Productivity Effects of Drawdown and Depletion in Open Hole Completions: Do Screens Plug?
J. Tronvoll, SPE, E.F. Sønstebø, SPE, IKU Petroleum Research

Abstract
Physical model experiments of sand production and productivity change in open hole, single screen completions have been performed. Synthetic and outcrop sandstone samples containing a drilled vertical scaled borehole with a concentric single screen in place were tested under conditions of realistic formation stresses and radial fluid flow. The increase of the drawdown and depletion, by raising the effective external stresses and the pore pressure gradient, to conditions by far exceeding the formation collapse stress, resulted in productivity reductions. The differential fluid pressure over the screen did, however, never exceed 10 kPa; which is negligible compared to the near-wellbore formation pressure drop. The variation of the screen-formation annular clearance and the mismatch of the screen slot opening to the formation grain size distribution did not alter the productivity significantly. However, transient sand production through the screen occurred when the screen slot opening was oversized. The productivity was, however, reduced when the screen-formation annulus was gravel-packed.

Introduction
The planning of well completions is in many ways an optimisation of the well’s inflow performance and the sand production risk. The inflow performance, as expressed through the near-wellbore skin, affects significantly the productivity of the well through inflow restrictions caused by e.g. poor mud filtercake removal, mud filtrate, near wellbore scaling, and water breakthrough. Indeed such restrictions may lead to increased drawdown to maintain economical production rates. On the other hand increasing drawdown provokes sand production and formation collapse near the wellbore. This implies that a reliable sand control method must be implemented, most often in the primary completion of the well. In particular in subsea template wells or gas wells a high level of security is required. Normally, this security is paid for by reduced well productivity, which may have dramatical economical impact. An additional concern is the long term ability of the sand control device to resist the downhole environment in terms of mechanical action due to formation collapse, chemically aggressive fluids, erosion of slot openings and grain packs, etc. These leads in many cases to the introduction of extra barriers to improve the lifetime of the completion, which again lead to productivity loss.

Depending on the environment, various methods such as external and internal gravel packing, plastic consolidation, open hole pre-packed liner completion and open hole single screen completion have been used by the industry in order to control sand production during production. The success experienced with the different methods varies, depending on several factors as formation grain-size distribution, pore-lining clay mineralogy, in situ stress states, drawdown and depletion, hydrocarbon properties, mechanical properties of the formations, flowback of drilling fluid contaminants during production, etc.

With respect to the productivity impairment due to particle accumulations, most studies so far have concentrated on the contamination of gravel packs by small particles as quartz grains and clay particles. As the producing formation never consists of homodispersive particles, the description of the formation sandstone in terms of its grain size distribution is widely accepted. Although in the past only the median or mean grain size, or equivalent parameters, have been used in design, it is still intuitively acceptable to formulate the stability criteria relating to sand production in terms of which fractions of the grain size distribution should be retained by the sand control equipment. Markestad et al. further refined this approach by developing a model optimising the slot width of screens with respect to sand production and pressure drop taking into consideration the entire formation grain size distribution. These models are based on the assumption of sand, i.e. single grains, being exposed to the screen surface as a result of
instabilities of the formation surface (wellbore wall in open hole completions). Recent studies\textsuperscript{9} have, however, demonstrated that formation failures and subsequent sand production, may not materialise only as single grains. A variety of rock fragments from small granules to larger flakes and slabs of rock reflecting the formation failure mechanism have been observed. The productivity of the formation itself is affected by compaction and/or dilation and subsequent macroscopic instabilities, and typically a productivity increase is observed during this failure process. The productivity of gravel packs is largely affected by the interaction of the formation and the gravel, and the restriction of the natural deformation of the formation rock when exposed to stresses induced by drawdown and depletion appears to be critical with respect to the resulting permeability\textsuperscript{10}. Moreover, a recent study\textsuperscript{11} demonstrated that the impact of the permeability impairment of the near-wellbore formation is quite significant. For the case of open-hole single-screen completion, previous tests have shown that formation collapse does not significantly alter the well productivity\textsuperscript{12}.

Here a dedicated experimental study of production in open hole completions has been performed to correlate observations of productivity changes and sand production through single screens with the formation failure mode.

**Equipment and procedures**

200 mm diameter and 200 mm long thick-walled hollow cylinder (hole-diameter 48 mm) sandstone samples have been applied in this study. Figures 1 and 2 show the experimental apparatus used for the formation-screen interaction tests. The main part is the pressure cell with a capacity of 100 MPa. Connected to this cell is a fluid flow system capable of delivering 4 litres per minute at a maximum pressure of 40 MPa. Isotropic formation stresses are generated by hydraulic pressure acting on the sample through a rubber sleeve, and radial fluid flow is applied through a thin layer of gravel between the sample and the sleeve (see Tronvoll and Fjaer\textsuperscript{9}, for further description of the pressure vessel and instrumentation). The hollow cylinder specimen is equipped with an internal concentric screen. Four different single well screens were utilised. Two had a slot-width of 340 \(\mu\)m and external diameter of 35 mm and 41 mm, and the other two 120 \(\mu\)m and again external diameter of 35 mm and 41 mm. A 2 mm diameter and 3 mm long pipeline was placed for measuring the differential pressure across the screen. Figure 1 shows the sample with the screen mounted in the wellbore, the end-cap pistons, the flow lines, the confining sleeve, and a sand- trap at the cell outlet enabling volumetric measurements of sand production during the test. Between the confining sleeve and the test specimen is coarse gravel for distribution of the inlet fluid on the outer surface.

All tests were performed by applying hydrostatic confining stress and simultaneous flowing fluid from the external surface through the hollow cylinder specimen. The parameters logged automatically during a test are the confining stress and fluid inlet pressure, the fluid flow rate, and the differential pressure across the screen.

**Test matrix**

The test program was designed to mimic different production situations, i.e. combinations of stresses and pore pressure in the reservoir as expressed by depletion and drawdown. Previous results\textsuperscript{9,12} have shown that sand is normally produced continuously from a diffuse plastified zone around the borehole, or through shear failure near the surface leading to macroscopic ruptures - ‘breakouts’. A major objective was to explore how these different sand production mechanisms of rock destabilization influence the productivity in a single screen completion. The failure modes depend indeed on the rock mechanical properties as well as other factors such as in situ stress anisotropy, formation strength anisotropy, and pore pressure gradients. Morita et al.\textsuperscript{14} describe depletion induced sand production as more violent and dangerous than drawdown induced sand production. This may be explained by higher effective stresses developed during depletion leading to mature ruptures occurring around the well. Large drawdown may, on the other hand, lead to a rapid, transient sand production once a small failure zone is developed.

Another aspect included in this study was the annular clearance between the borehole wall and the screen surface. Contact between the screen and the borehole wall will result in a mechanical support stress, and thus a reduced shear stress concentration at the wall, and possibly prevention of sand production and formation collapse. With large annular clearance eventual produced sand/’breakouts’ may result in changes in the productivity. Three cases were studied, namely a ‘small’ (3-5 mm), a ‘large’ (7 mm) annular space between the screen and the rock specimen, and a gravel-packed.

The size of the slot-width of the screen relative to the rock formation grain size distribution was also varied to observe possible effects of mismatch, i.e. slot-widths outside the classical design criteria for screen completions. According to the gravel-size criterion of Saucier\textsuperscript{1}, sand production can be expected if the slot-width is above the d\textsubscript{50} - value of the formation grain size (meaning that 20wt% of the formation grains is larger than d\textsubscript{50}-value). Similarly, if the slot width is below the d\textsubscript{50} value a high loss of permeability is expected. The criteria set by Saucier\textsuperscript{1} were for gravel-pack design, their applicability to screen sizing has to be questioned.

In all tests the fluid used was a composition of lamp oil and a medical paraffin resulting in a viscosity around 5 cP. The performed test matrix is listed in Table 1, while the materials used are described in the next section.

**Test materials**

The weak, triassic Red Wildmoor sandstone\textsuperscript{9} and a synthetic sandstone\textsuperscript{13} have been used as analogues to formation sandstone. The synthetic sandstone manufacturing procedure con-
sists of mixing sand and sodium-silicate (resin) in a casting cell and then apply a certain compaction stress. At a pre-determined consolidation stress, CO₂ is flown through the sample to cure the resin, and finally air is flown to dry the sample. The forming technique is described in detail by Holt and Kenter⁶. The result is a homogeneous material with a uni-axisal compressive strength (UCS) of about 1.5 MPa, and a permeability in the darcy range. After complete unloading and demounting, a 1.5 inch (38 mm) core is drilled through the center of the sample, leaving a circular hole with diameter of about 48 mm. Four types of synthetic sandstone were casted; two coarse grain material (Coarse 1, Coarse 2), one fine grain (Fine 1), and one called T15, which is a field analogue with high plugging potential. The Red Wildmoor sandstone contains significant amounts of clay-minerals, used widely as a North Sea reservoir sandstone analogue. Table 2 lists the d₅₀ - and d₂₀ - values for all the materials tested. These materials match the classical design-criteria for one of the two slot-widths used, i.e. either 120 μm or 340 μm.

**Experimental results**

Figure 3a shows the results from the test performed on synthetic - Fine 1 type sandstone, where the confining stress, the inlet fluid pressure, the resulting flow rate, and the manually detected sand produced through the screen, are plotted as functions of time. Figure 3b shows the screen differential pressure as a function of time. A large annular clearance (7 mm) was used while the slot-width (120 μm) matched the sand grain size according to the classical design rules⁶.

**Screen pressure drop.** The screen pressure drop was measured between a point 3 mm away from the outer surface of the screen and the wellbore. Even after substantial mechanical failure of the rock, this pressure seldom exceeded 10 kPa. As the total fluid pressure drop is in the MPa range, the screen pressure drop is 2-3 orders of magnitude lower than that in the rock sample. The behaviour seen in Figure 3b is representative of all the tests performed. This means that the screen pressure drop can be neglected in the interpretation of the test results, as no significant plugging occurs in this region.

**Productivity and sand production.** The productivity (or productivity index, PI) is the ratio between the PI in the beginning of the test and the PI by the end of the test without any correction for the confining stress.

Figure 6a shows the productivity versus confining stress under constant fluid inlet pressure, and Figure 6b the flow rate versus fluid inlet pressure under constant confining stress for the three Red Wildmoor tests. No sand production was observed. In this case Darcy’s law appears to apply, but a significant effect of confining stress on productivity is seen.

**Rock failure.** In all tests the applied external stress was raised to levels well beyond the critical stress with respect to sand production. This resulted in material yield, shear dilation, and formation of macroscopic shear-bands (Figure 7a). Clearly, the porosity in the failure zone is considerably higher than this of the intact part of the rock specimen. The resulting permeability of this zone is apparently very high, as indicated by the screen differential pressure measurements, which also measures the pressure drop of the first 3 mm of sand settled on the screen surface. Moreover, it is seen that the entire annulus is filled with failed material, although voids exist (Figure 7b). Figure 7c shows an example of erosion channeling (‘piping erosion’) leading to violent influx of high concentrations of sand particles. This failure mode may lead to screen erosion in e.g. gas wells where the fluid velocities are high.

**Annular clearance.** In weak and ultra-weak sandstones dominated by plastic deformations, and eventually pore collapse in high porosity materials, large borehole convergence normally occurs as a result of drawdown and depletion. The size of the annular space between the formation and the screen may in such cases affect the evolution of the near-well permeability by preventing excessive plastic yield of the rock. Figure 4a and 6a show the normalized PI (productivity index) against the confining stresses - i.e. the actual PI-value divided with the PI-value at the lowest confining stress shown, for coarse synthetic sandstones and Red Wildmoor sandstones, respectively. From the Red Wildmoor tests (Figure 6b) there seem to be some influence of the annular space on the PI. However, part of this is due to the way of plotting, and part of this was due to pressure drop caused by moving the external gravel. So for the sandstones tested, this reduction in annular space did not affect the productivity substantially.

**Screen-formation mismatch.** The T15 sandstone (and partly the Coarse 1 material) is tested with a mismatch between the test on the fine grain synthetic sandstone. Clearly the productivity is reduced with increasing confining stress level, i.e. increased depletion or drawdown. As the synthetic sandstone used here is a soft, weak rock that exhibits significant compaction upon loading⁶, this observation may be understood. Moreover, it appears that sand production results in transiently increased productivity, which was also observed in an earlier study on sand production in a weak sandstone⁹.

In Table 3 key data for all tests are listed. The reduction in PI (API) is the ratio between the PI in the beginning of the test and the PI by the end of the test without any correction for the confining stress.
slot-width and the grain size. For the T15-sample (Figure 4), it appears that the mismatch does not influence the productivity, although plugging could have been expected in this test by the combination of coarse grain rock and small slot-width.

For the Coarse 1-sample with slot-width closer to the sand-producing limit, more sand was produced through the screen compared to the other tests. However, most of this test was performed under stress conditions where severe sand-production was expected.

External gravel packing. One test on Red Wildmoor sandstone with coarse gravel packed between the screen and the sample was performed. The gravel appears to stabilize the system very well; as the sample is taken to confining stresses far above total collapse for samples without this gravel. Also, no sand is produced in this test. However, the gravel seems to have some influence on the initial permeability of the system. The total productivity loss is almost 40%, indicating significant compaction of the rock.

Discussion

Rock failure and sand production. Clearly, sand production in clean sandstone formations is expected since formation sand often is liberated as single grains. In shaly, often ductile, sandstone formations, such as Red Wildmoor sandstone, sand production is often limited to release of a few grains and grain assemblies along with larger flakes and slabs of failed rock. Indeed a mixed mode failure was observed through X-ray Computer Tomography of the tested samples. The occurrence of larger rock fragments around the screen as a result of the failure process, defines an annular sand pack around the screen even if the screen slot opening is rather large compared to the average grain size. In brittle rocks and clean sandstones with low clay content this sand pack is less likely to consist of larger fragments, and the chances of sand production through the screen are therefore higher. Moreover, this collapsed material will not transmit the formation stresses directly to the screen, and it may act as a graded-filter reducing the pore pressure gradient.

Productivity. Even though the mobilization of inter-grain clay minerals such as smectite, chlorite, and kaolinite are associated with rock failure processes, it is likely that these fine particles are transported through the pore space of the failed rock relatively easy, as a significant porosity increase is often associated with macroscopic failure of a free surface of a sandstone formation. It is thus believed that fines plugging in the failure zone is less likely to occur as a result of pure mechanical damage. This does, however, not exclude the possibility of deposition of particles transported longer distances in the near-wellbore formation due to e.g. the radial flow convergence.

Productivity decay with increasing total drawdown, i.e. effective stress increase, is obvious in most of the experimental data. Also, a time dependency of this behaviour is seen as the productivity often drops with time shortly after increase of the stress level. Even though experimental artefacts may be responsible for some of this apparent stress dependency, it can not be ignored in the interpretation of the data. The stress dependency of productivity is related to volumetric strains evolving with stress level. As the volumetric strain is a measure of porosity change, a resulting permeability reduction is likely. Models describing the relation between volumetric strains and permeability are available in the literature.

The pressure build-up over the screen and the near-screen zone, was observed to be in the kPa range, i.e. typically 1 - 10 kPa. For a total length of flow of 5 mm over this zone, the average pressure gradient is in the range of 0.2 - 2 kPa/mm. The pressure drop over the specimen radius (about 75 mm) was in the range of 0.1 - 3 MPa for realistic flow velocities, i.e. three orders of magnitude larger than the screen pressure drop. This makes pressure gradients in the range of 1.3 - 40 kPa/mm, which is comparable, but on average higher than this around the screen. The explanation of porosity, and thereby permeability, increase in the region close to the screen surface therefore appears plausible even though these estimates are based on average pressure gradients. Naturally, due to the radial flow convergence, the fluid accelerates towards the borehole, and consequently the pressure gradient increases. This may be to some extent counteracted by the deformation induced permeability increase near the borehole wall. Note also that the pressure gradients are interesting mainly as a quantification of the relative effects of formation damage, while the total pressure drop determines the volume of fluids flown through a given rock matrix, and thereby the formation productivity. Fines plugging should therefore be related to a trade-off between fines concentration increase due to flow convergence and matrix porosity increase due to rock dilation. Note, however, that not all rocks dilate when exposed to shear stress concentrations. Some high porosity soft sandstones exhibit significant compactive behaviour, which may lead to permeability reductions.

A second observation made during the experiments was the deviations from Darcian flow in tests on synthetic sandstone. In the literature several models exist based on mechanisms of inter-granular turbulence. Even though the flow rates used in our experiments did not exceed the critical Reynolds numbers referred in the literature, such effects can not be excluded. For field practice, non-linear effects due to high velocities can be determined as part of a special core analysis. These effects can then be included in the productivity estimates through the use of an appropriate model.

External gravel packing in combination with single screens. Even though few tests were performed on Red Wildmoor sandstone, the results appear to indicate a relative reduction of the initial productivity in the case of gravel packing the screen-formation annulus. In addition, increasing the drawdown, and thereby increasing the stresses around the wellbore, leads to reduced productivity. It is believed that this productivity reduction is due to the mechanical compaction of the
material taking place as a result of the increased effective stress level. The reduction of, or absence of, a shear stress concentration at the formation surface, prohibits dilation and thereby porosity increase with increasing drawdown, with the result being pore closure and reduced porosity and permeability.

**Annular clearance.** No clear results in terms of sand production and productivity were obtained in the experiments. It was, however, observed from the X-ray CT scans a larger volume of failed material in the tests carried out with the larger clearance. This may be explained by the smaller clearance requiring a smaller volume of failed material to completely fill the annulus, including the extended wellbore radius due to the failing rock, which subsequently will re-enforce the borehole wall effectively thus prohibiting further development of the plasticified/failed region. Further increase in total drawdown, i.e. effective stress increase, then leads to a compaction and stabilization of the annular sand pack resulting in permeability reduction. This means that a relatively smaller zone of a natural sand pack should occur in the case of a small annulus.

**Design criteria.** As all the measurements of the screen differential pressure have shown that minor plugging of the screen takes place, design criteria could be to establish the importance of sand control through minimizing the screen slot width, and relax the fear of plugging of the screen surface. Conservative designs could thus be considered with respect to sand production. It should be stated, however, that no long term effects, i.e. the time scale of weeks and months, have been investigated. Slow plugging processes related to migration of fines over longer distances can therefore not be neglected. Moreover, no chemical effects related to e.g. increased water cut, precipitation processes, and effects of cyclic loading (due to well shut-in and bean-up) are considered in this study. Indeed such factors have demonstrated their impact on well productivity and/or sand production. It has, however, not been demonstrated clearly that they are the results of, or have been triggered by, the completion equipment. It is believed that the major processes determining the productivity of the well are those acting in the near-wellbore formation, which are less affected by the screen.

**Conclusions**

Physical model experiments of vertical single screen completions have been conducted using hollow cylinder rock specimens containing a scaled single screen.

The tests have shown that productivity reductions relating to increased effective stresses, i.e. increased total drawdown, have been observed for all materials tested and for all conditions tested. Non-Darcian flow was experienced for the synthetic sandstones tested, while the Red Wildmoor sandstone shows more linear behaviour.

Differential fluid pressures over the screen were measured to the range of 1 - 10 kPa, while the corresponding pressure drops in the test sample was in the order of 1 - 3 MPa. The screen differential pressures are thus negligible compared to this of the near-wellbore formation, and will for the conditions tested not significantly affect the productivity of the well.

No effect of reducing the annular clearance between the formation and the screen was observed with respect to sand production and productivity changes. A smaller failed region around the screen was, however, seen for the cases of a small annulus.

Mismatch of the screen slot opening relative to the formation grain size distribution did not significantly affect the productivity of the formation, but could in certain cases cause transient sand production through the screen when altering either the formation stress level or the fluid flowrate.

Gravel-packing of the screen-formation annulus eliminates sand production and appears to reduce the initial productivity of the well. Also, a continued productivity loss with increasing effective formation stress, i.e. increasing total drawdown, was observed.

Red Wildmoor sandstone exhibited a mixed mode shear/extensional failure, while all synthetic sandstones showed classical shear failure mechanisms. Mobilization of failed rock occurred for all materials, but significant amounts of failed rock remained attached to the borehole wall. Most of the mobilized material was trapped at the screen surface.

**Acknowledgment**
The authors would like to thank Saga and Statoil for the funding of this study and the permission to publish this paper.

**References**

bore Re-Enforcement or Sand Filtering?, SPE Paper 37506, 1997


**SI Metric Conversion Factors**

Pa × 6.8948 × E+03 = psi
Pa·s × 1.0 × E+03 = cP
l × 3.7854 × E+00 = gallon (US)
µm² × 1.0132 × E+03 = mD
cm × 2.54 × E+00 = in.
Table 1  Test matrix for the formation-screen interaction tests (o:340 µm slot width, x: 120 µm slot width)

<table>
<thead>
<tr>
<th>Material</th>
<th>Large annulus</th>
<th>Small annulus</th>
<th>Mismatch</th>
<th>Annulus gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse 1</td>
<td>o</td>
<td></td>
<td>(o)*</td>
<td></td>
</tr>
<tr>
<td>Coarse 2</td>
<td>o</td>
<td>o</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T15</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Fine 1</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red Wildmoor</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

*Coarse 1 material was slightly more fine-grained than expected, resulting in a grain size distribution close to the sand production limit as far as the classical design criteria are concerning.

Table 2  Grain size distribution of the test materials in terms of the d50- and d20-value

<table>
<thead>
<tr>
<th>Material</th>
<th>d50 [µm]</th>
<th>d20 [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse 1</td>
<td>210</td>
<td>410</td>
</tr>
<tr>
<td>Coarse 2</td>
<td>220</td>
<td>500</td>
</tr>
<tr>
<td>Fine 1</td>
<td>110</td>
<td>150</td>
</tr>
<tr>
<td>T15</td>
<td>316</td>
<td>380</td>
</tr>
<tr>
<td>Red Wildmoor</td>
<td>107</td>
<td></td>
</tr>
</tbody>
</table>

Table 3  Summary of test results

<table>
<thead>
<tr>
<th>Material</th>
<th>Screen [µm]</th>
<th>Annulus [mm]</th>
<th>ΔPI [%]</th>
<th>Max ΔP&lt;sub&gt;screen&lt;/sub&gt; [kPa]</th>
<th>Prodused sand [g]</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse 1*</td>
<td>340</td>
<td>7</td>
<td>70</td>
<td>-</td>
<td>22.2</td>
<td>shear</td>
</tr>
<tr>
<td>Coarse 2</td>
<td>340</td>
<td>7</td>
<td>negligible</td>
<td>3</td>
<td>6.3</td>
<td>shear</td>
</tr>
<tr>
<td>Coarse 2</td>
<td>340</td>
<td>3.5</td>
<td>negligible</td>
<td>3</td>
<td>&lt;1</td>
<td>shear</td>
</tr>
<tr>
<td>Fine 1</td>
<td>120</td>
<td>7</td>
<td>60</td>
<td>4</td>
<td>&lt;1</td>
<td>shear</td>
</tr>
<tr>
<td>T15**</td>
<td>120</td>
<td>7</td>
<td>25</td>
<td>9</td>
<td></td>
<td>shear</td>
</tr>
<tr>
<td>Red Wildmoor</td>
<td>120</td>
<td>7</td>
<td>10 - 40</td>
<td>-</td>
<td>0</td>
<td>mixed***</td>
</tr>
<tr>
<td>Red Wildmoor</td>
<td>120</td>
<td>3.5</td>
<td>85</td>
<td>-</td>
<td>0</td>
<td>mixed***</td>
</tr>
<tr>
<td>Red Wildmoor</td>
<td>120</td>
<td>7 gravel-filled</td>
<td>35</td>
<td>-</td>
<td>0</td>
<td>mixed***</td>
</tr>
</tbody>
</table>

* - screen close to sand production limit used
** - mismatch - screen with ‘high’ potential for plugging used
*** - mixed failure mode: combination of shear- and extensional failure
Figure 1 Schematic overview of the set-up of the interior of the pressure vessel with the test sample, screen, and instrumentation.

Figure 2 Flow diagram of controlled and measured parameters during screen performance experiment.
Figure 3 Experimental results of the test on the FINE 1 material: (a) Confining stress, inlet fluid pressure, flow rate, and sand production rate through the screen, and (b) differential pressure over the screen as functions of time.
Figure 4 (a) Normalized productivity index (PI) versus confining stress under constant inlet fluid pressure, and (b) flow rate versus inlet fluid pressure under constant confining stress for tests on coarse grain synthetic sandstones.
Figure 5 Productivity and sand production rate as a function of time for the test on Fine 1 material with large annulus.
Figure 6 (a) Normalized productivity index versus confining stress under constant inlet fluid pressure and (b) flow rate versus inlet fluid pressure under constant confining stress for Red Wildmoor sandstone tests.
Figure 7  Post-test X-ray CT images of different tests specimens; (a) horizontal cross-section showing shear-bands, (b) vertical cross section showing total convergence of formation-screen annulus, and c) localized erosion channeling.