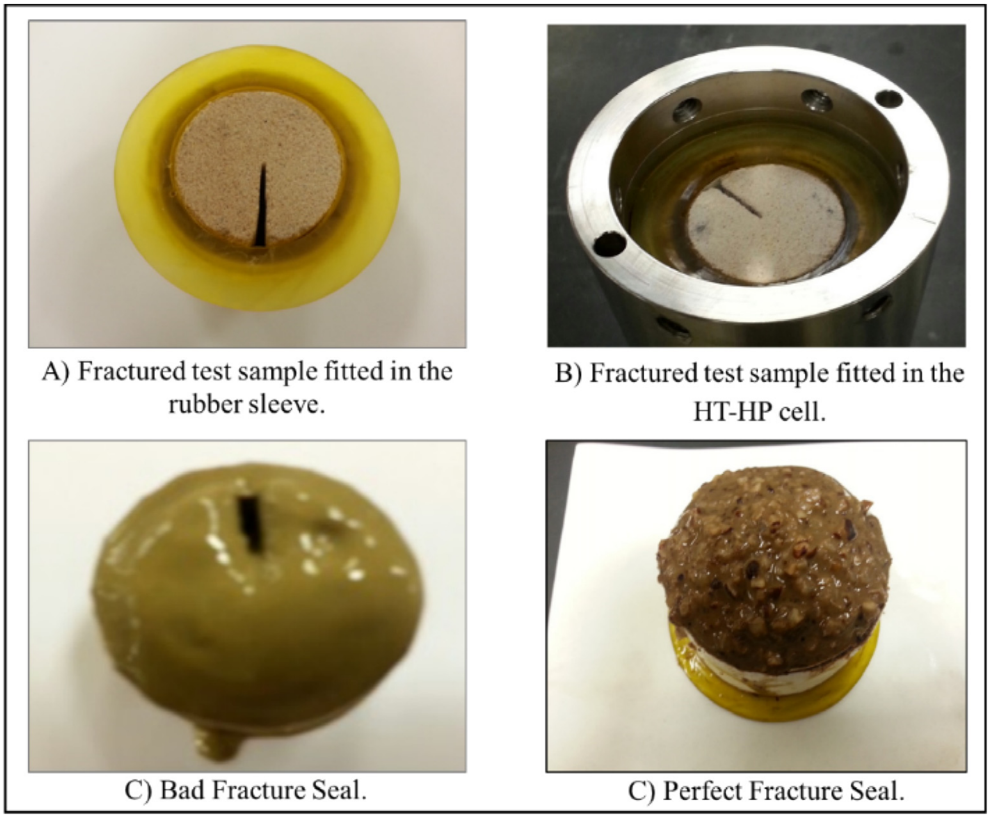


Fig. 5. Wellbore strengthening using crushed dates palm seeds (Musaed and Fattah, 2019).

Table 1
Properties of the tested sandstone.

Rock Type: Artificial (building) sandstone
Color: White, homogenous and free from natural fractures or vugs
Porosity: 30%
Permeability: 266 md

ing exactly how wellbore fractures sealing can lead to wellbore strengthening improvement by the plugging of the existing natural fractures and vugs as shown in Fig. 7.

The theoretical comparison between MS-TCS and wellbore strengthening presented in Fig. 7 can be applied using the results of the experimental work performed in this study as follows:

1. Fig. 6 represents a multi-stage triaxial compression test using one cylindrical core sample. The tested core is homogenous and fracture free.
2. Assuming that the unconfined compressive strength (UCS) of naturally fractured rock is equal to zero, the failure envelope shown in Fig. 6 can be shifted down to intersect with the origin point as shown in Fig. 8.
3. Fig. 8 indicates that even a naturally fractured core sample can exhibit an appreciable strength if a confining pressure is applied. Sealing natural fractures and vugs is exactly equivalent to the applied confining pressure at MS-TCS test.
4. Using the ratio between the measured indirect tensile strength (2.7 MPa) and the measured unconfined compressive strength (14 MPa) and, which is equal to 0.193 for the studied rock, the y-axis of Fig. 8 can be modified to represent the tensile strength while the x-axis title (confining pressure) is replaced by the identical term (wellbore strengthening) as shown in Fig. 9. Furthermore, the UCS value is scaled down to represent the BTS using the 0.193 factor.

Table 2
Experimental results for the UCS and BTS testes.

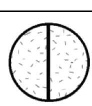
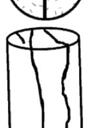
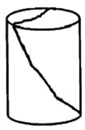
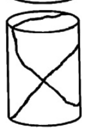
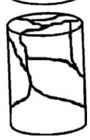
Test type	Sample shape after testing	Sample dimensions				Confining pressure, MPa	Axial stress at failure, MPa
		#	D, mm	L, mm	t, mm		
BTS		1	38.1	–	19.05	CP = 0	2.7
UCS		2	38.1	95.25	–	CP = 0	14.0

Table 3
Experimental results for the MS-TCS test.

Test type	Sample shape after testing	Sample dimensions				Confining pressure, MPa	Axial stress at failure, MPa
		#	D, mm	L, mm	t, mm		
MS-TCS		3	38.1	95.25	–	CP1 = 3.45	18.5
						CP2 = 6.89	25.5
						CP3 = 10.35	42.9

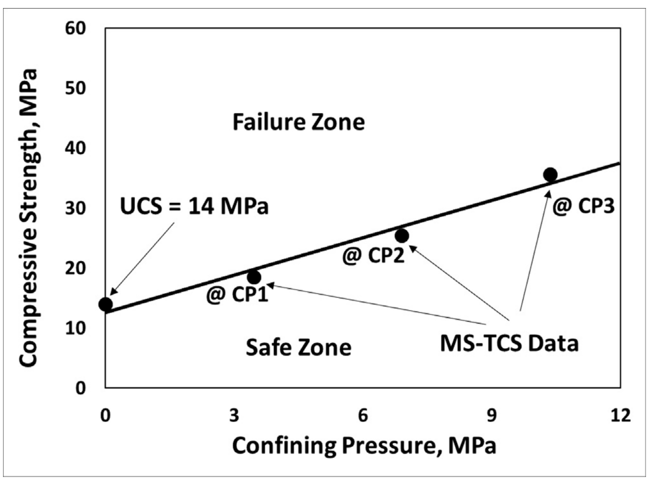


Fig. 6. Failure criteria of the tested rock using MS-TCS test.

5. Hence, the increase in the laboratory applied confining pressure is proportional to the degree of sealing of the formation natural fractures and vugs while drilling. The comparison is reflected by the dotted line in Fig. 9.
6. For example, Musaed and Fattah (2019) used crushed dates palm seeds to seal an artificial open fracture made in core samples cored from the same rock mentioned in Table 1 at temperatures up to 90° as shown in Fig. 5. Crushed Dates palm seeds materials provided excellent wellbore strengthening effect in which the applied wellbore pressure jumped from zero to 6.9 MPa.
7. Assuming fractured rock, enter the x-axis of Fig. 9 with 6.9 MPa to find the tensile strength value equivalent wellbore strengthening effect made by the crushed dates palm seeds material. The value of the equivalent tensile strength is equal to 2.56 MPa.
8. It can be noticed from the above points that, using crushed dates palm seeds fracture seal material has improved wellbore strengthening from zero tensile strength (complete lost

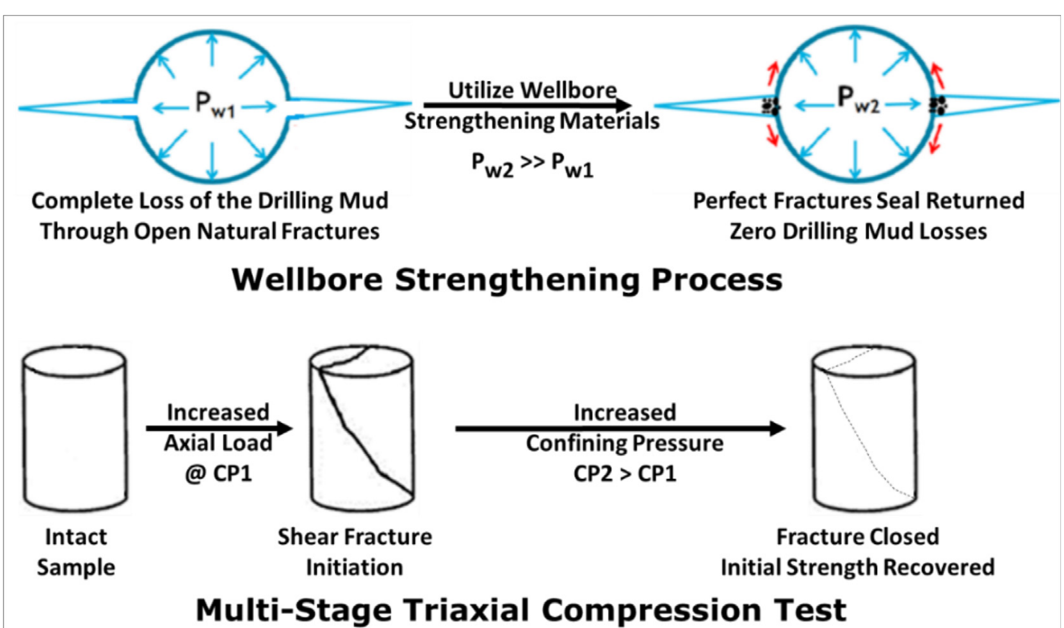


Fig. 7. Comparison between wellbore strengthening and MS-TCS tests.

Please cite this article as: M. N. J. AlAwad, A new approach for understanding the mechanism of wellbore strengthening theory, Journal of King Saud University – Engineering Sciences, https://doi.org/10.1016/j.jksues.2020.07.015

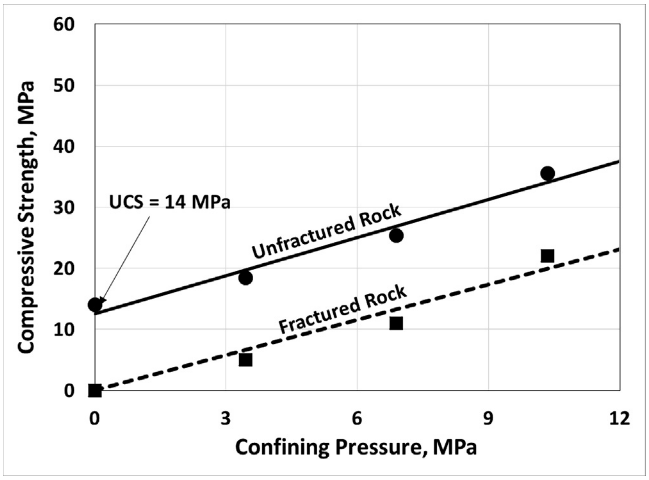


Fig. 8. MS-TCS test result (failure criteria) for the tested sandstone.

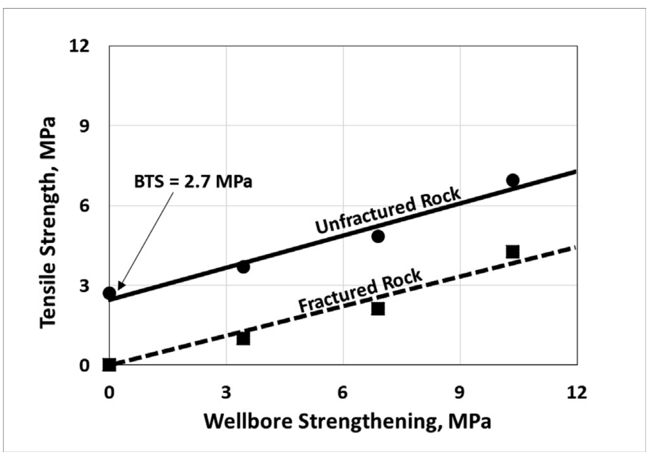


Fig. 9. Wellbore strengthening estimated from the MS-TCS test.

circulation) to 2.56 MPa which is approaching the intrinsic tensile strength of the unfractured similar rock (BTS = 2.7 MPa) with zero fluid loss indicating a prefect wellbore strengthening experiments.

Table 4 and Fig. 10 summarized the overall process of understanding wellbore strengthening using rock mechanical testing (MS-TCS, UCS and BTS). It can be observed in the Eq. (2) that formation fracturing pressure is directly proportional to the tensile strength of the formation. The tensile strength term in Eq. (2) is either the intrinsic (original) tensile strength in case of unfractured formations or a recovered tensile strength gained by the application of wellbore strengthening process in the case of treated fractured formations.

Wellbore strengthening using a proper fracture seal material can recover a tremendous portion of the tensile strength of the formation which in turn increases formation fracturing pressure. Increasing formation fracturing pressure provides a wide, safe and economic mud weight window without loss circulation problems.

7. Conclusions

1. Wellbore strengthening process for a particular rock (formation) can be easily evaluated if samples from the same rock (formation) are tested at laboratory using MS-TCS, UCS, and BTS tests.
2. For the tested sandstone, a wellbore strengthening effect generated by a complete fracture seal using crushed dates palm seeds is equivalent to applying a 6.9 MPa confining pressure on a fractured rock specimen during a multi-stage triaxial compression test.
3. For the tested sandstone, using crushed dates palm seeds as a fracture seal material has improved wellbore strengthening from zero tensile strength (complete mud lost circulation) to 2.56 MPa (zero mud lost circulation) which is approaching the intrinsic tensile strength of the non-fractured similar rock (BTS = 2.7 MPa).

Table 4
Understanding wellbore strengthening using rock mechanics tests.

Process	Conditions
Wellbore strengthening process (Musaed and Fattah, 2019).	Initial: • Rock sample with man-made fracture. • Complete mud loss through the open man-made fracture. • Maximum mud pressure = 0 MPa. • Equivalent tensile strength = 0 MPa Final: • Treatment with crushed dates palm seeds as a fracture seal material. • Zero mud loss with complete fracture seal (plugging). • Maximum allowable mud pressure = 6.9 MPa. • Recovered tensile strength = cannot be evaluated by wellbore strengthening process.
Mechanical tests: MS-TCS, UCS and BTS (This study)	Initial: • Confining pressure = 0 MPa. • Tensile strength = 0 MPa at completely open fracture. • Intrinsic tensile strength for unfractured rock using BTS test = 2.7 MPa. Final: • Plot Fig. 8 from MS-TCS test data. • Use ((BTS/UCS) = 0.193) ratio to convert Fig. 8 to Fig. 9. • Gained confining pressure = 6.9 MPa equivalent to Pw = 6.9 MPa. • Recovered tensile strength = 2.56 MPa estimated using Fig. 9. • Intrinsic tensile strength recovery = (2.56/2.70) = 95%
Summary	A wellbore strengthening effect generated by a complete fracture seal using crushed dates palm seeds is equivalent to applying a 6.9 MPa confining pressure on a fractured rock specimen during a multi-stage triaxial compression test that completely close the shear fracture in the test sample as shown in Fig. 7

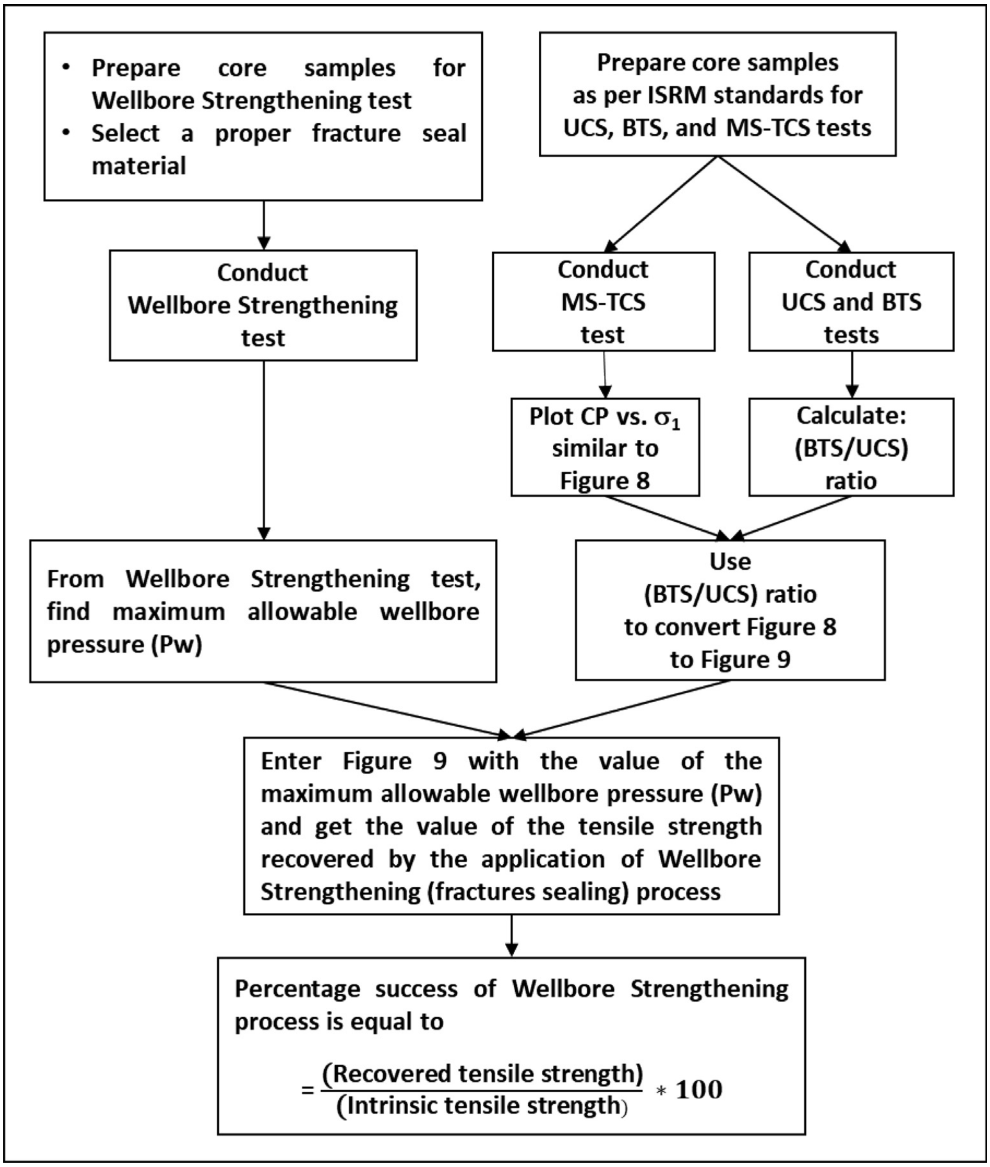


Fig. 10. The mechanism used for understanding wellbore strengthening process.

4. The low tensile strength of formations due to the existence of natural fractures and/or vugs can be improved using proper wellbore strengthening materials. Hence, a wide, safe and economic mud weight window for oil and gas well drilling through can be obtained.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Amanullah, M., 2016. Characteristics, behavior and performance of ARC plug-A date seed-based sized particulate LCM. SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition. Society of Petroleum Engineers.

Biao Ma, Xiaolin Pu, Zhengguo Zhao, Hao Wang, Wenxin Dong. Laboratory study on core fracturing simulations for wellbore strengthening. 2019 Hindawi Geofluids, 2019, 18, 7942064, https://doi.org/10.1155/2019/7942064.

Chellappah, K., Kumar, A., Aston, M., 2015. Drilling depleted sands: challenges associated with wellbore strengthening fluids. 2015 SPE/IADC Drilling Conference and Exhibition. Society of Petroleum Engineers.

Contreras, O., Hareland, G., Husein, M., Nygaard, R., Alsaba, M., 2014. Wellbore strengthening in sandstones by means of nonoparticles-based drilling fluids. A paper presented at the SPE Deepwater drilling and completions conference, Galvestone, Texas, USA, 10–11 September.

El-Sayed, M., Ahmad, E., Moataz, A., Arshad, W., 2007. Successes in curing massive lost circulation problems with a new expansive LCM. SPE/IADC 108290, SPE/IADC Middle East Drilling and Technology Conference and Exhibition, Cairo, Egypt, October 22-24.

Eric, V.O., Omid, S.R., 2014. Wellbore strengthening and casing smear: the common underlying mechanism. IADC/SPE Drilling Conference and Exhibition, Fort Worth, Texas, USA, 4-6 March.

Donald, L., Whitfill, T.H., 2003. All Lost-circulation material and systems are not created equal. SPE 84319, SPE Annual Technical Conference and Exhibition, 5-8 October, Denver, Colorado, October 5-8.

Hong, M.W., Mohamed, Y.S., Brian, F.T., 2008. Investigation of factors for strengthening a wellbore by propping fractures. IDAC/SPE 112629, IADC/SPE Drilling Conference and Exhibition, Orlando, Florida, USA, March 4-6.

ISRM, 2014. The ISRM suggested methods for rock characterization, testing and monitoring 2007–2014. In: Ulusay, R. (Ed.), The International Society for Rock Mechanics and Rock Engineering. Springer, p. 293.

Jaeger, J., Cook, N.G., Robert, Z., 2007. Fundamentals of Rock Mechanics. Wiley-Blackwell, p. 489.

Kumar A., Savari S., Whitfill D.L. Application of fiber laden pill for controlling lost circulation in natural fractures. In: Presented at the AADE National Technical

Conference and Exhibition, Houston, Texas, USA, 12–14 April. AADE-11-NTCE, 2011.

Knudsen K., Gustavo A.L., Andres E.S., Adel A., Rafael M.P. First application of thermal activated resin as unconventional LCM in the Middle East. In: International Petroleum Technology Conference, 10-12 December, Kuala Lumpur, Malaysia, 2014.

Mark W.A., Mclean M.R. A physical model for stress cage. In: SPE Paper No. 90493 Presented at the SPE Annual Technical Conference and Exhibition held in Houston, USA, 26-29, September, 2004.

Mansour, A.K., Taleghani, A.D., 2013. Smart loss circulation materials for drilling highly fractured zones. SPE/IADC Middle East drilling technology conference and exhibition. Society of Petroleum Engineers.

Matthew L.M., Jamison, Dale M., Robert J. Laboratory apparatus improves simulation of lost circulation conditions. In: AADE-13-FTCE-09, A presented at the AADE National Technical Conference and Exhibition, Oklahoma City, OK, February 26–27, 2013.

Musaed N.J. AlAwad. Rock mechanics applications in petroleum engineering practices. In: Oil and Gas European Magazine (International Edition of ERDOIL ERDGAS KOHIL), Germany, Vol. 4, No.1, pp. 18 to 20, December, 1998.

Musaed N. J. AlAwad. The Mechanism of Sand Production Caused by Pore Pressure Fluctuation. In: Oil & Gas Science and Technology Journal – Revue de L'IFP, pp. 339-345, Vol. 56, No. 4, 2001.

Musaed N.J. AlAwad. A rock mechanical model for overbalanced, managed pressure, and underbalanced drilling applications. In: International Journal of Rock Mechanics and Geomechanics for Gas, Petroleum and Water, Vol. 1, no. 2, February, 2016.

Musaed N.J. AlAwad, Fattah K.A. Superior fracture seal material using crushed dates palm seeds for oil and gas well drilling operations. In: Received in Nov. 20, 2016, Published in J. of King Saud Univ., Eng. Sci., Volume #31, p. 97-103, 2019.

Quanxin G., John C., Paul W., Lujun Ji, James E.F. A comprehensive experimental study on wellbore strengthening. In: IDAC/SPE 167957, Presented at the IDAC/SPE Drilling Conference and Exhibition held in Fort Worth, Texas, USA, March 4-6, 2014.

Sanders M.W., Young S., Friedheim J. Development and testing of novel additives for improved wellbore stability and reduced losses. In: AADE-08-DF-HO-19, A paper prepared at the 2008 AADE Fluids Conference and Exhibition, Houston, Texas, April 8–9, 2008.

Wang H.M., Towler B., Soliman M. Fractured wellbore stress analysis: sealing cracks to strengthen a wellbore. In: A paper presented at the SPE/IDAC Drilling Conference, Amsterdam, The Netherlands, February 20–22, 2007.

Yongcun, F., Gray, K.E., 2017. Review of fundamental studies on lost circulation and wellbore strengthening. J. Pet. Sci. Eng.,. https://doi.org/10.1016/j.petrol.2017.01.052. 0920-4105.

Please cite this article as: M. N. J. AlAwad, A new approach for understanding the mechanism of wellbore strengthening theory, Journal of King Saud University – Engineering Sciences, https://doi.org/10.1016/j.jksues.2020.07.015