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Forced oscillation measurements of seismic wave attenuation and stiffness moduli
dispersion in glycerine-saturated Berea sandstone

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Abstract

Fluid pressure diffusion occurring on the microscopic scale is believed to be a significant source of intrinsic attenuation of seismic waves propagating through fully saturated porous rocks. The so-called squirt flow arises from compressibility heterogeneities in the microstructure of the rocks. To study squirt flow experimentally at seismic frequencies the forced oscillation method is the most adequate, but these studies are still scarce. Here we present the results of forced hydrostatic and axial oscillation experiments on dry and glycerine-saturated Berea sandstone, from which we determine the dynamic stiffness moduli and attenuation at micro-seismic and seismic frequencies (0.004 – 30 Hz). We observe frequency-dependent attenuation in response to the drained-undrained transition (~0.1 Hz) and squirt flow (>10 Hz). The frequency-dependent attenuation and associated modulus dispersion at 5 MPa effective stress is in fairly good agreement with the results of the analytical solutions for the drained-undrained transition and squirt flow. The comparison with
very similar experiments performed also on Berea sandstone indicates that squirt flow can
potentially be a source of seismic wave attenuation across a large range of frequencies
because of its sensitivity to small variations in the rock microstructure, especially in the
aspect ratio of micro-cracks or grain contacts.

**Key Words**
- Attenuation
- Rock physics

**1. Introduction**

Porous rocks saturated with fluids can strongly attenuate seismic waves. Different forms of
wave-induced fluid flow (WIFF) are thought to be the primary intrinsic mechanism for
seismic wave attenuation (e.g. Pride *et al.* 2004). Fluid flow arises predominantly from
contrasts in compressibility either in the solid matrix of the rock, for instance between
compliant grain contacts and stiff pores, or in the saturating fluids, such as a heterogeneous
distribution of water and gas. In response to such compressibility contrasts, seismic waves
induce pressure gradients, resulting in viscous fluid flow and the conversion of the waves
mechanical energy into heat. The frequency dependence of the associated seismic attenuation
depends strongly on the spatial distribution or geometry of the heterogeneities in the rock
matrix and/or in the saturating fluids (Masson and Pride 2007, 2011; Müller *et al.* 2008). A
direct consequence of the frequency dependent attenuation is that the corresponding stiffness
modulus of the rock will also be frequency dependent.
Much focus has been given to squirt flow, pressure diffusion arising from microscopic compressibility heterogeneities in the rock, as one of the dominant mechanisms for wave attenuation in fluid saturated rocks. Numerous theoretical models (e.g. O’Connell and Budiansky 1977; Mavko and Jizba 1991; Chapman et al. 2002; Gurevich et al. 2010; Adelinet et al. 2011) have been developed to try to explain laboratory observations at sonic and ultrasonic frequencies. More recently, with the progress made in using the forced oscillation method (e.g. McKavanagh and Stacey 1974), squirt flow has been studied also at seismic frequencies by using high viscosity fluids such as glycerine.

On a Fontainebleau sandstone sample saturated with glycerine, Pimienta et al. (2015a) observe an extensional mode attenuation peak at between 1 and 10 Hz, which was reduced in amplitude with increasing effective stress. Subramanyian et al. (2015) also measured the extensional mode attenuation and Young’s modulus in Fontainebleau sandstone with similar properties, in this case varying the fluid viscosity by mixing water and glycerine. For the fully glycerine-saturated sample they observe an attenuation peak in a similar frequency range and with similar amplitude, supporting the observation of Pimienta et al. (2015a). In addition Subramanyian et al. (2015) used Gurevich et al.’s (2010) analytical solution of squirt flow to interpret their observations, however the analytical solution consistently underestimated the attenuation magnitude measured in the laboratory. The broad attenuation peaks observed were attributed to a distribution of crack aspect ratios.

In a glycerine saturated Berea sandstone sample Mikhaltsevtich et al. (2015; 2016) measured the dynamic Young’s modulus and Poisson ratio, from which they inferred the bulk and shear moduli as well as the corresponding attenuation modes. By performing measurements at temperatures from 31 to 23 °C, they observe a shift of the extensional-mode attenuation peak
from ~ 2 to ~ 0.4 Hz, associated with the reduction of the glycerine viscosity. Mikhaltsevtich et al. (2015) interpreted the attenuation as being caused by squirt flow. Spencer and Shine (2016) also performed forced oscillation experiments on a fully saturated Berea sandstone sample, however only observing a partial attenuation curve. Similar to Mikhaltsevtich et al. (2016) the impact of fluid viscosity was studied, however instead of modifying the temperature, fluids of varying degrees of viscosity were used. Pimienta et al. (2017) investigated frequency-dependent attenuation and modulus dispersion in four different types of sandstone, including Berea sandstone, under full water and glycerine saturation. In the Wilkenson and Bentheim sandstones both showed frequency dependent attenuation likely in response to squirt-flow, showing a strong sensitivity to changes in effective pressure. However in the Berea sandstone samples the presence of squirt flow could not be verified in the considered frequency range.

Even though there has been a recent surge in the availability of laboratory data from fully saturated sandstones at seismic frequencies (<100 Hz), the overall understanding of the physical processes responsible for the frequency-dependent attenuation and modulus dispersion remains incomplete. Comparing experiments is especially challenging given the variation in microstructure between samples and the use of a range of different saturating fluids. Furthermore the analysis is considerably complicated by the impact or not of boundary conditions on the observed frequency-dependent attenuation, which is associated with the design of the experimental apparatus (e.g., Pimienta et al., 2016).

To contribute to the available data, we present in the following sections the results of forced hydrostatic and axial oscillation experiments on a Berea sandstone sample. The experiments were performed on the dry and fully glycerine-saturated sample for a range of effective
stresses. We will provide a description of the sample and the experimental conditions. The
discussion of our results for the dispersion of the stiffness moduli and corresponding
attenuation modes will focus on the uncertainty in our measurements, the physical processes
responsible for our observations, how the theoretical predictions compare to our observations,
and how our observations compare to those of Mikhaltsevtich et al. (2016), whose
experiments are the most similar to ours.

2. Samples and experimental methodology

2.1 Sample description

Three samples with a ~4 cm diameter and ~8 cm length were cored from a block of Berea
sandstone with poorly defined bedding planes, running parallel to the samples vertical axis.
The Berea sandstone was acquired from Cleveland Quarries in the United States with a brine
permeability estimated at 75 to 250 mD. The glycerine permeability of sample BS-V5 was
subsequently measured at an effective stress of 2.5 MPa by imposing a pressure gradient
across the sample and measuring the associated flow. The porosity was determined with a
pyknometer, using a subsection of sample BS-V6. The dry density is the mean density
determined from the dry masses and dimensions of the three samples. These properties are
listed in Table 1. Scanning electron microscopy (SEM) and energy dispersion spectrometry
(SEM-EDS) analysis (Figure 1) shows that our sample is composed largely of quartz (Si),
with smaller amounts feldspar and clays (Al) [can we be more precise and give the
composition according Fig1?]. Kareem et al. (2017) performed an extensive characterisation
of Berea sandstone cores, also purchased from Cleveland Quarries, showing that clays make
up between 3 and 9 % of the bulk composition, with the predominant clay being kaolinite.
Table 1. Sample properties

<table>
<thead>
<tr>
<th></th>
<th>BS-V4 to BS-V6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glycerine Permeability (mD)</td>
<td>58.7 ± 1.14*</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>22.15</td>
</tr>
<tr>
<td>Dry Density (kg/m³)</td>
<td>2087 ± 6.55</td>
</tr>
</tbody>
</table>

* Measured at 2.5 MPa effective stress.

Figure 1. a) Scanning electron microscopy (SEM) image of the polished surface of BS-V6. Energy dispersion spectrometry (EDS-SEM) images of the same sample portion showing the distribution of b) potassium (K), c) iron (Fe), d) silicon (Si), e) aluminium (Al) and f) magnesium (Mg).

2.2 Experimental setup - dynamic moduli and attenuation modes

Forced oscillation measurements were performed in a tri-axial cell at ENS Paris. Borgomano et al. (2017) provide a detailed description of the experimental setup and data processing. Pimienta et al. (2015a,b) provide further details on the calibration of the apparatus with
standard materials. We will briefly list the governing relations used to determine the various
moduli and associated attenuation modes.

Two types of stress oscillation on the sample, producing strains on the order of ~$10^{-6}$, can be
performed in this cell: hydrostatic and axial. The hydrostatic oscillation (4×$10^{-3}$ to ~1 Hz) is
induced by the confining pressure pump (Adelinet et al. 2010; David et al. 2013) and allows
for directly measuring the sample’s dynamic bulk modulus from the confining pressure
oscillation $\Delta P_c = -\sigma_{ii}/3$, where $\sigma_{ii}$ (i = 1,2,3) are the principal stresses, and the associated
volumetric strain $\varepsilon_{\text{vol}}$ as follows: [In formula 1, we don’t need the negative sign, if we
consider $E_{\text{vol}}$ positive in compaction]

$$K_{\text{hydro}} = \frac{P_c}{\varepsilon_{\text{vol}}}.$$  \hspace{1cm} (1)

The volumetric strain is determined from the average strain measured by 8 strain gauges,
comprising four pairs of radial and axial strain gauges, as $\varepsilon_{\text{vol}} = 3\varepsilon_{\text{avg}}$.

The axial oscillation (1×$10^{-1}$ to ~20 Hz) is induced by a piezo-electric actuator placed
between the sample and the axial piston of the cell and allows for measuring the sample’s
Poisson ratio $\nu$ and Young’s modulus $E$:

$$= \frac{\varepsilon_{\text{rad}}}{\varepsilon_{\text{ax}}} \text{ and } E = \frac{\sigma_{\text{ax}}}{\varepsilon_{\text{ax}}},$$ \hspace{1cm} (2)

where the axial stress $\sigma_{\text{ax}}$, is determined from the deformation of the aluminium end plate of
known Young’s modulus, and $\varepsilon_{\text{rad}}$ and $\varepsilon_{\text{ax}}$ are the average radial and axial strains on the
sample. Given the Poisson ratio and Young’s modulus, the axial bulk $K_{\text{ax}}$ and shear $G_{\text{ax}}$
moduli can be inferred as follows:
\[
K_{ax} = \frac{E}{3(1 - \nu)} \quad \text{and} \quad G_{ax} = \frac{E}{2(1 + \nu)}. \tag{3}
\]

For each mode of deformation, the attenuation can be determined from the phase shift between the applied stress and resulting strain \((\Delta \phi = \phi_{\text{stress}} - \phi_{\text{strain}})\). The bulk attenuation for the hydrostatic oscillation can be determined from the phase shift between the hydrostatic stress \(\Delta P_c\) and the volumetric strain \(\varepsilon_{\text{vol}}\), such that:

\[
\Delta P_c = \varepsilon_{\text{vol}}. \quad \text{[Here again, the negative sign in \(P_c\) is not useful]} \tag{4}
\]

The extensional mode attenuation is in turn determined from the phase shift between the axial stress \(\sigma_{ax}\) and strain \(\varepsilon_{ax}\), such that:

\[
\text{extensional} = \frac{\sigma_{ax}}{\varepsilon_{ax} + \varepsilon_{rad}}. \tag{5}
\]

Assuming that the sample is isotropic, the bulk and shear attenuation can be inferred from the phase shift between the axial stress \(\sigma_{ax}\) and the axial and radial strains \(\varepsilon_{ax}\) and \(\varepsilon_{rad}\) (Borgomano et al. 2017):

\[
b\text{bulk} = \frac{\sigma_{ax}}{\varepsilon_{ax} + 2\varepsilon_{rad}} \quad \text{and} \quad \text{shear} = \frac{\sigma_{ax}}{\varepsilon_{ax} - \varepsilon_{rad}}. \tag{6}
\]

where the phases of \(\varepsilon_{ax} + 2\varepsilon_{rad}\) and \(\varepsilon_{ax} - \varepsilon_{rad}\) are derived from combining equations 2 and 3.

The attenuation corresponding to each deformation mode can be calculated as (O’Connell and Budiansky 1978):

\[
Q^{-1} = \tan(\quad ) \tag{7}
\]

\[ \]

2.3 Experimental conditions
Axial and hydrostatic oscillations, were performed on the dry and glycerine-saturated sample (BS-V5). Axial oscillations were performed at effective stresses between 2.5 and 25 MPa, with an additional static axial load of 2 MPa. We will refer to the effective stress as the difference between the confining and fluid pressure, $\sigma_{\text{eff}} = P_c - P_f$. The static axial load is applied to ensure coupling between the sample and the piezoelectric actuator. The hydrostatic oscillations were performed for the same range of effective stresses, however without imposing an additional static axial load. Before saturating the sample with glycerine, a vacuum pump was used to remove air from its pore space. Glycerine was then pumped into the sample using two Quizix pumps that subsequently regulated the fluid pressure at 4 MPa.

3. Results and Discussion

3.1 Measurement Uncertainty

To assess the uncertainty in our measured frequency-dependent moduli and attenuation we look at the repeatability of the measurements and the variation of the data with respect to an idealized model. The moduli and attenuation are inferred from the strain measured on the sample. For hydrostatic forced oscillations we have eight measurements of strain, while for axial forced oscillations we have a pair of averages consisting of two axial and radial measurements of strain on opposing sides of the sample. We determine the repeatability of our moduli and attenuation for hydrostatic oscillations by taking the standard deviation over the eight measurements of strain. In the case of the axial oscillations we only have two measurements of each moduli and its corresponding attenuation, we therefore estimate the repeatability of our measurements from their range. To assess the variation of our data with respect to an idealized model we follow Adam et al.’s (2006) procedure of fitting a linear
function of $\log_{10}(\text{frequency})$ to the mean of our measured data and determining the root-mean-squared-error (RMSE).

Figure 2 shows the moduli and corresponding attenuation inferred from axial and hydrostatic oscillations performed on the dry sample at 5 MPa effective stress. The moduli increase moderately towards higher frequencies and the measurement range generally exceeds the variation of the measurement mean around the fit. For the corresponding attenuation the measurement range is much more variable and, for the Young’s and shear components, it increases towards higher frequencies. Attenuation is only shown up to 10 Hz, because at higher frequencies it strongly deviates from the fitting trend (Figure 2b, d and f). The measurement range appears to largely over estimate our uncertainty, however it also shows that the uncertainty is not independent of frequency. In the following sections we will therefore present the range when error bars are displayed.
Figure 2. Frequency-dependent moduli and corresponding attenuation inferred from axial and hydrostatic forced oscillations on the dry sample at 5 MPa effective stress. The data points represent the mean measurement and the error-bars indicate the range of the measurements for axial oscillations (a – f) and the standard deviation in the measurements for hydrostatic oscillations (g – h). A linear function of $\log_{10}(\text{frequency})$ is fit to the data and the root-mean-squared-error (RMSE) is indicated in the legend.

3.2 Frequency dependence – glycerine saturation
When the sample is glycerine saturated all modes show significant frequency dependent attenuation (Figures 3a, 4a and 5a). For the extensional (Figure 3a) and bulk attenuation (Figure 4a) two peaks are observed: one at ~0.1 Hz and another beginning at ~3 Hz and above. For the shear attenuation (Figure 5a) however only the attenuation peak at higher frequencies is observed. The attenuation peak at ~0.1 Hz is reduced in amplitude as the effective stress is increased. The second partial peak at higher frequencies is likewise reduced in amplitude, however at 15 MPa effective stress the measured attenuation is comparable in amplitude to the attenuation measured for the dry sample.

As with the attenuation the various stiffness moduli are frequency-dependent once the sample is saturated with glycerine (Figures 3b, 4b and 5b). The overall increase in the sample’s stiffness from dry to glycerine saturated is particularly observed in the Young’s modulus (Figure 3b). The shear modulus at low frequencies is on the order of the shear modulus of the dry sample (Figure 5b). Towards higher frequencies the shear modulus shows some dispersion. The Young’s and bulk moduli are dispersive at both ~0.1 Hz and again beginning at ~3 Hz. Overall the moduli become less dispersive with increasing effective stress. At high frequencies the bulk modulus possibly converges to a common limit. The Poisson ratio (Figure 3c) is significantly increased with respect to the Poisson ratio measured in the dry sample and is frequency dependent (Figure 3c). For the saturated sample, with increasing effective stress the Poisson ratio is reduced and at high frequencies it is nearly frequency independent.

Because the stress applied to the sample for the hydrostatic oscillation is determined from a pressure transducer close to the sample in the confining oil, while for the axial oscillation the stress it is determined from the deformation of the aluminium end plate on which the sample
is placed, the bulk modulus and attenuation can be measured independently by these two methods. If the sample BS-V5 is in fact isotropic then the bulk modulus and attenuation measured by these two methods should be the same. In Figure 4 we show the bulk modulus and attenuation determined from both the hydrostatic and axial oscillations. We observe that the bulk modulus and attenuation are generally independent of the measurement type. However as the effective stress is increased the hydrostatic measurements do show a slightly higher bulk modulus than the axial measurements.

In the dry measurements our measurement uncertainty increased with frequency and we observed significant frequency dependent attenuation above 10 Hz, indicating misalignments in the experimental set up or an inability of the piezo-electric actuator to generate a sinusoidal signal. To verify the quality of our measurements on the glycerine-saturated sample we therefore make use of the Kramers-Kronig relations to check for the causality between our measured attenuation and moduli. We perform a linear interpolation to the attenuation and apply the Kramers-Kronig relations given by Mikhaltsevitch et al. (2016). We do this for the bulk (Figure 4) and shear (Figure 5) components and observe a satisfactory fit between the moduli and the respective attenuation.

The attenuation peak observed at ~0.1 Hz is caused by the drained-undrained transition, which is a boundary condition problem of fluid saturated samples. The forced oscillation of the sample induces fluid pressure diffusion from the sample into the connecting pore fluid lines. The diffusion of pore fluid pressure can be described in terms of a pseudo-skempton coefficient, defined as (Pimienta et al. 2015b):

\[ B' = \frac{p_r}{P_c} \]  

(10)
where $\Delta p_f$ is the fluid pressure amplitude measured in the pore fluid line and $\Delta P_c$ is the confining pressure amplitude. In Figure 4c we see that the pseudo-skempton coefficient is elevated at low frequencies, indicating that the glycerine had enough time to flow in response to the confining pressure oscillation and raise the pressure in the pore fluid lines. At low frequencies (0.01 Hz) the sample can therefore be considered partially drained. The pseudo-skempton coefficient approached zero as the frequency of the confining pressure oscillation increases, because the fluid no longer has the time to diffuse form the sample and raise the pressure in the pore fluid lines. At high frequencies (1 Hz) the sample is therefore undrained. Increasing the effective stress increases the sample stiffness, which means that a larger portion of the load is carried by the frame of the sample and not transferred to the fluid. The consequence of increasing the effective stress is that the pseudo-skempton coefficient is also reduced, which is consistent with the observations of Hart and Wang (1999) for the variation of the Skempton’s coefficient with effective stress for Berea sandstone.

The second partial attenuation peak observed at above ~3 Hz on the other hand is likely in response to squirt flow arising from microscopic compressibility heterogeneities in the rock. This is indicated in part by the sensitivity of the measured attenuation to an increase in effective stress resulting in a reduction of the compliant porosity and a corresponding reduction in attenuation. Indicative of squirt flow is also the dispersion in the shear modulus and corresponding attenuation, which is not the case for attenuation associated with the drained-undrained transition (Figure 5).
Figure 3. a) Extensional attenuation $Q^{-1}$, b) Young’s modulus $E$ and c) Poisson ratio for the dry and glycerine-saturated sample BS-V5 inferred from forced axial oscillations. The sample was subjected to a static axial stress of 2 MPa. The legend provides the applied effective stress $\sigma_{\text{eff}}$. Open symbols indicate the dry sample and filled symbols indicate glycerine-saturated sample.
Figure 4. a) Attenuation $Q_K^{-1}$, b) bulk modulus $K$ and c) the Pseudo-Skempton coefficient $B^*$ for the glycerine-saturated sample BS-V5 determined from forced axial (open symbols) and hydrostatic oscillations. Also shown are the results of Kramers-Kronig (KK) relations determined from a cubic spline fit to the measured attenuation. For the axial oscillations the sample was subjected to a static axial stress of 2 MPa. The legend provides the applied effective stress $\sigma_{\text{eff}}$. 
Figure 5. a) Attenuation $Q^{-1}_G$ and b) shear modulus $G$ for the dry and glycerine-saturated sample BS-V5 determined from forced axial oscillations. Also shown are the results of Kramers-Kronig (KK) relations. The sample was subjected to a static axial stress of 2 MPa. The legend provides the applied effective stress $\sigma_{\text{eff}}$. Open symbols indicate the dry sample and filled symbols indicate the glycerine-saturated sample.

3.3 Drained-undrained transition and squirt flow

A number of analytical solutions have been developed to explain modulus dispersion and attenuation related to squirt flow (e.g. Mavko and Jizba 1991; Chapman et al. 2002). Here we will use Gurevich et al.’s (2010) analytical solution which describes the pressure diffusion between compliant and stiff pores for an oscillating stress. At low frequencies the solution converges to Gassmann’s (1951) undrained limit and at high frequencies converges to Mavko and Jizba (1991) unrelaxed limit. The analytical solution assumes that the rock is isotropic, making it applicable to sample BS-V5, with penny shaped cracks having a uniform aspect.
ratio. To investigate the drained-undrained transition we will in turn use the 1-D analytical solution from Pimienta et al. (2016) for the fluid pressure diffusion along the vertical axis of a sample subjected to a hydrostatic pressure oscillation. At high frequencies the solution converges to Gassmann’s (1951) undrained limit.

The input parameters for both models are given in Tables 2 and 3 and correspond to a sample subjected to an effective stress of 5 MPa. The drained bulk and shear moduli are measured from the forced axial oscillations on the dry sample. The compliant porosity, $\phi_c$, was estimated from the volumetric strain measured on the dry sample, following the procedure described in Appendix A of Gurevitch et al. (2010). The high pressure bulk modulus required by the squirt flow model corresponds to the bulk modulus measured at 25 MPa confining pressure form the forced axial oscillations on the dry sample. The aspect ratio of the compliant cracks cannot be accurately determined from the mechanical and SEM data and is therefore used as a fitting parameter, as it only impacts the frequency dependence. However, an order of magnitude estimation of the aspect ratio can be obtained from Walsh (1965):

$$\frac{4P_{\text{closure}}}{E}\left(1 - \frac{n^2}{n}ight),$$  \hspace{1cm} (11)

where $P_{\text{closure}}$ is the confining pressure at which the compliant cracks closed in the dry sample, while $E$ is the Young’s modulus and $\nu$ is the Poisson’s ratio. Considering a closure pressure of around 25 MPa, at which we measured a Young’s modulus of ~28 GPa and Poisson’s ratio of ~0.14, we can infer that the characteristic aspect ratio should be on the order of $\sim 1 \times 10^{-3}$, which is consistent with our choice of aspect ratio (Table 4).
Figure 6 shows the combined result of the two analytical models together with the moduli and attenuation measured on the dry and glycerine-saturated sample at 5 MPa effective stress. Neither model accounts for the attenuation resulting from frictional dissipation along grain contacts, therefore the attenuation measured in the dry sample is added to the model result (Tisato and Quintal 2013; 2014). The Young’s modulus (Figure 6a) and attenuation (Figure 6b) derived from the models reproduce well the laboratory observation, while for the bulk modulus dispersion (Figure 6c) and attenuation (Figure 6d) are slightly underestimated. The shear modulus measured in the glycerine-saturated sample is reduced relative to the dry sample (Figure 6e) and the model therefore does not fit it as well. However the shear-mode attenuation (Figure 6f) is reasonably well reproduced.
Figure 6. The measured moduli and attenuation for the dry and glycerine saturated sample BS-V5 at 5 MPa effective stress determined from both axial and hydrostatic oscillations together with the results of the analytical solutions (AS) for the drained-undrained transition and squirt flow.

Table 2. Rock and fluid properties for the simple isotropic squirt flow model for sample BS-V5 subjected to an effective stress of 5 MPa.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Model Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid Bulk Modulus</td>
<td>$K_f$</td>
<td>4.36 GPa</td>
</tr>
<tr>
<td>Viscosity</td>
<td>$\eta$</td>
<td>1.087 Pa s</td>
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<tr>
<td>Rock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stiff Porosity</td>
<td>$\phi_s$</td>
<td>0.2213</td>
</tr>
</tbody>
</table>
Compliant Porosity \( \phi_c \) \( 1.55 \times 10^{-4} \)
Grain Bulk Modulus \( K_g \) \( 36 \) GPa
Drained Bulk Modulus \( K_d \) \( 9.2 \) GPa
Drained Shear Modulus \( G_d \) \( 9.1 \) GPa
High Pressure Bulk Modulus \( K_h \) \( 13.3 \) GPa
Crack aspect ratio \( \alpha \) \( 0.0025 \)

Table 3. Rock and fluid properties for the 1D-model of the drained-undrained transition for sample BS-V5 subjected to an effective stress of 5 MPa.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Model Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid Bulk Modulus</td>
<td>( K_f )</td>
<td>4.36 GPa</td>
</tr>
<tr>
<td>Viscosity</td>
<td>( \eta )</td>
<td>1.087 Pa s</td>
</tr>
<tr>
<td>Length</td>
<td>( L )</td>
<td>0.083 m</td>
</tr>
<tr>
<td>Diameter</td>
<td>( D )</td>
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<tr>
<td>Porosity</td>
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<td>Permeability</td>
<td>( \kappa )</td>
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<tr>
<td>Grain Bulk Modulus</td>
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<td>36 GPa</td>
</tr>
<tr>
<td>Drained Bulk Modulus</td>
<td>( K_d )</td>
<td>9.2 GPa</td>
</tr>
<tr>
<td>Dead Volume</td>
<td>( V_{dead vol.} )</td>
<td>( 26 \times 10^{-6} ) m(^3)</td>
</tr>
</tbody>
</table>

3.4 Comparison with previous experimental results

Our experiments are very similar to those performed by Mikhaltsevitch et al. (2015; 2016), also on a glycerine-saturated Berea sandstone sample. Their sample D had a permeability of 71 mD, a porosity of 19 %, and while mainly composed of quartz (80 %) and feldspar (12 %) also had substantial amounts of kaolinite (8 %), making it very similar to our sample BS-V5. In their study, the forced axial oscillation measurements were performed on both the dry and glycerine-saturated sample at 10 MPa effective stress. Under glycerine saturation the pore
pressure was maintained at 3 MPa. The measurements were also performed at different temperatures ranging from 23 to 31 °C. For the sake of comparing our data to theirs we will only consider the measurements performed at 23 °C. Mikhaltsevitch et al. (2015) are confident that their measurements are performed under undrained conditions, based on Gassmann’s predictions, matching well their measured bulk modulus at low frequencies. They interpret the observed frequency-dependent attenuation to be in response to squirt flow.

In Figure 7 we compare the Young’s modulus and attenuation measured in the dry and glycerine-saturate sample D of Mikhaltsevitch et al. (2016) (Figure 7a and b) to that measured in our sample BS-V5 (Figure 7c and d). It is important to note that we are showing our measurements performed at 5 MPa effective stress, because we did not perform measurements at 10 MPa effective stress. However, as seen in section 3.2 we observed that increasing the effective stress reduces the attenuation amplitude but does not result in a large shift of the attenuation peaks with respect to frequency. While sample D is more compressible, under dry conditions it is less attenuating than sample BS-V5, which could indicate a minor dependence of our sample on the strain amplitude (e.g. Gordon and Davis 1968; Winkler et al. 1979). However frequency-dependent attenuation in response to wave-induced fluid flow should be approximately independent of strain (Tisato and Quintal 2014).

Mikhaltsevitch et al. (2016) observe the attenuation peak that they attribute to squirt flow at ~0.4 Hz (Figure 7b), while for our sample the attenuation peak we attribute to squirt flow is at >10 Hz (Figure 7d). A shift of the attenuation peak by 1 to 2 orders of magnitude can be explained by a minor variation in the characteristic crack aspect ratio of the sample, given that the characteristic frequency of squirt flow is proportional to the cube of the aspect ratio (O’Connell and Budiansky 1977; Gurevich et al. 2010).
Included in Figure 7a and b we show the result of Gurevich et al.’s (2010) squirt flow model. As input parameters we use the bulk and shear modulus and porosity of the dry sample D (Mikhail’tsevitch et al. 2015). The other rock parameters for the model where not available, therefore the other parameters are the same as for sample BS-V5 (Table 2), with the exception of the crack aspect ratio which is again used as a fitting parameter. Both the Young’s modulus (Figure 7a) and the attenuation (Figure 7b) are underestimated by the analytical solution, which is possibly related to the choice of the high-pressure bulk modulus that controls the bulk modulus dispersion. Mikhail’tsevitch et al. 2015 show the frequency dependent bulk modulus inferred from the measured Young’s modulus and Poisson’s, which is highly dispersive and which the analytical solution cannot account for with the choice of parameters. An important aspect of the analytical solution is that it does not account for a distribution of aspect radii and therefore the asymptote of attenuation at low frequencies scales as $Q^{-1} \propto f$, while at high frequencies scales as $Q^{-1} \propto f^{-1}$ (Gurevich et al. 2010). The comparison between the measured attenuation and result of the analytical indicates that the sample D indeed has a distribution of aspect radii as would be expected (e.g. Cheng and Toksöz 1979, Subramanyian et al. 2015). In sample BS-V5 (Figures 7c and d) it is not clear whether the sample has a narrower distribution in aspect radii, given that the attenuation curve is only partially observed.

Berea sandstone has been extensively studied in the past and it contains substantial amounts of clay, which fills pores and coats grains (e.g. Kareem et al. 2017). Christensen and Wang (1985) observed an increase in compressional wave velocities and a decrease in shear wave velocities with pore pressure in water saturated Berea sandstone, attributing the observations to the high compressibility of clays that make up parts of the cement. Zoback and Byerlee (1975) also attribute the compressibility of clay to the increase in permeability with increasing
pore pressure in Berea sandstone. At seismic frequencies Pimienta et al (2017) observe a
sensitivity of the frequency dependent Poisson ratio to fluid pressure in a Berea sandstone
sample saturated with a glycerine-water mixture. They apply different fluid pressures up to 9
MPa at a constant effective stress of 1 MPa, however they do not elaborate on what may be
inducing the increase in Poisson’s ratio with fluid pressure. Although the experiments carried
out in our study are very similar to those of Mikhaltsevitch et al. (2016) in terms of rock type,
fluid properties and the range of effective stresses applied, the fluid pressure was 4 MPa in
sample BS-V5 and 3 MPa for sample D. The difference in fluid pressure is not very large,
however, for future research on squirt flow as an attenuation mechanism, the impact of
changes in fluid pressure could be very interesting because of the sensitivity of squirt flow to
crack aspect ratio. In Berea sandstone, where clays coat grains, a variation in fluid pressure at
constant effective stress could facilitate a change in crack aspect ratio, which could in turn be
identified in the measured frequency dependence of attenuation and modulus dispersion.
Figure 7. a) Young’s modulus and b) attenuation $Q_{E}^{-1}$ for the dry and glycerine-saturated Berea sandstone (sample D) measured at 10 MPa effective stress by Mikhaltsevitch et al. (2016), together with the results of the analytical solution (AS) for squirt flow. For comparison, c) the Young’s modulus and d) attenuation $Q_{E}^{-1}$ of the dry and glycerine-saturated sample BS-V5 at 5 MPa effective stress, together with the results of the analytical solutions for the drained-undrained transition and squirt flow.

4. Conclusions

We performed hydrostatic and axial forced oscillations experiments on a dry and glycerine-saturated Berea sandstone sample. In the glycerine saturated sample the measured attenuation is frequency dependent with an attenuation peak at ~0.1 Hz and a second, partial, peak beginning at ~3 Hz. The first attenuation peak is in response to fluid pressure diffusion from the sample into the pore fluid lines, referred to as the drained-undrained transition. The second partial attenuation peak is likely in response to squirt flow, resulting from microscopic
heterogeneities in the compressibility of the porous solid frame of the rock. The fit of analytical solutions for the drained-undrained transition and squirt flow satisfactorily reproduced the measured attenuation and moduli. A comparison with independently conducted experiments on a very similar sample under comparable conditions appears to confirm the sensitivity of squirt flow to variations in the characteristic aspect ratios of the compliant porosity.

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