Effect of the variations of clinker composition on the poroelastic properties of hardened class G cement paste

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Abstract

The effect of the variations of clinker composition on the poroelastic properties of class G oil-well cement pastes is studied using a multiscale homogenization model. The model has been calibrated in a previous work based on the results of a laboratory study. Various compositions of class G cements from literature are used in a hydration model to evaluate the volume fractions of the microstructure constituents of hardened cement paste. The poroelastic parameters such as drained bulk modulus, Biot coefficient, Skempton coefficient are evaluated using the homogenization model. The results show that the variations in chemical composition of class G cements have not an important effect on the variations of the poroelastic properties.

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1. Introduction

Oil-well cements have a wide application in exploration and production of oil and gas, and also for sealing water wells, waste disposal wells and geothermal wells. The American Petroleum Institute (API) Standard specifies eight classes of oil-well cements for use at different well depths and conditions. Oil-well cements are specified in classes A to H and different grades corresponding to ordinary (O), medium sulphate-resistant (MSR) and high sulphate-resistant (HSR) [1]. These classes of oil-well cement have different requirements in terms of chemical composition and physical properties. For example, the HSR class G cement requires, among other specifications, a C_3S volume fraction between 0.48 and 0.65, C_3A volume fraction smaller than 0.03 and C_4AF volume fraction smaller than 0.24. Among these oil-well cements, the classes G and H are the most widely used ones.

The knowledge of the poromechanical behaviour of the oil-well cement is essential for the prediction of the well performance during the life of the well. Recently, Ghabezloo et al. [2, 3, 4, 5] studied experimentally the thermo-poro-mechanical behaviour of a hardened oil-well cement paste. The evaluated poroelastic parameters are presented in Table (1) in which K_d and K_u are respectively drained and undrained bulk modulus, G is shear modulus, b and B are respectively Biot and Skempton coefficients. The definitions of these parameters are presented in [3]. These parameters are evaluated for a cement paste prepared with a class G cement at w/c=0.44 and hydrated at 90 °C for at least 90 days in saturated condition. It is known that the physical and mechanical properties of cement paste vary with clinker composition, water-to-cement ratio, cement age and curing conditions. Because of its very low permeability, the complete characterization of the poromechanical properties of the hardened cement past in an experimental study would be very expensive and time consuming. It is thus interesting to find alternative ways to evaluate the poroelastic properties of cement pastes corresponding to different conditions. This is done by Ghabezloo [6, 7] by association of the experimental re-

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sults of Ghabezloo et al. [2, 3, 4] with micromechanics modelling and homogenization method. A multi-scale homogenization model is calibrated on the experimental results and is used to extrapolate the thermo-poro-elastic parameters to cement pastes with different water-to-cement ratios. These parameters, which are evaluated experimentally for w/c=0.44, are predicted using the homogenization model for w/c between 0.4 and 0.65. The predictive capacity of the model is verified in [6] by comparing the evaluated Young's modulus with some experimental results from literature. The model permits also the evaluations of pore volume bulk modulus and thermal expansion which are difficult to evaluate experimentally. This homogenization model is used here to study the effect of the variations in the composition of class G cement on its poroelastic properties.

Table 1: Experimentally evaluated poroelastic parameters of hardened class G cement paste [2, 3] (w/c=0.44, hydrated at 90°C and tested at laboratory temperature)

K_d (GPa)	b (-)	G (GPa)	B (-)	K_u (GPa)
8.7	0.59	5.7	0.4	11.2

For each class of oil-well cement, API specifies requirements in terms of maximum volume fractions of different constituents of clinker, but within these limitations the exact composition of the clinker may be different from one cement to another. Table (2) presents the compositions of five different class G cements from literature. The experimental study of Ghabezloo et al. [3] is performed using the cement G1.

Table 2: Compositions of different class G oil-well cements

Cement	C_3S	C_2S	C_3A	C_4AF	Reference
G1	0.629	0.140	0.018	0.126	[3]
G2	0.512	0.270	0.023	0.144	[8]
G3	0.612	0.152	0.005	0.160	[9]
G4	0.589	0.152	0.023	0.192	[10]
G5	0.604	0.172	0.037	0.156	[11]

Notations: C: CaO, S: SiO_2, A: Al_2O_3, F: Fe_2O_3

Regarding these variations in the clinker composition an interesting question is raised: Is it possible to use the poroelastic parameters evaluated for cement G1 to other class G cements? In other words, what is the effect of the variations of the chemical composition of class G cements on their poroelastic properties? This question is studied in this paper using the homogenization model calibrated by Ghabezloo [6] for the poroelastic properties of the hardened cement paste.

2. Clinker composition and cement paste microstructure

The cement clinker is composed of four main phases: C_3S, C_2S, C_3A and C_4AF where in the standard cement chemistry the notation C stands for CaO, S for SiO_2, A for Al_2O_3 and F for Fe_2O_3. The setting and hardening of the cement paste are the results of complex reactions, called hydration reactions, between clinker phases and water. In a simplified view, the main phases of the microstructure of the cement paste are calcium-silicate-hydrate (C-S-H), Portlandite (CH), Aluminates (AL), unhydrated clinkers (CK) and macro-porosity (V). More details about the microstructure of cement paste are presented in [6]. The homogenization method needs the evaluation of the volume fractions of different constituents of the microstructure of cement paste. These volume fractions can be evaluated by knowing cement composition, water-to-cement ratio and degree of hydration, using the method presented by Bernard et al. [12] which is explained in details in [6]. This method assumes simple stoichiometric reactions for the hydration of the four dominant compounds in Portland cement. The complete set of chemical reactions is presented in [13]. The following relations show the production of C-S-H and CH during the hydration of C_3S and C_2S:

$$\begin{aligned} C_3S + 5.3H &\rightarrow C_{1.7} - S - H_4 + 1.3CH \\ C_2S + 4.3H &\rightarrow C_{1.7} - S - H_4 + 0.3CH \end{aligned} \tag{1}$$

For the cements presented in Table (2) the volume fractions of the microstructure phases are calculated considering w/c=0.44 and complete hydration. The results, presented in Table (3), show the effect of variations of clinker composition on the volume fractions of microstructure phases. The variations of volume fractions of C-S-H, CH and AL are smaller than 6% and the macro-porosity variations are only about 1%.

3. Effect of clinker composition on the poroelastic properties

The homogenization model permits the evaluation of the poroelastic properties of cement paste by knowing the volume fractions and the elastic parameters of different microstructure phases. This model is calibrated based on the experimental results presented in [2, 3] and

Table 3: Volume fractions of the microstructure phases of fully hydrated cement paste (w/c=0.44)

Cement	C-S-H	CH	AL	CK	V
G1	0.575	0.183	0.130	0.00	0.112
G2	0.591	0.155	0.148	0.00	0.106
G3	0.565	0.176	0.142	0.00	0.117
G4	0.533	0.165	0.190	0.00	0.112
G5	0.554	0.168	0.172	0.00	0.106

is explained in details in [6, 7]. The needed volume fractions are presented in Table (3) and the elastic parameters of the microstructure constituents are given in [6]. The poroelastic parameters of the oil-well cements of Table (2) are evaluated using the homogenization model and presented in Table (4).

Table 4: Poroelastic parameters of different class G cements

Cement	K_d (GPa)	b (-)	G (GPa)	B (-)	K_u (GPa)
G1	8.54	0.598	5.76	0.392	11.15
G2	8.40	0.598	5.71	0.396	11.00
G3	8.35	0.606	5.65	0.396	10.99
G4	8.35	0.603	5.66	0.396	10.97
G5	8.53	0.595	5.77	0.396	11.16

The predicted parameters for different cements vary in a very narrow range. The drained bulk modulus varies between 8.35 and 8.54 GPa that is less than 5% variation. Similarly, Biot and Skempton coefficients, the shear modulus and the undrained bulk modulus show small variations due to the difference between the chemical compositions of class G cements. These small variations are mainly due to the small variations of volume fractions of microstructure constituents in Table (3). The results show that the variations of the clinker composition, in the limits of the values in Table (2), have not an important effect on the poroelastic properties of hardened class G cement paste.

4. Conclusions

The effect of the variations of clinker composition on the poroelastic properties of class G oil-well cement pastes is studied using a multiscale homogenization model. Various chemical compositions of class G cements from literature are used to evaluate the poroelastic parameters of the hardened cement paste such as drained bulk modulus, Biot coefficient, Skempton coefficient, etc. The results show that the difference in the chemical compositions of these cements has not an important effect on the variations of the poroelastic properties. The variation of the drained bulk modulus of different cements at the same water-to-cement ratio is evaluated less than 5%. Consequently the poroelastic parameters evaluated by Ghabezloo et al. [2, 3] can be used for other class G cement pastes corresponding to different clinker compositions. The use of homogenization method permits to extrapolate the results of an experimental study on a particular cement paste to other cement pastes with different chemical composition. This is a considerable advantage that gives the possibility of parametric study and reduces the number of needed tests to evaluate the poroelastic properties of cement pastes corresponding to different conditions.

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