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Pore Compressibility in Rocks

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ABSTRACT: The unjacketed pore compressibility in a porous rock is the change in pore volume due to change in pore pressure for constant differential pressure. This parameter affects how the saturated bulk modulus of a rock is related to the drained frame modulus and the pore fluid compressibility. Recent measurements of poroelastic constants and effective medium theories are used to estimate how the pore compressibility depends on effective stress and how uncertainty in the pore compressibility affects uncertainty in Gassmann's equation estimates of the saturated bulk modulus. Results for Berea sandstone and for models of sand-clay mixtures show that the estimate of the change in the saturated bulk modulus due to substitution of different fluids in the rock may differ in size by a factor of two or more if the pore compressibility is approximately equal to the fluid compressibility instead of the grain compressibility. In general, the order of magnitude and sign of the pore compressibility cannot be determined from solid and fluid compressibility information alone.

1 INTRODUCTION

In the quasi-static limit, Gassmann's equation relates the bulk modulus K_{sat} of a saturated porous rock to the bulk modulus K_d of the drained rock and the properties of the fluid and solid components of the rock:

$$K_{sat} - K_d = \frac{\alpha^2}{\alpha/K_s + \phi\,(1/K_f - 1/K_\phi)} \tag{1}$$

(Gassmann, 1951; Biot & Willis, 1957; Brown & Korringa, 1975). Here ϕ is the porosity of the rock, K_f is the bulk modulus of the pore fluid, K_s is the unjacketed bulk modulus related to the solid components of the rock, $1/K_\phi$ is the unjacketed pore compressibility, and α is the Biot-Willis coefficient $\alpha = 1 - K_d/K_s$ (Biot & Willis, 1957; Brown & Korringa, 1975; Rice & Cleary, 1976). It is common practice in the oil and gas industry to use Gassmann's equation to estimate how different pore fluids change the bulk modulus of the saturated rock, for interpretation of sonic logs or amplitude anomalies seen in seismic reflection data (e.g., Brown & Korringa, 1975; Blangy et al., 1993; Murphy et al., 1993).

The dependence of the saturated rock's bulk modulus on the fluid bulk modulus is contained in the term $\phi(1/K_f - 1/K_\phi)$ in Gassmann's equation. Estimates of the unjacketed pore modulus K_ϕ are required when calculating how K_{sat} changes for different values of K_f. K_ϕ is defined by

$$\frac{1}{K_\phi} \equiv -\frac{1}{V_\phi}\left(\frac{\partial V_\phi}{\partial p_f}\right)_{p_d=const.} \tag{2}$$

(Gassmann, 1951; Biot & Willis, 1957; Brown & Korringa, 1975; Rice & Cleary, 1976). The rock is assumed to have a total volume V and a pore volume V_ϕ where $V_\phi \equiv \phi V$.

For homogeneous porous media, K_ϕ is exactly the same as K_s, where K_s in this case is the bulk modulus of a solid grain in the rock (Brown & Korringa, 1975; Rice & Cleary, 1976). But if the porous rock contains more than one kind of solid, then K_ϕ is independent of K_s. In general, the value of K_ϕ is not bounded by the bulk moduli of the solid components (Berryman & Milton, 1991; Berryman, 1992). K_ϕ can even have a negative sign, if the bulk moduli of the solid components are greatly different from each other (i.e., vary by a factor of about five or more), as may be possible for sand-clay mixtures (Berge & Berryman, 1995; Berge, 1998).

The parameter K_ϕ is extremely difficult to measure, because such a measurement requires an accurate determination of small changes in pore volume, while avoiding the measurement uncertainties caused by having a pore fluid reservoir with a volume that would be significant compared to the pore volume, or uncertainties caused by tubing between the rock sample and the transducer measuring the change in pore fluid pressure. To date, there are no reliable measurements of K_ϕ for any porous rock (Berge & Berryman, 1995), although K_ϕ values can be estimated using measurements of Skempton's (Skempton, 1954) pore pressure buildup coefficient B (e.g., Green & Wang, 1986; Berge et al., 1993; Hart & Wang, 1995; Berge, 1998).

K_ϕ is estimated from B by making use of another form of Gassmann's equation that is written in terms of B:

$$K_{sat} = \frac{K_d}{1 - \alpha B} \tag{3}$$

(Biot & Willis, 1957; Green & Wang, 1986). This equation can be combined with Eqn. 1 and rearranged to give an expression for K_ϕ:

$$1/K_\phi = 1/K_f - \left(\frac{\alpha}{\phi K_d}\right)(1/B - 1) \tag{4}$$

(e.g., Berge, 1998). Such estimation of K_ϕ using measured values of B requires having values for the unjacketed solid modulus K_s and the drained frame modulus K_d for the rock. Because poroelastic rock properties are highly dependent on effective pressure (e.g., Fredrich et al., 1995; Hart & Wang, 1995), measurements of B, K_d, and K_s must be obtained for the same rock sample at the same effective pressure conditions in order to be useful for estimating K_ϕ.

It is also possible to estimate K_ϕ for simple models of porous rocks. Berryman and Milton (1991) have shown that for the special case of a rock with two porous components that are in welded contact everywhere, assuming the whole rock contains no more than two types of solid, K_ϕ for the rock is given by

$$\frac{\phi}{K_\phi} = \frac{\alpha}{K_s} - \left\langle \frac{\alpha_i - \phi_i}{K_{si}} \right\rangle - (\langle \alpha_i \rangle - \alpha)\left(\frac{\alpha_1 - \alpha_2}{K_{d1} - K_{d2}}\right), \tag{5}$$

where the brackets $\langle\rangle$ and the i subscripts denote weighted averages over the properties of the two porous components. This method of estimating K_ϕ requires values of K_d and K_s for the whole rock and for the porous components. Effective medium theories can be used to estimate the K_d values (e.g., Berryman, 1992; Berge, 1998). The K_s values for the porous components are given by the grain moduli since only one type of solid is present in each of the porous components. Berryman and Milton (1991) provide an expression giving the theoretical relationship between K_s for the whole rock, K_d for the whole rock, and the K_s and K_d values of the two porous components. Although K_s for the whole rock is bounded by the K_s values for the porous components, K_ϕ is not; thus, K_ϕ may be much larger than K_s or much smaller than K_s or even negative (Berryman, 1992; Berge & Berryman, 1995; Berge, 1998).

Recent measurements of B and other poroelastic constants in rocks (e.g., Berge et al., 1993; Hart & Wang, 1995) suggest that K_ϕ may have values approaching the fluid bulk modulus K_f, particularly when the effective stress is low (Hart & Wang, 1995; Berge, 1998). At high effective stresses (e.g., Fredrich et al., 1995), flat cracks are closed, and K_ϕ may approach K_s as would be expected for a monomineralic porous rock (Berge, 1998). Theoretical estimates of K_ϕ for simple two-component models of rocks also show that K_ϕ may have values that differ greatly from K_s (Berryman, 1992; Berge & Berryman, 1995; Berge, 1998). In this paper, I use recent measurements of poroelastic constants (e.g., Hart & Wang, 1995) and effective medium theories to estimate how K_ϕ depends on effective stress and how uncertainty in K_ϕ affects uncertainty in estimates of K_{sat} or K_f determined using Gassmann's equation.

2 K_ϕ DEPENDENCE ON EFFECTIVE STRESS

K_ϕ can be estimated from laboratory measurements of B, K_d, and K_s. The measured value of B decreases with increasing effective stress. Table 1 shows how the measured value of B changes with changing differential pressure p_d, where p_d is the difference between the confining pressure and the pore fluid pressure, for various rocks that have been studied extensively in the literature. These data show that for high porosity rocks with porosities of about 0.3 to 0.4, typical values of B are about 0.9 to 1 at relatively low differential pressures of about 0 to 20 MPa; B ranges between about 0.7 to 1 at somewhat higher differential pressures of 20 to 50 MPa; and one high porosity sample had an even lower value of $B = 0.55$ at relatively high differential pressures between 60 and 120 MPa. For rocks having lower porosities of about 0.1 to 0.2, the decrease in B with increasing p_d is even larger than for the high porosity samples. B typically has values of 0.5 to 1 at the lowest differential pressures of 0 to 20 MPa shown in Table 1; B had a value of about 0.7 for a low porosity rock for moderately high differential pressures of about 20 to 30 MPa; and B values were between 0.4 and 0.7 for low porosity samples at even higher differential pressures of about 80 to 300 MPa.

The K_d values at similar pressures must be used with the B values, for estimating K_ϕ. For a drained sample, the differential pressure is simply the confining pressure. Corresponding measured values of K_d are not available for most of the B values listed in Table 1. A value of $K_d = 0.25$ GPa was reported for the Nevada tuff (Fredrich et al., 1995), but the porosity and pressure conditions were not identified. Dropek et al. (1978) found $K_d = 9.5$ GPa for the Kayenta sandstone, but did not give the pressure for that measurement. Green and Wang (1986) found measured values from the literature for K_d for Berea sandstone at various pressures, but did not make K_d measurements on their Berea sandstone samples. Hart and Wang (1995) made some measurements of K_d but did not make measurements at all the pressures they used for their B measurements for Berea sandstone and Indiana limestone. A value of $K_d = 0.2$ GPa was given for the fused glass bead sample having a porosity of 0.39 for pressures near 0 MPa (Berge et al., 1993), but measured values are unavailable for higher pressures.

Dynamic values of K_d have been computed for the fused glass bead samples, from ultrasonic velocity measurements (Berge et al., 1995). Static values are expected to be much lower than the dynamic values at low pressures, with the difference decreasing at high pressures. Cheng & Johnston (1981) found that the ratios of static to dynamic bulk moduli measured for Berea sandstone and Navajo sandstone samples were about 0.4 at pressures near 0 MPa, rising to about 0.8 at pressures near 100 MPa and about 1 at pressures over 200 MPa. For comparison, Jizba et al. (1990) found values of K_d near 10–15 GPa at pressures of about 0–20 MPa, rising to about 15–25 GPa at pressures of about 20–60 MPa, and about 25–30 GPa at pressures over 60 MPa. These data suggest that the dynamic K_d values of 6 GPa, 15 GPa, and 25 GPa corresponding to the fused glass bead samples having porosities of 0.39, 0.31, and 0.22 (Berge et al., 1995) should be multiplied by 0.4 to obtain static K_d estimates for pressures below 100 MPa and a factor of 0.8 for pressures near 100 MPa.

Table 2 presents K_d values for some of the samples having B values listed in Table 1. Values given in parentheses were not obtained at the same pressure as the B values (e.g., Hart & Wang, 1995), or were estimated from literature data (e.g., Green & Wang, 1986), or from dynamic K_d values as described above. These results show that K_d is very small at pressures near 0 MPa and increases rapidly with increasing pressure. K_d is larger for lower porosity samples.

Estimates of K_ϕ also depend on K_s, in addition to B and K_d. K_s may vary with effective pressure, although it is generally assumed to be constant and to have values close to the bulk modulus of the mineral forming most of the solid part of the rock. Hart & Wang (1995) measured values of $K_s = 26$–36 GPa for Berea sandstone at $p_d = 3$–5 MPa and $K_s = 71$–74 GPa for Indiana limestone at $p_d = 2$–10 MPa. For comparison, the bulk moduli of quartz and calcite are about 38 GPa and 75 GPa, respectively (e.g., Wilkens et al., 1984). The bulk modulus of the glass from Berge et al. (1993, 1995) is 46 GPa.

Using Eqn. 4, I calculated estimates of K_ϕ for the materials having the measured B and K_d values given in Tables 1 and 2. Appropriate K_f values were obtained from the references discussing the laboratory measurements (Dropek et al., 1978; Green & Wang, 1986; Berge et al., 1993; Fredrich et al., 1995; Hart & Wang, 1995). The resulting estimates of how K_ϕ changes with pressure are presented in Table 3.

For the case of $B = 1$ in Eqn. 4, $K_\phi = K_f$. The Kayenta sandstone results in Table 3 show that K_ϕ may approach K_s at very high effective stress. All the other rocks have very low values for the estimated K_ϕ, and these values increase slightly with increasing p_d. The uncertainty in K_ϕ is large because of the lack of measured K_d values at the same effective stresses as the measured B values. Nevertheless, these results indicate that K_ϕ depends strongly on effective stress and probably has values that are much lower than K_s except at extremely high stresses.

3 ESTIMATING K_ϕ FOR TWO-COMPONENT MATERIALS

Consider a two-component material made up of quartz grains and kaolinite, with water as the saturating fluid. Eqn. 5 can be used to estimate K_ϕ, together with appropriate values for the K_s's and K_d's. The component K_s values can be approximated by using the grain moduli for quartz, 38 GPa (Wilkens et al., 1984), and for kaolinite, 56 GPa (Katahara, 1996). The K_d values can be estimated using an appropriate effective medium theory that correctly models the microstructure of the material. Examples include the Reuss average for an unconsolidated sediment, the self-consistent effective medium theory of Berryman for a weakly consolidated sandstone, or the differential effective medium theory for a strongly cemented sandstone (e.g., Berryman, 1995; Berge et al., 1995). Table 4 presents estimates for K_ϕ obtained for models of a sand-clay mixture made up of a relative volume of 0.92 of a material having quartz grains and 17% water-filled pores (where $K_f = 2.3$ GPa) combined with a relative volume of 0.08 of a material having kaolinite grains and about 50% water-filled pores. The total water-filled porosity for the sand-clay mixture is thus about 0.20, which is similar to the Berea sandstone (Green & Wang, 1986; Hart & Wang, 1995) with about 8% clay. The K_ϕ estimates were obtained using Eqn. 5 together with K_d values estimated using effective medium theories as described above. The K_s value for the sand-clay mixture in each case was calculated from the component K_s and K_d values using an expression derived by Berryman and Milton (1991), except that for the Reuss average case, K_s is simply assumed to be bounded by the K_s values of the components. (In this unconsolidated case, $\alpha = B = 1$, and Eqn. 4 gives $K_\phi = K_f$). Table 4 includes estimates of B values obtained by inverting Eqn. 3 and using the appropriate K_d and K_{sat} values from the effective medium theories.

The results in Table 4 show that for increasing effective stress, i.e. moving from the unconsolidated to the strongly cemented case, B decreases, K_d and K_{sat} increase, K_s does not change significantly, and K_ϕ increases. These results can be compared to the measured values for the Berea sandstone, in Tables 1–3. The effective medium theory models may represent fairly high stresses where $K_\phi \to K_s$.

4 DISCUSSION

The results from the previous sections indicate that K_d, B, and K_ϕ all depend strongly on effective stress. For example, a sand-clay mixture or clay-bearing sandstone may have K_d values that vary by an order of magnitude or more at different stresses, e.g., near 1 to 5 GPa at very low stresses and near 20 to 30 GPa at high stresses. The B values may approach unity at very low stresses, and may drop to values below 0.5 at high stresses. Different combinations of K_d and B values used in Eqn. 4 will produce K_ϕ estimates that may vary by an order of magnitude, and it is even possible for estimates of K_ϕ to have a negative sign (e.g., Berge & Berryman, 1995; Berge, 1998).

The strong dependence of K_ϕ on K_d, B, and on effective stress has important implications for applications of Gassmann's equation. For example, suppose Eqn. 1 is used to estimate K_{sat} for given values of K_d, using K_ϕ values obtained for given values of B in Eqn. 4. Letting K_f, K_s, and the porosity remain constant at 2.3 GPa, 38 GPa, and 0.2, the influence of K_d, B, and K_ϕ on the K_{sat} estimates is shown in Table 5.

Note that the estimated K_{sat} value may vary by a factor of two or more for a given K_d value, depending on the values of K_ϕ and B. Similarly, for a given value of B, the estimated K_{sat} value may vary by a factor of two or more, depending on the values of K_ϕ and K_d. Similar uncertainties would be obtained for estimates of K_f for given K_d and K_{sat} values, using different estimates for K_ϕ (Berge, 1998).

5 CONCLUSIONS

The unjacketed pore modulus K_ϕ is important because it appears as a term in Gassmann's equation as one of the parameters controlling how the saturated bulk modulus of a rock is related to the drained frame modulus and the pore fluid bulk modulus. Although this parameter never has been measured successfully for any rock, it may be estimated from laboratory measurements of other poroelastic constants. Theoretical constraints may also be applied to improve estimates of K_ϕ. Results from this paper suggest the following:

- Estimation of K_ϕ requires using measured values of Skempton's coefficient B, the drained frame modulus K_d, and the unjacketed solid modulus K_s obtained under the same effective pressure conditions for the same rock sample.

- Theoretical considerations show that K_ϕ may be much larger than K_s, much smaller than K_s, or even negative in sign. (Typically, K_s is close to the grain bulk modulus.)

- K_ϕ may have values approaching the fluid bulk modulus K_f at low effective stress. At high effective stress, K_ϕ may approach K_s.

- For increasing effective stress, B decreases, K_d and K_{sat} increase, K_s does not change significantly, and K_ϕ apparently increases.

- Estimates of K_{sat} from Gassmann's equation may vary by a factor of two or more for a given value of K_d, depending on whether K_ϕ has a value that is close to K_f or a value that is close to K_s. Similar uncertainties would be obtained for estimates of K_f for given values of K_d and K_{sat}, using various K_ϕ values.

Clearly it is necessary to have effective stress information to accompany any laboratory measurements of poroelastic parameters. It may also be useful to make laboratory measurements using different pore fluids, to avoid problems of the fluids interacting chemically with the grains and changing the rock properties in unknown ways. Finally, the parameter K_ϕ needs to be measured directly, to improve the current understanding of poroelastic rock response.

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Table 1: Pressure effects on measured B

ϕ	p_d (MPa)	B	Material
0.40	20–50	0.93–0.98	Nevada Tuff[1]
0.39	0–1	1.	Fused Glass Beads[2]
”	8–20	0.9	”
0.37	20–50	0.93–0.98	Nevada Tuff[1]
0.35	0–5	0.9–1.	”
”	20–30	0.78	”
0.31	0–5	1.	Fused Glass Beads[1]
”	20–30	0.7	”
”	60–120	0.55	”
0.29	0–5	0.9–1.	Nevada Tuff[1]
”	20–30	0.78	”
0.22	0–5	1.	Fused Glass Beads[1]
”	20–30	0.7	”
”	80–170	0.35	”
0.20	0	0.99	Berea Sandstone[3]
”	0.9	0.95	”
”	2	0.87	”
0.19	0–2	0.84–0.95	Berea Sandstone[4]
”	3–5	0.77–0.88	”
”	7	0.68	”
0.20	75–240	0.58–0.67	Kayenta Sandstone[5]
”	240–280	0.55–0.67	”
0.13	2–10	0.53–0.69	Indiana Limestone[4]

[1] Fredrich et al. (1995)
[2] Berge et al. (1993)
[3] Green & Wang (1986)
[4] Hart & Wang (1995)
[5] Dropek et al. (1978)

Table 2: Effects of increasing pressure on K_d

ϕ	p_d (MPa)	K_d (GPa)	Material
0.39	0–1	0.2	Fused Glass Beads[1]
”	8–20	(2)	”
0.31	0–5	(6)	Fused Glass Beads[2]
”	20–30	(6)	”
”	60–120	(10)	”
0.22	0–5	(10)	”
”	20–30	(10)	”
”	80–170	(20)	”
0.20	0	(0.31)	Berea Sandstone[3]
”	0.9	(1.)	”
”	2	(1.64)	”
0.19	0–2	(5.6–7.6)	Berea Sandstone[4]
”	3–5	5.6–7.6	”
”	7	(5.6–7.6)	”
0.20	75–240	(9.5)	Kayenta Sandstone[5]
”	240–280	(9.5)	”
0.13	2–10	22–23	Indiana Limestone[4]

[1] Berge et al. (1993)
[2] Fredrich et al. (1995)
[3] Green & Wang (1986)
[4] Hart & Wang (1995)
[5] Dropek et al. (1978)

Table 3: Effects of increasing pressure on K_ϕ

ϕ	p_d (MPa)	K_ϕ (GPa)	Material
0.39	0–1	2.	Fused Glass Beads[1]
”	8–20	3.	”
0.31	0–5	2.–3.	Fused Glass Beads[2]
”	20–30	7.	”
”	60–120	7.	”
0.22	0–5	2.–3.	”
”	20–30	5.	”
”	80–170	9.	”
0.20	0	1.7	Berea Sandstone[3]
”	0.9	3.	”
”	2	11.	”
0.19	0–2	2.4–3.5	Berea Sandstone[4]
”	3–5	2.7–5.1	”
”	7	4.9–16.	”
0.20	75–240	6.6–17.	Kayenta Sandstone[5]
”	240–280	6.5–46.	”
0.13	2–10	3.0–4.6	Indiana Limestone[4]

[1] Berge et al. (1993)
[2] Fredrich et al. (1995)
[3] Green & Wang (1986)
[4] Hart & Wang (1995)
[5] Dropek et al. (1978)

Table 5: Gassmann's eqn. K_{sat} estimates

K_d (GPa)	B	K_ϕ (GPa)	K_{sat} (GPa)
5.0	0.50	-2.3	8.8
5.0	0.60	-7.1	10.
5.0	0.70	16.	13.
5.0	0.80	4.6	16.
5.0	0.90	3.0	23.
10.	0.50	15.	16.
10.	0.70	3.6	21.
10.	0.90	2.5	30.
20.	0.50	3.2	26.
20.	0.70	2.6	29.
20.	0.90	2.4	35.

Table 4: Effective medium theory modeling results

Material	K_{sat} (GPa)	K_d (GPa)	K_s (GPa)	α	K_ϕ (GPa)	B
Unconsolidated Sand-Clay	9.4	0.0	38–56	1.0	2.3	1.0
Weakly Consolidated Sandstone with Clay	26.	23.	38.	0.38	36.	0.22
Strongly Cemented Sandstone with Clay	27.	26.	38.	0.32	38.	0.14