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Effect of Mechanical and Geometrical Properties of Cement on Wellbore Stability Using 3-D Analysis

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Abstract

Especially in the long term, the role of the mechanical and geometrical properties of cement is very important to prevent cement failure and wellbore instability. Cement failure is the result of developed plastic strain. In this study, based on the Drucker-Prager criterion and using 3-D finite element analysis, the role of the mechanical and geometrical properties of cement on its stability are scrutinized. In addition, because cement must be designed based on the properties that are the least horizontal stress sensitive, to prevent cement failure and wellbore instability in the long term, stress sensitivity analysis is done. According to the results, when cement is in the plastic mode, improving the mechanical properties of the cement (either Young's modulus or Poisson's ratio or uniaxial compressive strength) could be helpful to prevent plastic strain development in cement. However, in such conditions, an increase of the cement's thickness might be helpful. When the casing is not located in the center of the well, where the ratio of the cement thickness to the casing thickness is less than one, plastic strain will develop in the cement if the cement's mechanical properties are weak. The results show that by increasing Poisson's ratio of the cement, developed plastic strain in the cement decreases logarithmically. Moreover, by increasing either cohesion or the internal friction angle of the cement, the developed plastic strain in the cement decreases exponentially. In addition, among the cement's mechanical properties, Poisson's ratio and elastic modulus are the least horizontal stress sensitive ones.

Keywords: Cement, stability, plastic strain, finite element, 3-D analysis

Introduction

The wellbore stability is considered as one of the critical problems in well drilling operations. Instability leads to wasting much time and money in all areas of the world. Therefore, the analysis and prediction of wellbore stability are very important [1,2]. The plastic strain development at the wellbore wall results in the instability. Therefore, to prevent instability, accurate analysis of the induced stresses and their effects on the stability is necessary for suitable design of casing and cement. Because the cement is mechanically weaker than the casing and the rock, cement failure is more probable. Therefore, especially in the long term, the cement has a very important role in preventing wellbore instability. On the other hand, because the cement is more controllable than the casing for a design standpoint, a study of the cement design and its effect on the wellbore stability is more interesting than the casing design in recent years. Many laboratory studies concerning cement design have been done; e.g. Darbe *et al*. [3] have evaluated the effect of elastomers and fibers additives on the mechanical properties of the cement by using uniaxial compressive tests. Because the laboratory design and testing of the mechanical and geometrical properties of the cement are very expensive and time consuming, numerical methods are more advantageous for this purpose. Shahri [4], using a 2-D finite element method (FEM), studied the effect of changing temperature on cement stability. He has shown that changing temperature can cause unexpected behavior in the cement sheath, which leads to failure in the casing/cement bond. Hyunil [5] has developed comprehensive analytical and numerical models to explain near wellbore phenomena such as cement failure. By using plane strain analysis, he has shown that Young's modulus of the cement and wellbore pressure are important factors in cement failure. In this study, based on the Drucker-Prager criterion and using a 3-D finite element analysis, the role of the mechanical and geometrical properties of the cement on strain development in the cement and the cement failure are scrutinized. In addition, because the cement must be designed based on the properties that are the least horizontal stress sensitive to prevent cement failure and wellbore instability in the long term, stress sensitivity analysis is done.

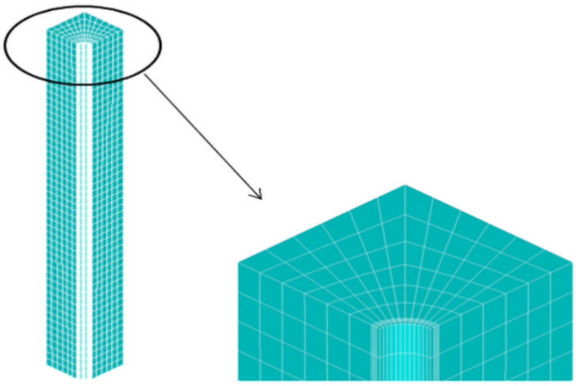
Materials and methods

In this study, based on FEM, 3-dimensional modeling has been used to investigate the role of the mechanical and geometrical properties of cement on strain development in the cement and cement failure. FEM is a tool for better understanding of how a design will be made under different sets of impacts or stresses under certain conditions. FEM is a computer-based mathematical representation method of solving problems numerically. Since this is a numerical solver, the answer is not exact. It works based on material properties, type of model, and boundary conditions. Since the finite element is a simultaneous multi-partial-differential equations solver, it is a time saver. Finite elements can handle complex boundary conditions; that is why we still use this type of programming for investigating problems more realistically than the FDM [4,6,7].

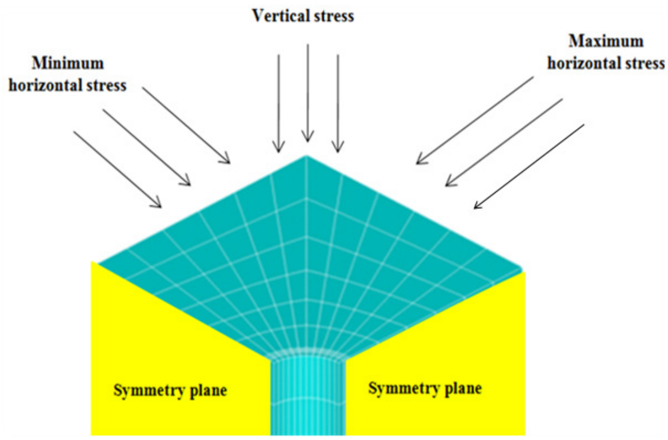
The studied well is located in one of the Iranian southwest oil fields. The height of the model is 5 meters and its length and width are 5 times the radius of the open hole well. The element of SOLID95 was used for the analysis of the model. This element consists of 20 nodes and 3 degrees of freedom in each node. This element may have any spatial orientation and has plasticity, stress stiffening, large deflection, and large strain capabilities. To analyze the contact surface of cement/casing and cement/rock, contact elements included CONTACT174 and TARGET170 were applied. Due to the existence of axial symmetry in the geometry, only a quarter of the model is considered to reduce the computation time and cost (**Figure 1**). Both the horizontal and vertical stress were applied as 3-dimensional. Because the elements must also be affected by their own weight, gravity was defined as a volumetric load. The model was fixed in the bottom. The schematic of the 3-D loading is shown in **Figure 1a**.

Mechanical properties of the rock, cement, casing and stresses values are listed in **Table 1**. Also, the geometrical characteristics of the well and casing are listed in **Table 2**. In this study, the Drucker- Prager yield criterion is used for investigation of the plastic strain. In this criterion, the yield surface will not change by increasing yield, so there is no hardening rule and the material is perfectly elastic-plastic [10].

The constructed model was calibrated by determination of the mud weight for the open hole well. In other words, the hydrostatic pressure equivalent to reported drilling mud weight from the drilling site was applied and the model settings, especially the number of the meshes, were adjusted such that the open hole well is in the stability mode. This operation was done at 2 different depths.



(a)



(b)

Figure 1 (a) The geometry of the model and (b) schematic of the 3-D loading.

Table 1 Mechanical properties and values of the stresses.

Property	Material		
	Rock	**Cement**	**Casing**
Young's modulus (GPa)	20	8.3	200
Density (kg/m^3)	2280	1570	3000
Poisson's ratio	0.25	0.1	0.27
Cohesion (MPa)	2	1.5	-
Internal friction angle (Degree)	25	20	-
Vertical stress (MPa)	68	7	47.5
Maximum horizontal stress (MPa)	79.2	-	-
Minimum horizontal stress (MPa)	58.1	-	-
Pore pressure (MPa)	33	-	-
Hydrostatic pressure equivalent to the well fluid (MPa)	-	-	43

Table 2 Geometrical characteristics of the system.

Property	Well (Open hole)	Casing
Inner diameter (in)	8.75	6.184
Outer diameter (in)	-	7
Eccentricity (%)	0	0
Inclination (degree)	0	0

By using the constructed model, the role of the geometrical and mechanical properties (Young's modulus, Poisson's ratio, uniaxial compressive strength and cement thickness) of the cement on the cement failure were scrutinized. The Young's modulus is one of the most important mechanical properties of cement. It is a good basis for the flexibility of each medium or solid [4]. If this parameter is too low, the medium will act plastically. However, if this number is low, the range of stresses which can be handled by the system will increase [2]. The stress ratio, which is the ratio of equivalent stress to yield stress, is used to investigate role of the Young's modulus on the cement behavior. If the stress ratio is less than one, the material (cement) will be in the elastic mode; however, if it is equal to or greater than one, the material (cement) is in the plastic mode [7,8]. Poisson's ratio measures the ratio of lateral strain to axial strain in the direction of the applied force. Therefore, it could be an important parameter in material (cement) deformation. Uniaxial compressive strength is another one of the most important mechanical properties of rock material which is used in analysis and modeling. It is the most common measure of compressive strength. Compressive strength is the capacity of a material to withstand axially directed compressive forces.

Results and discussion

To investigate the role of the mechanical and geometrical properties of the cement on cement stability, under different values of mechanical and geometrical properties the developed plastic strains in the cement were obtained and analyzed.

Figure 2 shows the effect of the Young's modulus on the cement behavior in the cement/casing contact location. According to **Figure 2**, when the Young's modulus of the cement is different from the Young's modulus of the rock, the cement acts as a separate layer and has a ductile behavior and plastic strain develops in it. When the Young's modulus of the cement is close to the value of the Young's modulus of the rock, rock and cement act as a uniform layer. In such conditions, the development of plastic strain is decreased and the cement is in an elastic mode (**Figure 2**). By increasing the Young's modulus of the cement, when the cement is in an elastic mode, the elastic strain developed in the cement decreases linearly (**Figure 3**).

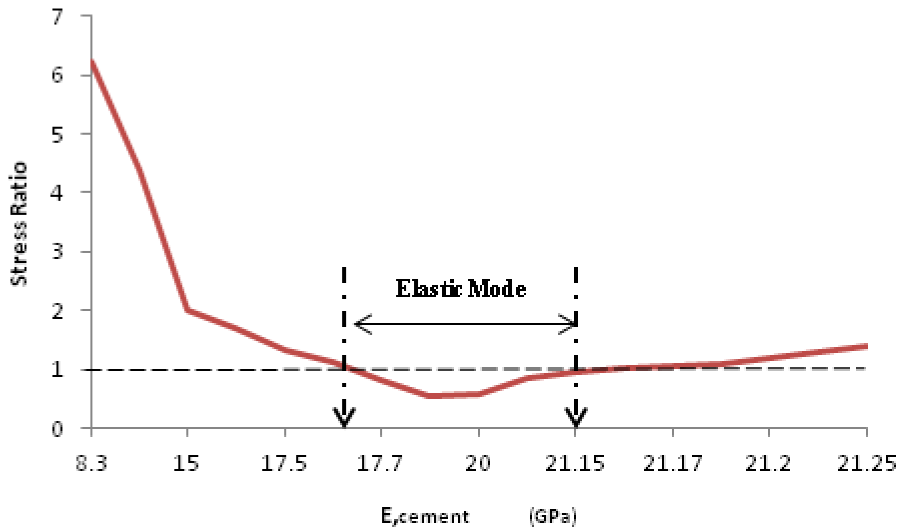


Figure 2 Effect of the Young's modulus on the cement behavior in contact with the casing.

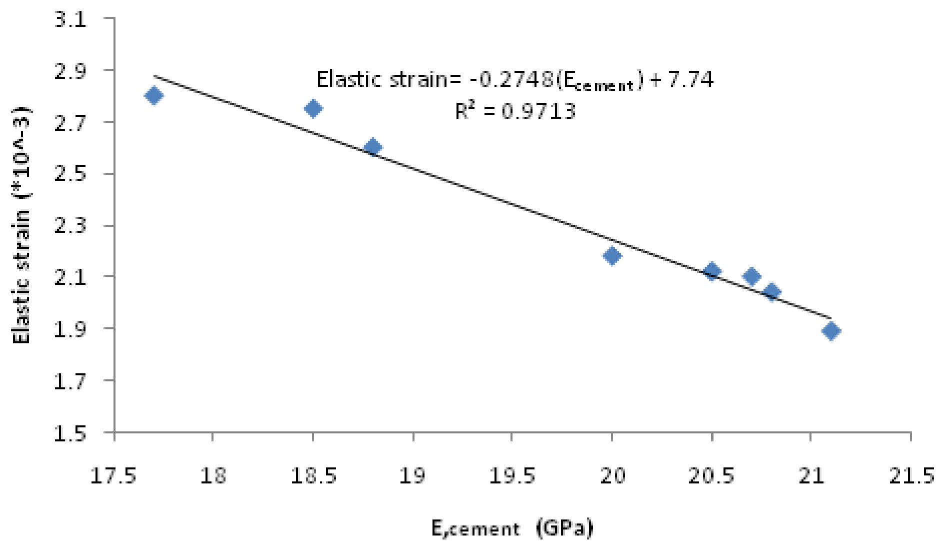


Figure 3 Developed elastic strain in the elastic cement in contact with the casing.

Figure 4 shows the effect of Poisson's ratio on the portion of developed plastic and elastic strain in the cement in contact with the casing. According to **Figure 4**, by increasing Poisson's ratio of the cement, the total mechanical strain decreases, and the portion of elastic strain from the total mechanical strain increases but the portion of the plastic strain from the total mechanical strain decreases. **Figure 5** shows that by increasing the Poisson's ratio of the cement, the plastic strain developed in the cement decreases logarithmically.

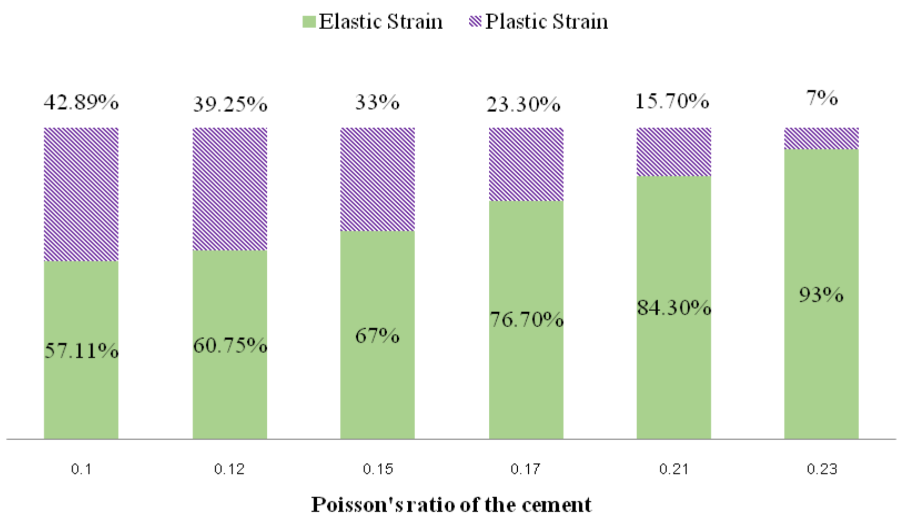


Figure 4 Effect of Poisson's ratio on the portion of developed plastic and elastic strain in the cement in contact with the casing.

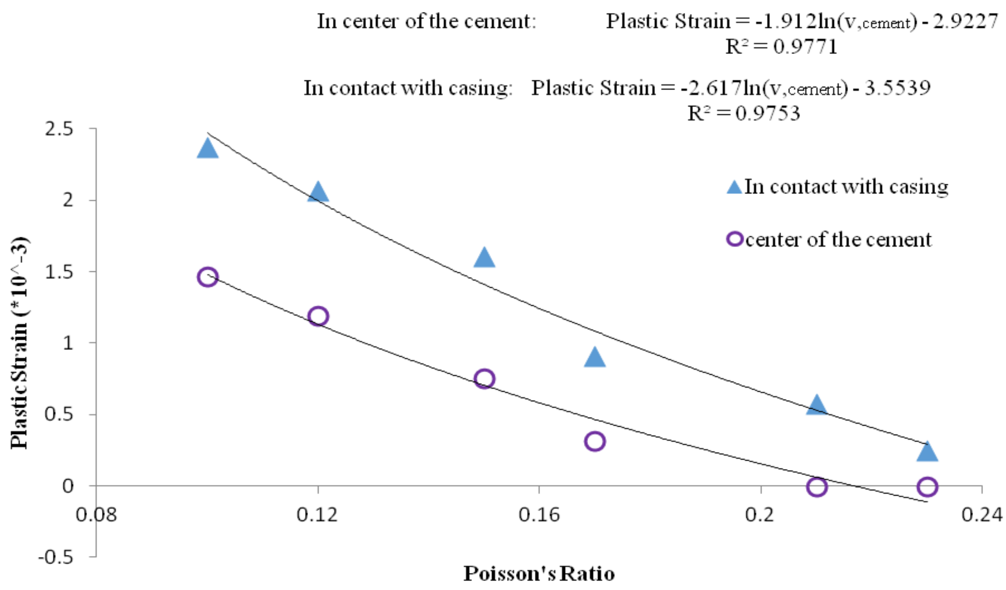


Figure 5 Effect of Poisson's ratio on developed plastic strain in the cement in contact with the casing.

Uniaxial compressive strength (UCS) is another mechanical property of cement. UCS is a function of the internal friction angle, phi, and cohesion, C {Eq. (1)}. Therefore, the effect of the internal friction angle and cohesion could be investigated instead of uniaxial compressive strength.

$$UCS = \frac{2*C*\cos(phi)}{1-\sin(phi)} \tag{1}$$

Figures 6 and **7** show the effects of the cement's cohesion and its internal friction angle on the development of plastic strain in the cement in contact with the casing, respectively. According to **Figure 6**, by increasing the cement's cohesion, the plastic strain developed in the cement decreases exponentially. According to **Figure 7**, by increasing the cement's internal friction angle, the plastic strain developed in the cement decreases exponentially. Therefore, by increasing the cement's UCS, either by increasing the cement's internal friction angle or by increasing the cement's cohesion, the plastic strain developed in the cement decreases exponentially.

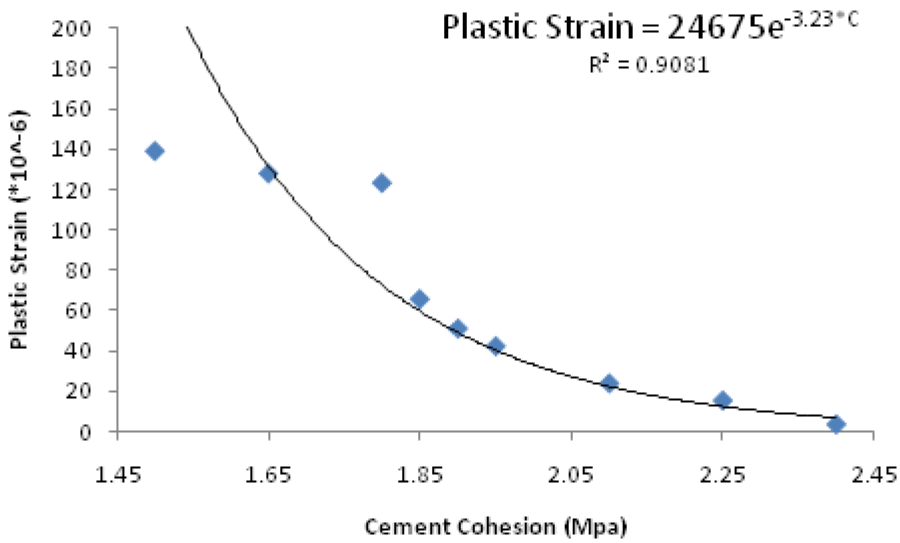


Figure 6 Effect of cohesion on the developed plastic strain in the cement in contact with the casing.

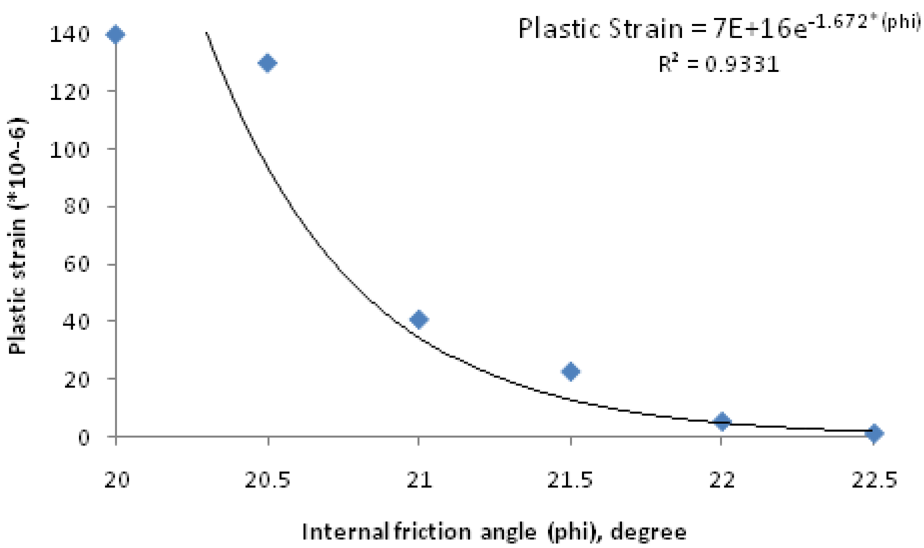


Figure 7 Effect of internal friction angle on the developed plastic strain in the cement in contact with the casing.

The role of the cement's thickness in cement stability could be investigated in two cases: 1) the case that the cement is in the elastic mode. 2) the case that the cement is in the plastic mode. According to **Figure 2**, the cement is in the elastic mode from 17.65 GPa up to 21 GPa of the Young's modulus of the cement. By talking the Young's modulus of the cement equal to 19 GPa (other data are the same as that listed in **Table 1**), the role of the cement's thickness could be investigated in the case that the cement is in the elastic mode. The amounts of developed mechanical strains in the cement for different values of ratio of cement's thickness to casing's thickness are listed in **Table 3** (the casing's thickness is constant). According to **Table 3**, maximum strains occur at the location of the cement in contact with the casing. When the ratio of cement's thickness to casing's thickness is less than one, a plastic strain develops in the cement (**Table 3**).

Table 3 Developed mechanical strains in the cement.

(Cement/casing) thickness ratio, (in/in)	In contact with the formation			In the center of the cement			In contact with the casing		
	Total mechanical strain ($\times 10^{-3}$)	Elastic strain ($\times 10^{-3}$)	Plastic strain ($\times 10^{-3}$)	Total mechanical strain ($\times 10^{-3}$)	Elastic strain ($\times 10^{-3}$)	Plastic strain ($\times 10^{-3}$)	Total mechanical strain ($\times 10^{-3}$)	Elastic strain ($\times 10^{-3}$)	Plastic strain ($\times 10^{-3}$)
0.8	1.819	0.179	1.64	1.76	0.179	1.58	1.853	0.183	1.67
1	1.60	0.13	1.47	1.56	0.137	1.428	1.718	0.138	1.58
1.2	1.13	1.13	0	1.11	1.11	0	1.1	1.1	0
1.5	1.21	1.21	0	1.35	1.35	0	1.72	1.72	0
1.68	1.357	1.357	0	1.64	1.64	0	2.38	2.38	0

According to **Figure 2**, the cement is in the plastic mode when its Young's modulus is less than 17.6 GPa and above of 21.15 GPa. **Figures 8a** and **8b** show the developed plastic strain in the cement for the different values of the ratio of cement's thickness to casing's thickness when the cement's Young's modulus is equal to 25 and 8 GPa, respectively. According to **Figures 8a** and **8b**, an increase in the cement's thickness could be helpful to prevent cement failure when the Young's modulus of the cement is greater than the Young's modulus of the rock (**Figure 8a**). However, an increase in the cement's thickness would not prevent cement failure when the Young's modulus of the cement is significantly less than the Young's modulus of the rock (**Figure 8b**).

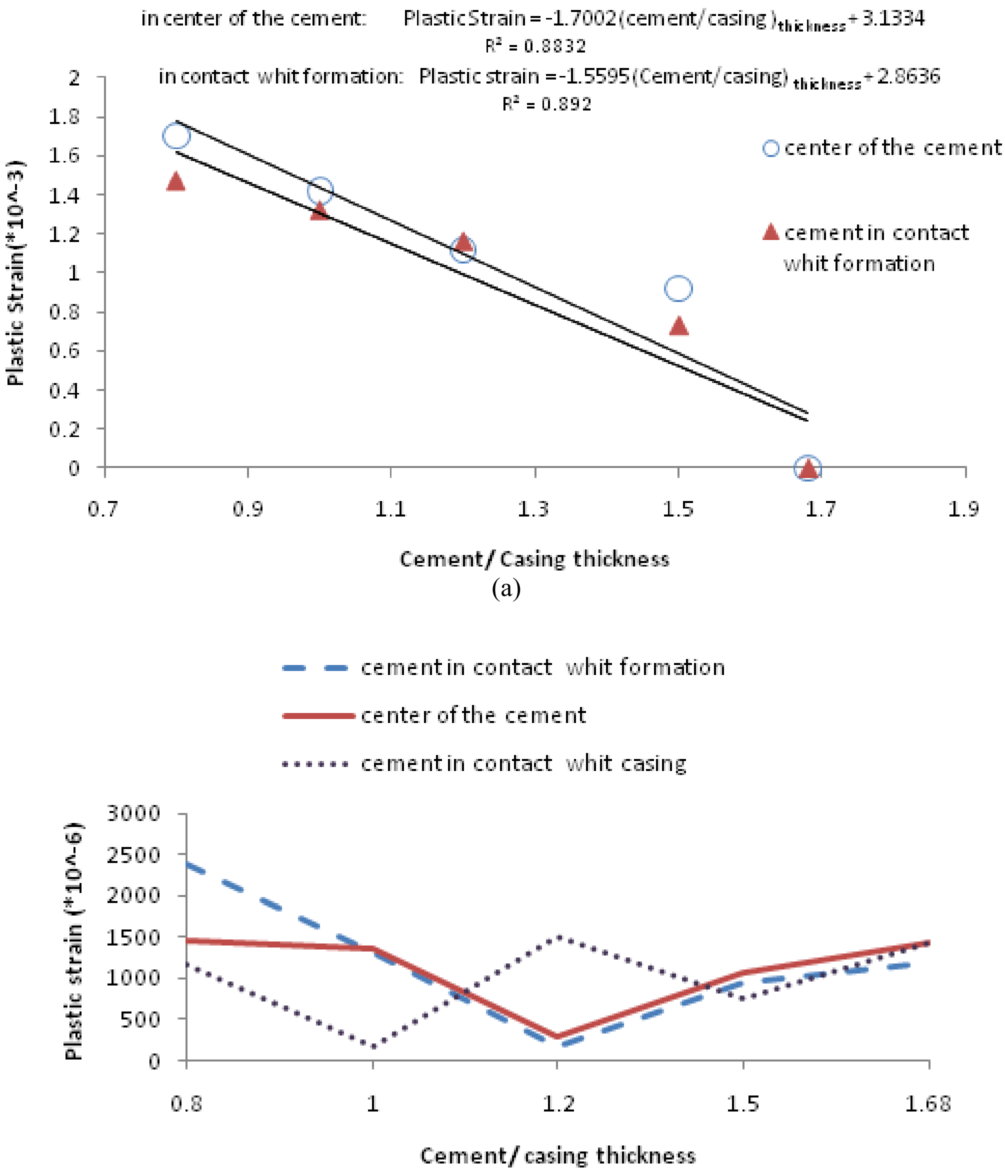


Figure 8 Effect of cement/casing thickness on the developed plastic strain in the cement in contact with the casing (a) Young's modulus = 25 GPa and (b) Young's modulus = 8 GPa.

Therefore, according to the above results, when the casing is not located in the center of the well, where the ratio of cement thickness to the casing thickness is less than one, plastic strain will develop in the cement if the cement's mechanical properties is weak. In plastic formations, especially in salt formations, horizontal stresses and thereby the induced stresses on the wellbore wall are increased with increasing time. Actually, this is the result of the creep phenomenon. Therefore, to prevent cement failure and wellbore instability in the long term, the cement must be designed based on the cement's mechanical properties so that they are less sensitive to horizontal stress. According to **Figures 2** and **5**, the optimum values of the Young's modulus and Poisson's ratio of the cement are 17.7 GPa and 0.23, respectively (because there is no plastic strain or the developed plastic strain in the cement is at minimum at these amounts) and according to **Figures 6** and **7**, the optimum values of cohesion and internal friction angle of the cement are 2.4 MPa and 22.5 degrees (because the developed plastic strain in the cement is at minimum for these amounts), respectively.

To investigate the stress sensitivity of each property, the optimum values of the parameters have been used and values of other parameters are the same as that listed in the **Table 1**. Then, the horizontal stresses were increased gradually. The results of the stress sensitivity analysis could be seen in **Table 4**. According to **Table 4**, among the cement mechanical properties, the cohesion is the most horizontal stress sensitive one but Poisson's ratio is the less horizontal stress sensitive one.

Table 4 Results of the stress sensitivity analysis.

$K = \frac{\sigma_H}{\sigma_h}$	Developed plastic strain in the cement in contact with the casing *(10^{-6})			
	Investigated parameter: Young's modulus	**Investigated parameter: Poisson's ratio**	**Investigated parameter: Internal friction angle**	**Investigated parameter: Cohesion**
1.36	0	0	0	0
1.50	0	0	0	0
1.64	0	0	0	0
1.70	0	0	0	1.14
2.00	0	0	0.95	138
2.50	139	0	862	1204

σ_H: Maximum horizontal stress, (MPa); σ_h: Minimum horizontal stress, (MPa)

Conclusions

1) When the Young's modulus of the cement is close to the value of the Young's modulus of the rock, the rock and the cement act as a uniform layer. In such conditions, the development of plastic strain is decreased and the cement is in an elastic mode. Moreover, by increasing the Young's modulus of the cement, when the cement is in an elastic mode, the elastic strain in the cement decreases linearly.

2) By increasing the cement's Poisson's ratio, the total mechanical strain decreases and the proportion of elastic strain from the total mechanical strain increases but the proportion of the plastic strain from the total mechanical strain decreases. Therefore, increasing the Poisson's ratio results in more flexibility. Moreover, by increasing the Poisson's ratio of the cement, the plastic strain in the cement logarithmically decreases.

3) Increasing the uniaxial compressive strength, either by increasing cohesion or increasing internal friction angle, results in prevention of cement failure.

4) Because Poisson's ratio is less horizontally stress sensitive among the cement's mechanical properties, cements with higher Poison's ratio are more stable in the long term.

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