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UNCONFINED COMPRESSIVE STRENGTH, THICK-WALLED CYLINDER AND TRIAXIAL TESTS ON HALLADALE-1 DW2 SANDSTONE AND SHALE CORE SAMPLES

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NOTATION

E	Young's moduli
ν	Poisson's ratios
l_0, d_0	Sample length and diameter
$\Delta l_1, \Delta l_2$	Incremental axial displacements
$\Delta d_1, \Delta d_2$	Incremental radial displacements
$\varepsilon_a, \varepsilon_r$	Average axial and radial strains respectively
F	Deviatoric load for unconfined compressive strength and multiple stage triaxial tests
σ_1'	Effective maximum principal stress or axial stress respectively
σ_3'	Effective minimum stress or confining pressure
c	Cohesion
ϕ	Angle of internal friction

EXECUTIVE SUMMARY

A rock mechanics study has been carried out on sandstone and shale core samples obtained from Halladale-1 DW2. The study included unconfined compressive strength tests, consolidated undrained triaxial tests and thick-walled cylinder tests. Unconfined compressive strength, TWC collapse pressure, elastic parameters, such as Young's modulus and Poisson's ratio, and strength parameters (cohesion and internal friction angle) for Mohr-Coulomb strength criterion were determined based on the experimental results.

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1 INTRODUCTION

CSIRO Petroleum (CSIRO) has been requested by Woodside/Origin to conduct a rock mechanics study on downhole sandstone and shale cores obtained from Halladale-1 DW2. The prime objective of the study is to conduct rock mechanical testing to determine unconfined compressive strength, triaxial and thick-walled cylinder collapse strengths of the core materials. The parameters to be measured include

- Young's modulus and Poisson's ratio;
- Unconfined compressive strength (UCS) of sandstones;
- Compressive strength parameters such as cohesion and angle of internal friction of shale; and
- Thick-walled cylinder (TWC) collapse strength of sandstones.

This report describes the test equipment, test procedures and conditions, and results and their analyses.

2 TEST EQUIPMENT

The UCS tests were conducted using a WF loading frame with a loading capacity of 5 ton. The axial force, sample axial and radial displacements were measured.

The triaxial tests on shale were conducted using a triaxial cell with a confining pressure capacity of 45 MPa. The cell has provision for measurements of sample deformations, axial load and confining and pore pressures.

The instruments used to measure the behaviour of the test sample during a triaxial test were as follows:

- two diametrically-opposed LVDTs (Linear Variable Differential Transformers) mounted between the sample end platens to measure axial deformation of the sample;
- four cantilever (orthogonal) radial gauges mounted at mid-height of the sample to measure radial deformation;
- a load cell located underneath the bottom steel platen to measure deviatoric axial load;
- a pressure transducer to measure confining (cell) pressure; and
- two pressure transducers to measure pore pressure at both ends of the sample.

A 300 MPa capacity high pressure triaxial cell was used for the TWC tests, with provision for measurement of sample radial deformations, axial load, and confining and pore pressures. The instruments used to measure the behaviour of the TWC sample were:

- cantilever radial gauges mounted at mid-height of the sample to measure radial deformation; and
- a pressure transducer to measure confining pressure.

Computer-controlled systems were used to control the deviatoric axial stress or displacement, and confining and pore pressures, and to perform data acquisition.

3 TEST SAMPLES

A total of 14 sandstone and 4 shale core plugs were received from Core Laboratories Australia Pty Ltd (Corelab). All the plugs were cut from recently obtained core materials. The sample plugs for sandstones had a nominal diameter of 38 mm and length ranging from 55 mm to 77 mm and for shale a nominal diameter of 25 mm and a length ranging from 50 mm to 55 mm. The shale plugs were cored along the core axis (vertical plugs) and the sandstone samples perpendicular to the core axis (horizontal plugs). The shale plugs were immersed in a low viscosity mineral oil during transportation to CSIRO from corelab and prior to testing at CSIRO.

The sample ends were prepared at CSIRO by trimming the plugs to the required length or the maximum possible length for short plugs using a diamond-tipped saw. The end surfaces of the sample were then ground with a grinding wheel. The perpendicularity of the end surfaces to circumferential surface and flatness of the end surfaces of the finished samples were in general accordance with the specifications recommended by ISRM (Brown, 1981). For TWC samples, a central borehole with a diameter of 1/3 of the sample diameter was drilled along the sample axis.

The sample dimensions, depth and test type are summarised in *Table 1*. All the sandstone samples, except one, had a length to diameter ratio of approximately 2, consistent with that suggested by ISRM (Brown 1983). The short sample had a length to diameter ratio of 1.5, lower than that suggested by ISRM. However, previous research showed that a ratio of between 1.5 and 2 had little effect on Young's modulus, although it may increase peak strength slightly, in comparison with the strength measured on a sample with a length to diameter ratio of between 2 and 3 (Brady and Brown, 1985).

4 TEST PROCEDURES AND RESULTS FOR UNCONFINED COMPRESSIVE STRENGTH AND TRIAXIAL TESTS

4.1 Unconfined Compressive Strength Tests

The UCS samples were saturated under vacuum with an equivalent formation brine solution (2.58% NaCl) prior to testing.

The test sample was jacketed with a flexible rubber membrane (0.5 mm thick Viton) and installed in WF loading frame. This was followed by installation of the transducers for measuring the sample axial and radial displacements, and axial force.

The sample was then axially loaded under a constant average axial strain rate of 1%/hour until the sample failed.

4.2 Consolidated Undrained Triaxial Tests

The procedure for conducting a consolidated undrained triaxial test on shale was as follows:

Installation of stainless steel mesh sidedrain and installation in the Autonomous Triaxial Cell. Sidedrain mesh strips were installed on the sample surface taped at the middle height of the sample. The purpose of the mesh sidedrain was to shorten the pore fluid flow path during saturation and consolidation stage, therefore significantly reducing test time. The sample was installed in the cell with radial and axial displacement transducers mounted;

Back pressure saturation. After the sample installation, a confining pressure of 5 MPa was applied. Sample saturation was started by injecting the simulated pore fluid from one end of the sample at 3 MPa while the pore pressure valve at the other end of the sample was closed. When the pore pressure measured at the other (undrained) end reached 3 MPa, the sample was assumed to be fully saturated. The pore water composition of the shale is given in Appendix;

Undrained pressurisation. The confining pressure was increased to the required level for the test at a constant rate of 0.5 MPa/min. under undrained condition by closing the pore pressure valves at both ends of the sample;

Consolidation. After the pore pressure inside the sample had stabilised, open the back pressure line (top pore pressure valve) and controlled at 3 MPa. The sample was assumed to be fully consolidated when the difference in the top pore and back pressures was less than 0.25 MPa, or the sample deformation ceased; and

Deviatoric Loading. The back pressure line was closed and the deviatoric stress was applied at a constant axial strain rate determined from the consolidation stage. Both the top and bottom pore pressure valves were closed during loading (undrained). The axial strain rate adopted was 6.0 x 10^{-5}/hour (or 0.003mm/hour for a 50mm long sample). As the deviatoric axial loading progressed, the pore pressure inside the sample would increase or decrease depending on the volumetric deformation of the sample. The deviatoric axial stress was increased and allowed to proceed beyond the failure stress (peak strength) until a residual strength was observed.

4.3 Triaxial Test Conditions for Shale Samples

The confining and pore pressures at consolidation stage are summarised in *Table 2*. The selection of the effective confining pressure range was based on the estimated effective in-situ stresses. The effective confining pressure range was selected to cover the mean effective in-situ stress.

4.4 Test Results and Analyses

The average axial and radial strains ($\varepsilon_a, \varepsilon_r$) are calculated from Equations 1 and 2 respectively:

$$\varepsilon_a = \frac{\Delta l_1 + \Delta l_2}{2 \times l_0} \tag{1}$$

$$\varepsilon_r = \frac{\Delta d_1 + \Delta d_2}{2 \times d_0} \tag{2}$$

where Δl_1 and Δl_2 are axial displacements measured at two diametrically opposed positions; Δd_1 and Δd_2 are radial displacements measured in two orthogonal directions; and l_0 and d_0 are sample length and diameter respectively. Note that extension radial strain and compression axial strain are defined as positive. The deviatoric stress ($\sigma_1 - \sigma_3$) is calculated from Equation 3:

$$\sigma_1 - \sigma_3 = \frac{4F}{\pi\left[d_0 + \left(\Delta d_1 + \Delta d_2\right)/2\right]^2} \tag{3}$$

where F is the deviatoric load measured by the load cell.

The experimental results are presented as curves of deviatoric stress (or axial stress for UCS tests) vs average axial strain and average radial strain vs average axial strain, as shown in Figures 1 and 2 for the UCS tests on sandstone samples and Figures 3 to 8 for the consolidated undrained triaxial tests on shale samples. The failure mode observed on the tested samples was shear failure for both UCS and triaxial tests.

Elastic Parameters

The Young's modulus (E) and Poisson's ratio (ν) are determined as the tangential slope of the curve of deviatoric axial stress vs average axial strain, and the tangential slope of the curve of average radial strain vs average axial strain at approximately 50% of the maximum deviatoric stress respectively. The derived Young's moduli and Poisson's ratios are summarised in *Table 3* for the UCS tests and *Table 4* for the consolidated undrained triaxial tests.

Peak Strength Parameters

The peak strength is simply taken as the maximum deviatoric stress on a deviatoric stress vs average axial strain curve. *Tables 3* and *4* summarise all the strength data. Figure 9 show the Mohr circles representing peak strength data for the consolidated undrained triaxial tests on the shale samples. The Mohr-Coulomb strength criterion is applied to the peak strength data. In terms of principal effective stresses, the Mohr-Coulomb criterion can be expressed as (Goodman, 1989):

$$\sigma_1 = 2c\tan\left(\frac{\pi}{4} + \frac{\phi}{2}\right) + \sigma_3\tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \tag{4}$$

where c and ϕ are cohesion and angle of internal friction respectively. The strength parameters derived from linear regressional analysis and the strength envelope are presented in Figure 9.

5 THICK-WALLED CYLINDER TESTS

5.1 Test Procedure

The TWC sample was saturated with brine solution (2.58% NaCl) prior to testing. It was then jacketed with a rubber membrane and installed in the high pressure triaxial cell. The TWC sample was pressurized hydrostatically at a constant rate of 1 MPa/min. until the sample collapsed. The collapse pressure was detected from the measurements on sample diameter change using radial gauges. During the test, the borehole was filled with the brine solution and opened to atmosphere.

5.2 Test Results

All the TWC test results are presented as curves of radial displacement versus confining pressure, as shown in Figures 10.

The radial displacement is a measurement of the sample diameter reduction, and is found to be the most reliable measurement to detect the failure of TWC samples. As shown in Figure 10, some non-linearity of the curves of radial displacement versus confining pressure was observed at the beginning of the test (up to 2 to 3 MPa confining pressure). This was probably due to a "contact" effect between the radial displacement transducers and sample surface, rather than a true sample behaviour, an observation similar to the "bedding down" effect of axial deformation in a triaxial test. Towards the end of the test, large radial deformations were observed with small change in confining pressure, which indicates sample collapsing. The maximum confining pressure that the TWC sample experienced during the test is defined as the TWC collapse pressure, and is summarised in *Table 5.*

Observations on the tested samples showed that the TWC samples collapsed on one side. The collapse was along almost the full sample length, apart from the area close to the sample ends, where part of the borehole still remained open, probably as a result of fiction between the sample ends and steel platens.

6 CONCLUDING STATEMENT

A rock mechanics study has been carried out on sandstone and shale core samples obtained from Halladale-1 DW2. The study included unconfined compressive strength tests, consolidated undrained triaxial tests and thick-walled cylinder tests. Unconfined compressive strength, TWC collapse pressure, elastic parameters, such as Young's modulus and Poisson's ratio, and strength parameters (cohesion and internal friction angle) for Mohr-Coulomb strength criterion were determined based on the experimental results.

7 REFERENCES

Brown, E. T. (1981). Rock Characterisation, Testing and Monitoring, *ISRM Suggested Methods*. Pergamon Press, Oxford, U.K.

Brady, B. H. G. and Brown, E. T. (1985). Rock Mechanics for Underground Mining. George Allen & Unwin, London, U.K.

Goodman, R. E. (1989). Introduction to Rock Mechanics. John Wiley & Sons, 2nd Edition, New York, U.S.A.

APPENDIX

PORE WATER COMPOSITION OF HALLADALE-1 SHALE

Pore Water Composition of Halladale-1 Shale

The pore water composition of Halladale-1 shale was determined by pore water compositional analysis. The formation samples were dried in an oven at 100 °C to remove any water and then crushed to a powder with a pestle and mortar. A weighed portion of the samples was added to a pre-determined quantity (five times of formations sample weight) of de-ionised distilled water (Mill Q water). The solutions were then mixed in a magnetic stirrer overnight. The resulting solutions were filtered for water compositional analysis. Simulated pore fluid prepared based on the pore water composition is given in *Table A1*

Table A1. Pore Fluid Composition of Halladale-1 Shale

Constituent	**Weight per Litre (g/L)**
$CaSO_4$	23.09
$NaHCO_3$	4.51
$MgSO_4$	3.30
NaCl	18.01
$CaCl_2$	0.00
K_2SO_4	31.54

TABLES

Table 1: Summary of Test Sample Details

Sample	**Depth (m MDBRT)**	***Rock Type***	***Length (mm)***	***Diameter (mm)***	***Test Type***
A	1809.45	Sandstone	77.11	37.20	TWC
B	1809.50	Sandstone	77.23	37.17	UCS
C	1812.4	Sandstone	76.01	36.95	TWC
D	1812.45	Sandstone	71.69	37.18	UCS
E	1812.5	Sandstone			No test
F	1817.77	Sandstone	75.21	37.33	UCS
G	1817.83	Sandstone	59.37	37.44	TWC
H	1817.88	Sandstone			No test
I	1819.62	Sandstone	75.67	36.87	TWC
J	1819.67	Sandstone	55.15	37.12	UCS
K	1822.91	Sandstone	75.43	37.28	TWC
L	1822.95	Sandstone	76.54	37.25	UCS
M	1826.27	Sandstone	77.27	37.31	TWC
N	1826.33	Sandstone	75.8	37.31	UCS
W	1831.21	Shale	55.51	23.53	Triaxial
X	1831.21	Shale			No test
Y	1831.21	Shale	53.30	23.62	Triaxial
Z	1831.21	Shale	50.87	23.55	Triaxial

Table 2: Consolidation Conditions for Shale Samples

Sample	***Confining Pressure (MPa)***	***Pore Pressure (MPa)***	***Effective Confining Pressure (MPa)***
W	18	3	15
Y	13	3	10
Z	8	3	5

Table 3: Summary of UCS Test Results on Sandstones

Sample	***Depth (m MDBRT)***	***Elastic Parameter***		***UCS (MPa)***
		E (GPa)	***ν***	
B	1809.50	1.62	0.41	10.36
D	1812.45	0.84	0.44	4.63
F	1817.77	1.74	0.29	6.92
J	1819.67	0.83	0.31	4.48
L	1822.95	1.70	0.17	10.71
N	1826.33	1.71	0.22	9.17

Table 4: Summary of Consolidated Undrained Triaxial Test Results on Shale

Sample	***Depth (m MDBRT)***	***Elastic Parameter***		***Peak Strength***	
		E (GPa)	***ν***	σ_3' ***(MPa)***	σ_1-σ_3 ***(MPa)***
W	1831.21	4.77	0.40	10.50	40.11
Y	1831.21	6.15	0.44	4.35	27.25
Z	1831.21	4.48	0.47	2.62	26.38

Table 5: Summary of Thick-Walled Cylinder Test Results on Sandstone

Sample	***Depth (m MDBRT)***	***TWC (MPa)***
A	1809.45	28.87
C	1812.40	21.04
G	1817.83	47.78
I	1819.62	22.15
K	1822.91	31.27
M	1826.27	35.07

FIGURES

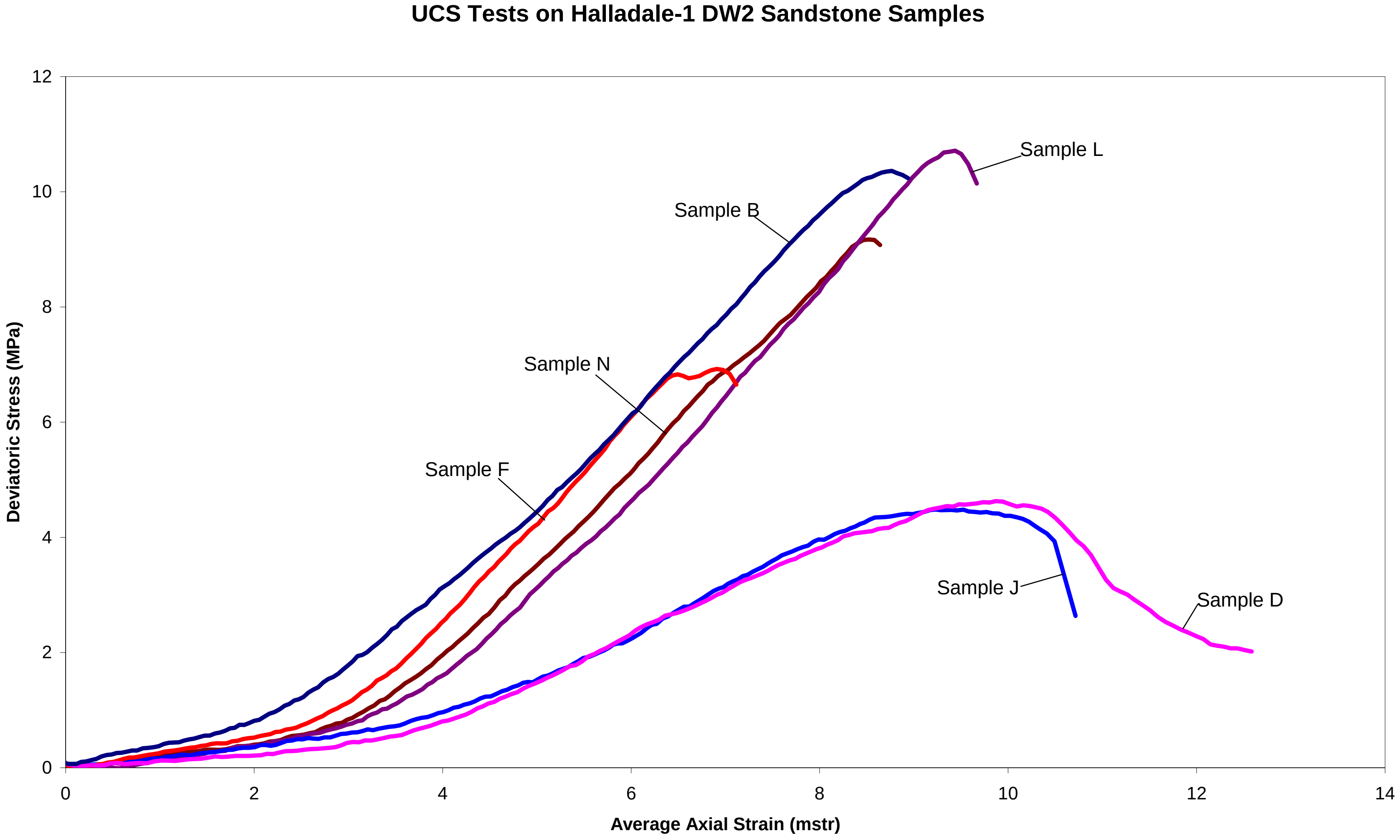

Figure 1. Deviatoric stress versus average axial strain behaviour for the unconfined compressive strength tests.

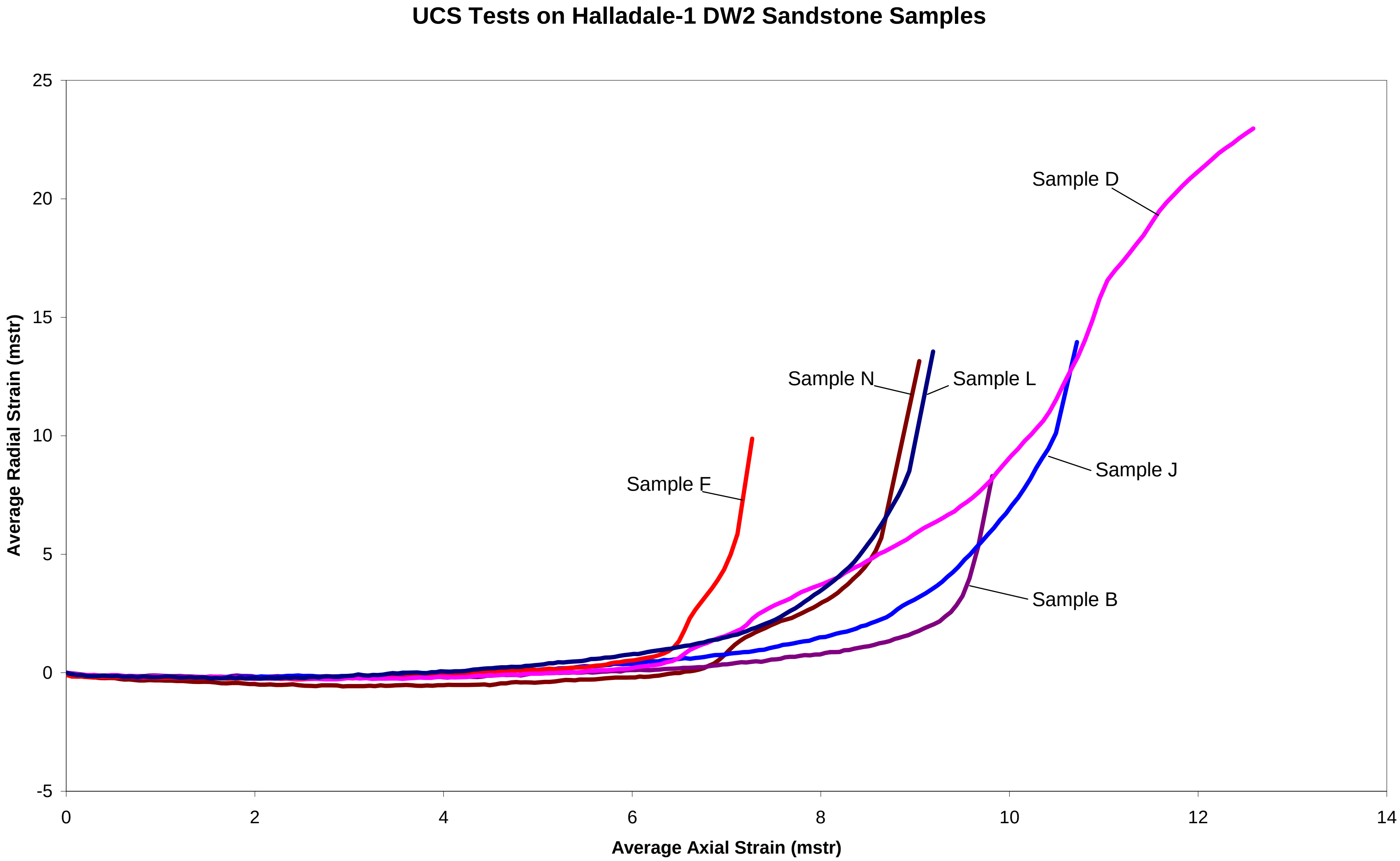

Figure 2. Average radial strain versus average axial strain behaviour for the unconfined compressive strength tests.

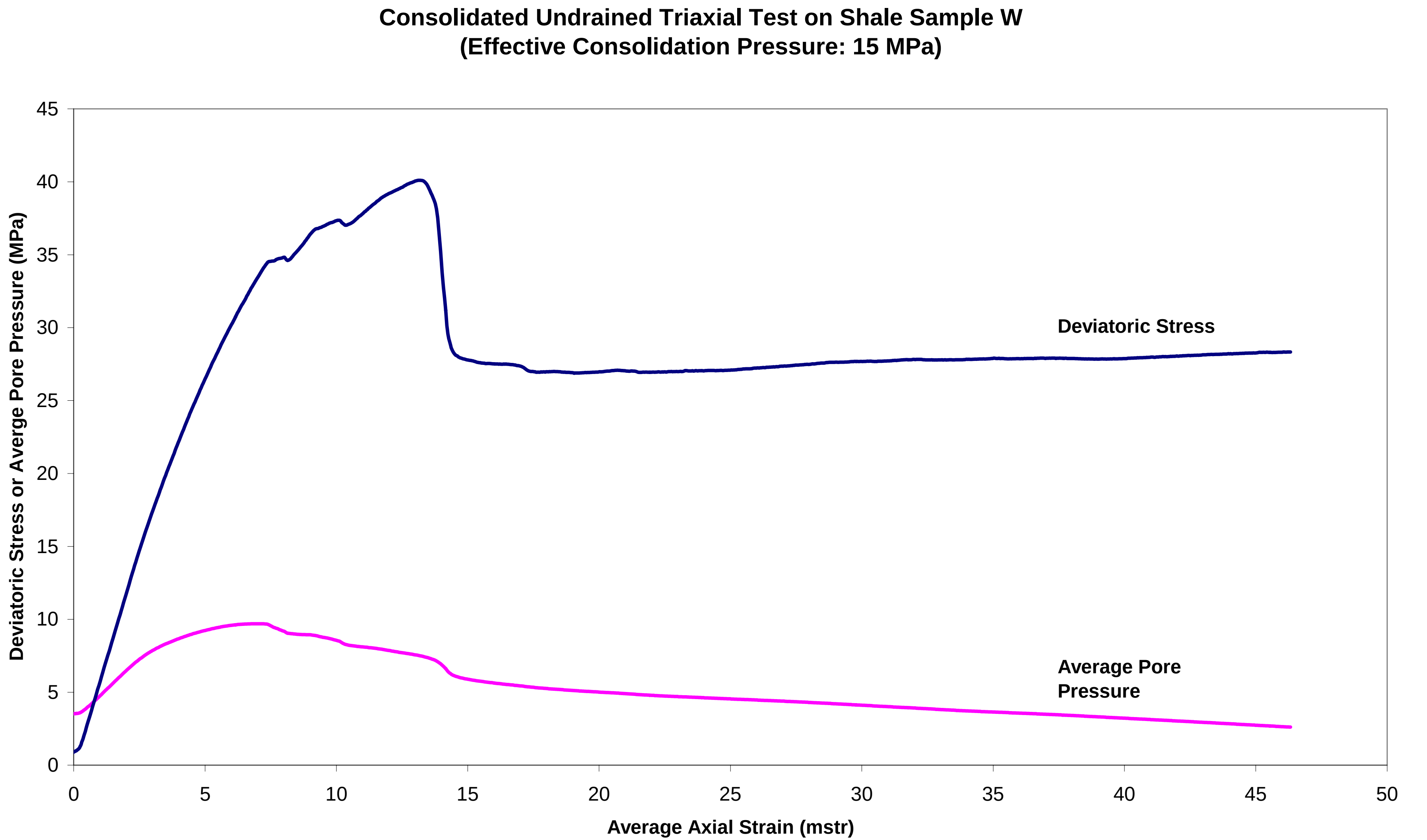

Figure 3. Deviatoric stress and average pore pressure versus average axial strain behaviour for the consolidated undrained triaxial test on shale Sample W.

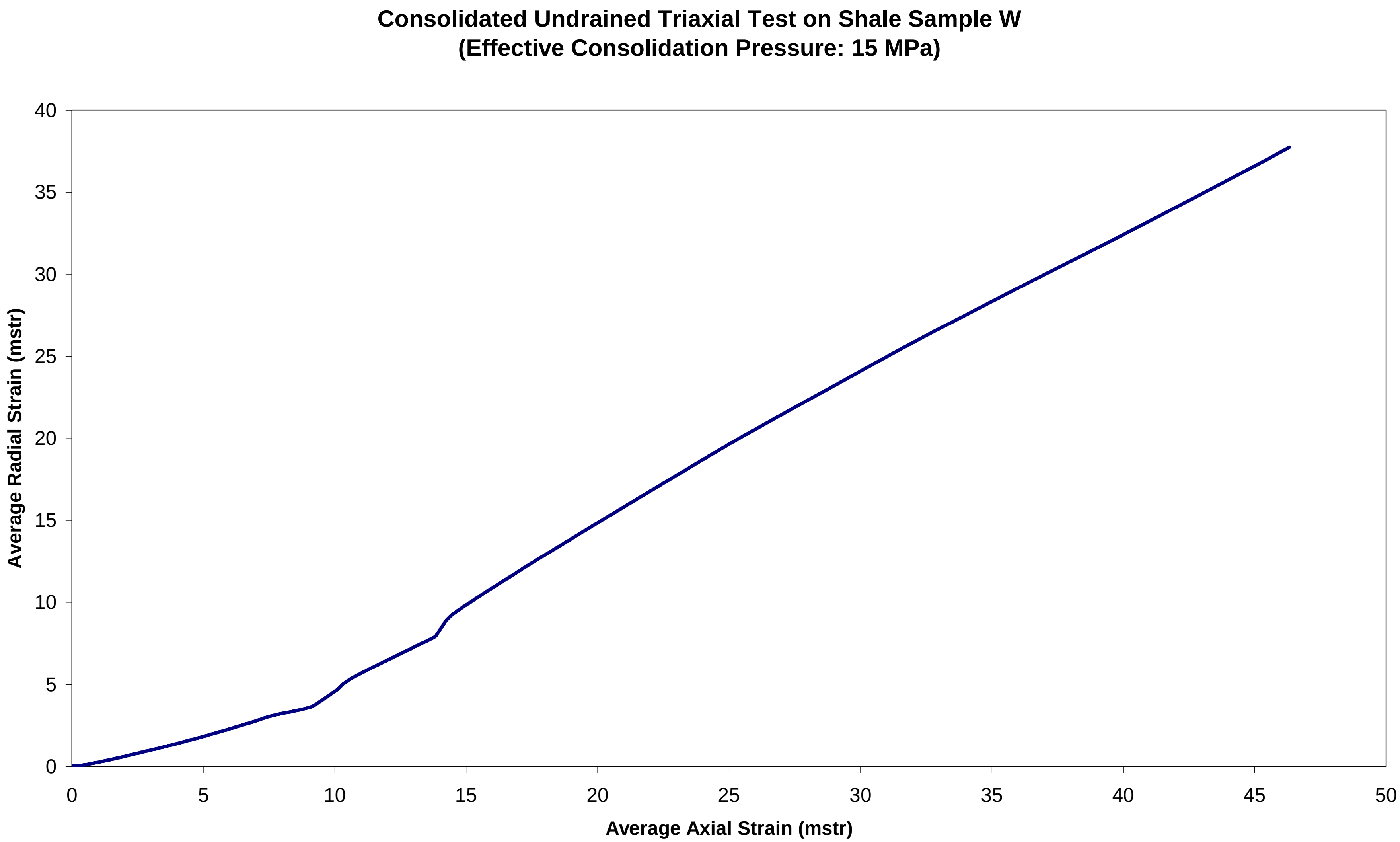

Figure 4. Average radial strain versus average axial strain behaviour for the consolidated undrained triaxial test on shale Sample W.

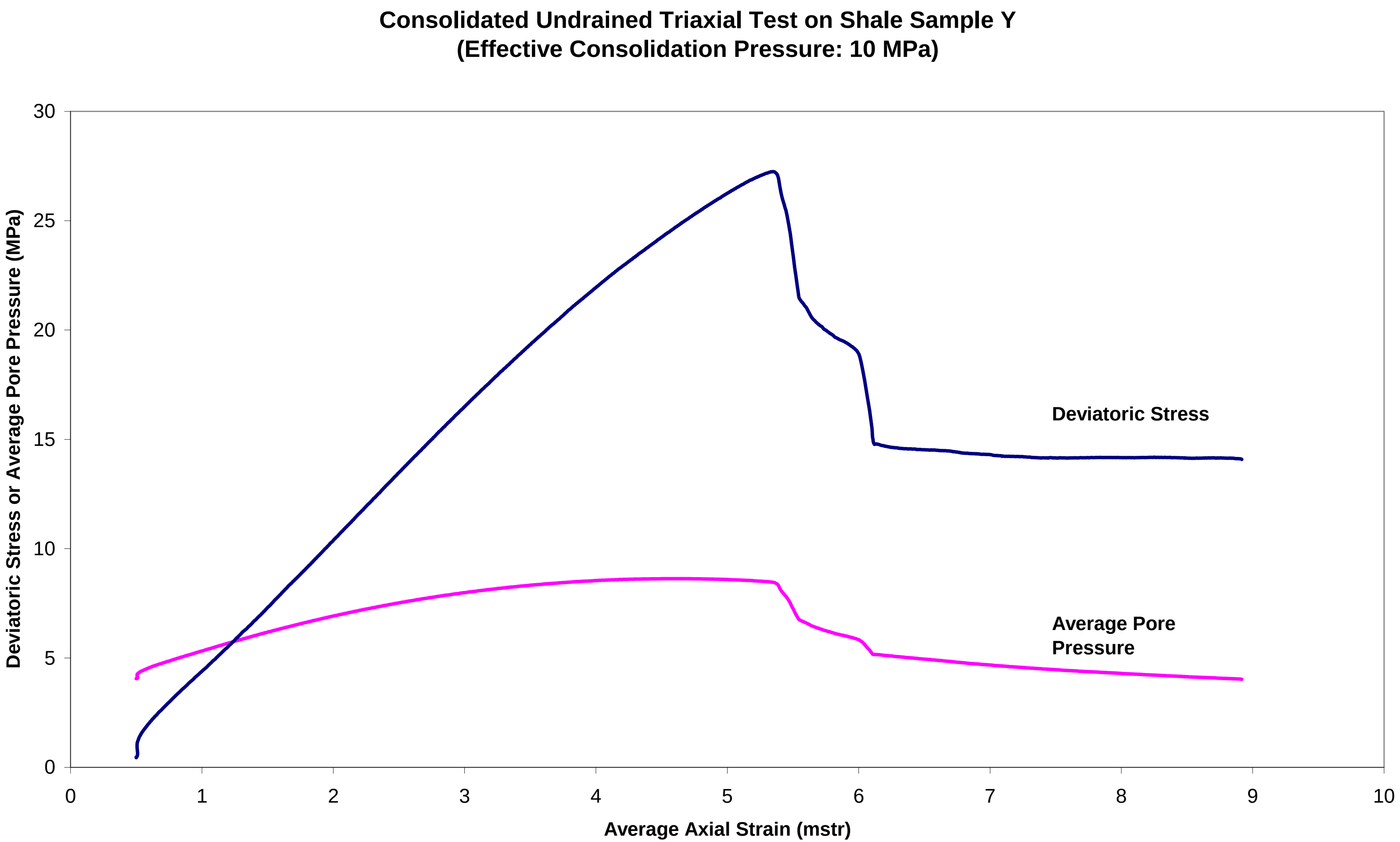

Figure 5. Deviatoric stress and average pore pressure versus average axial strain behaviour for the consolidated undrained triaxial test on shale Sample Y.

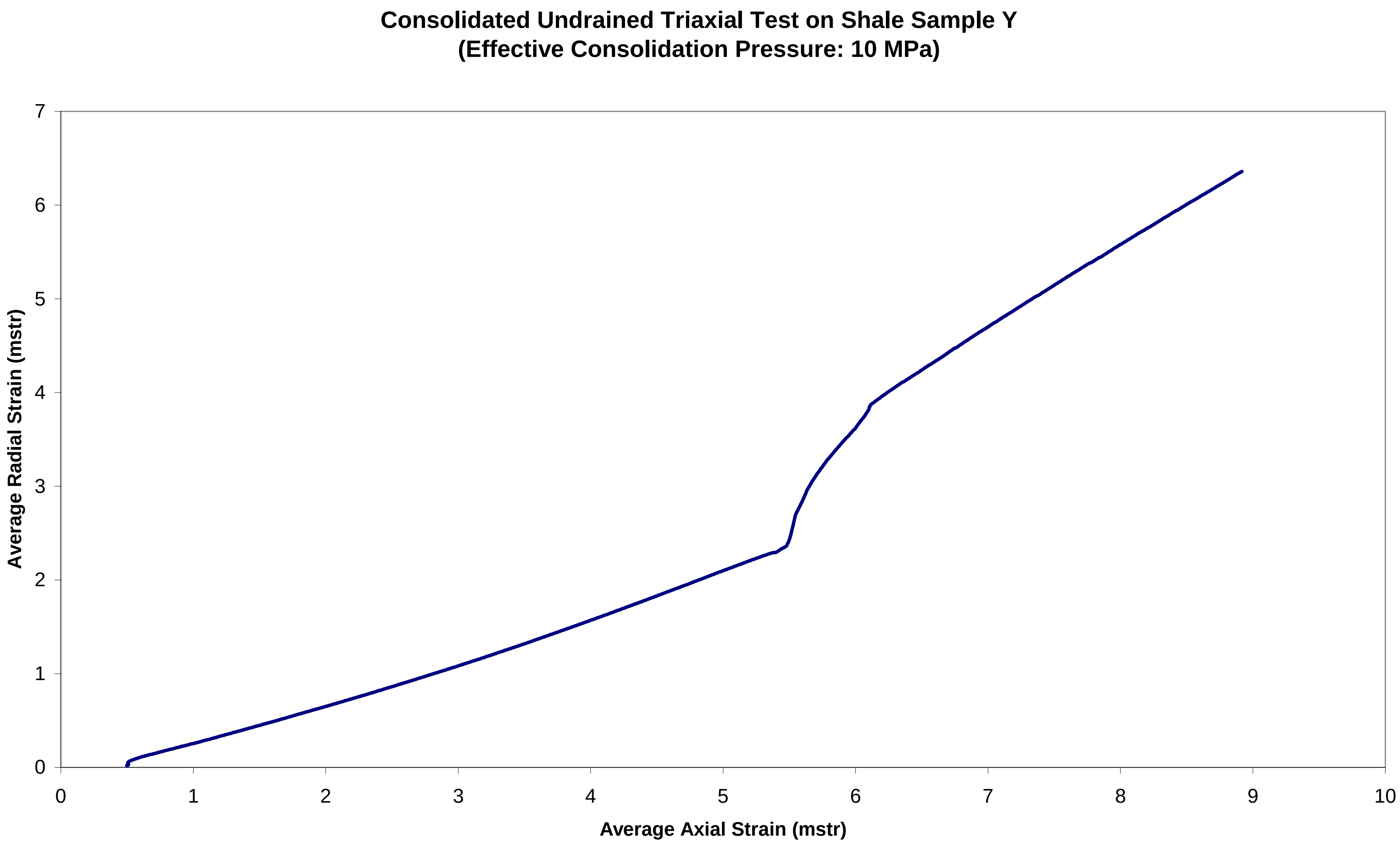

Figure 6. Average radial strain versus average axial strain behaviour for the consolidated undrained triaxial test on shale Sample Y.

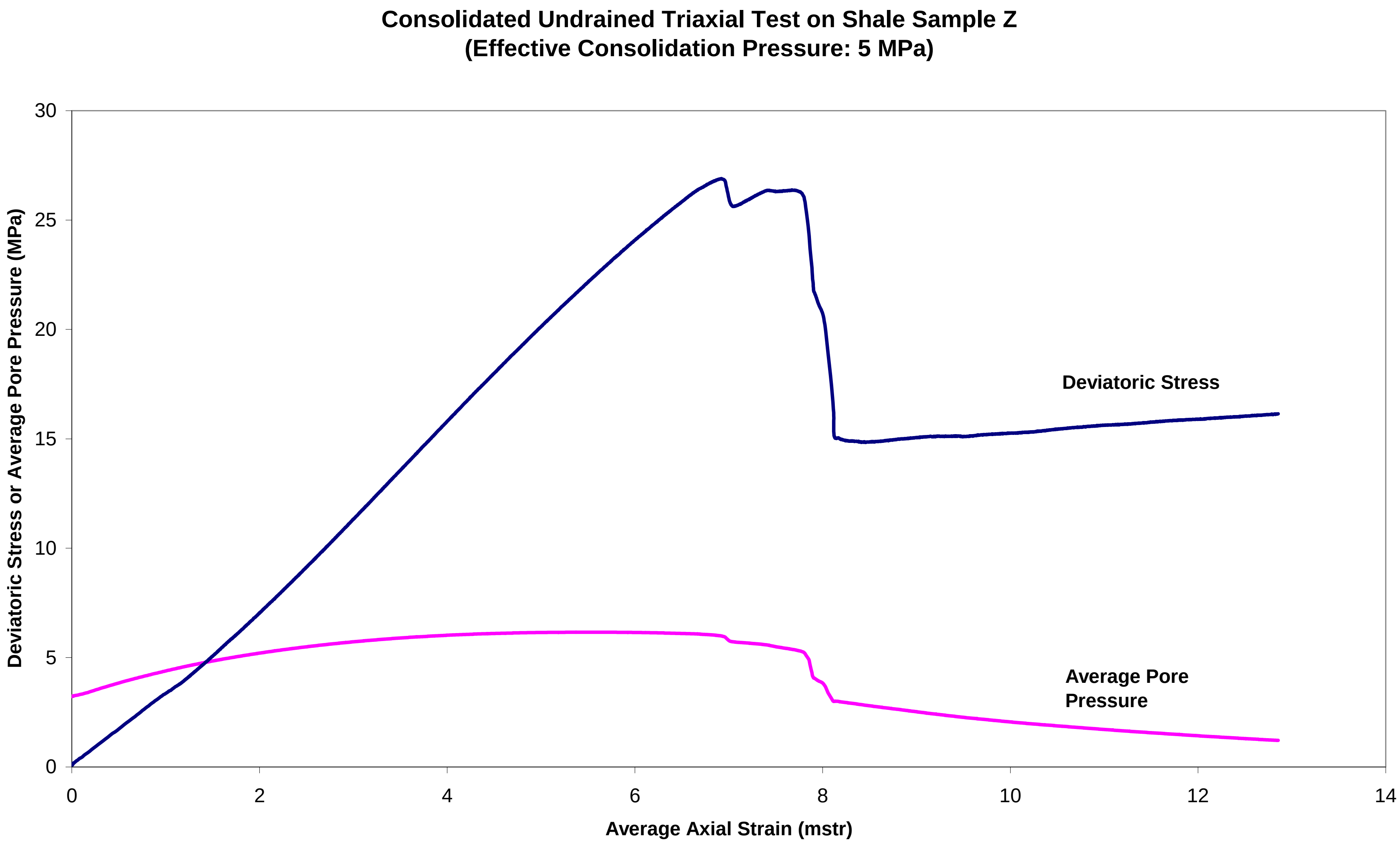

Figure 7. Deviatoric stress and average pore pressure versus average axial strain behaviour for the consolidated undrained triaxial test on shale Sample Z.

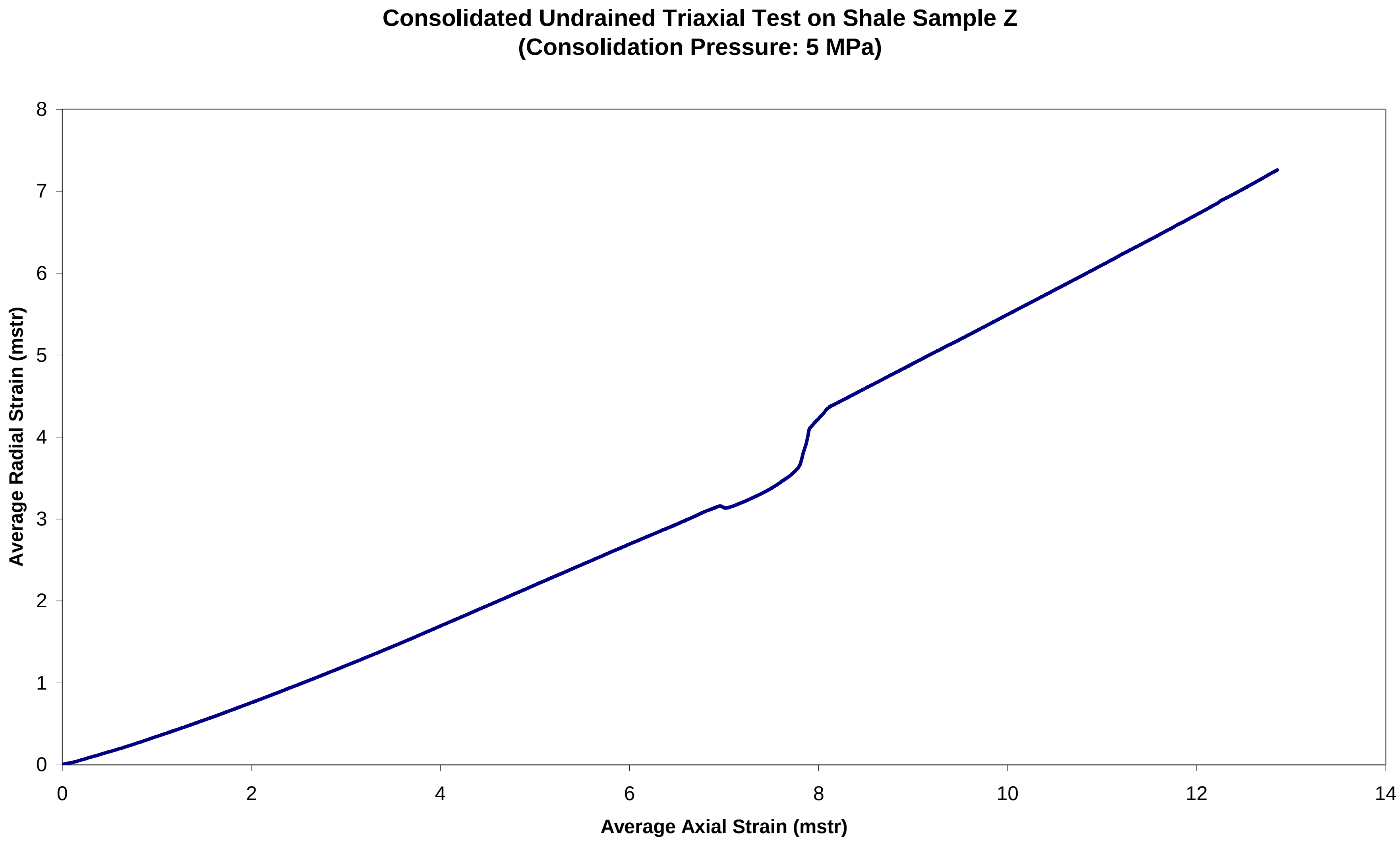

Figure 8. Average radial strain versus average axial strain behaviour for the consolidated undrained triaxial test on shale Sample Z.

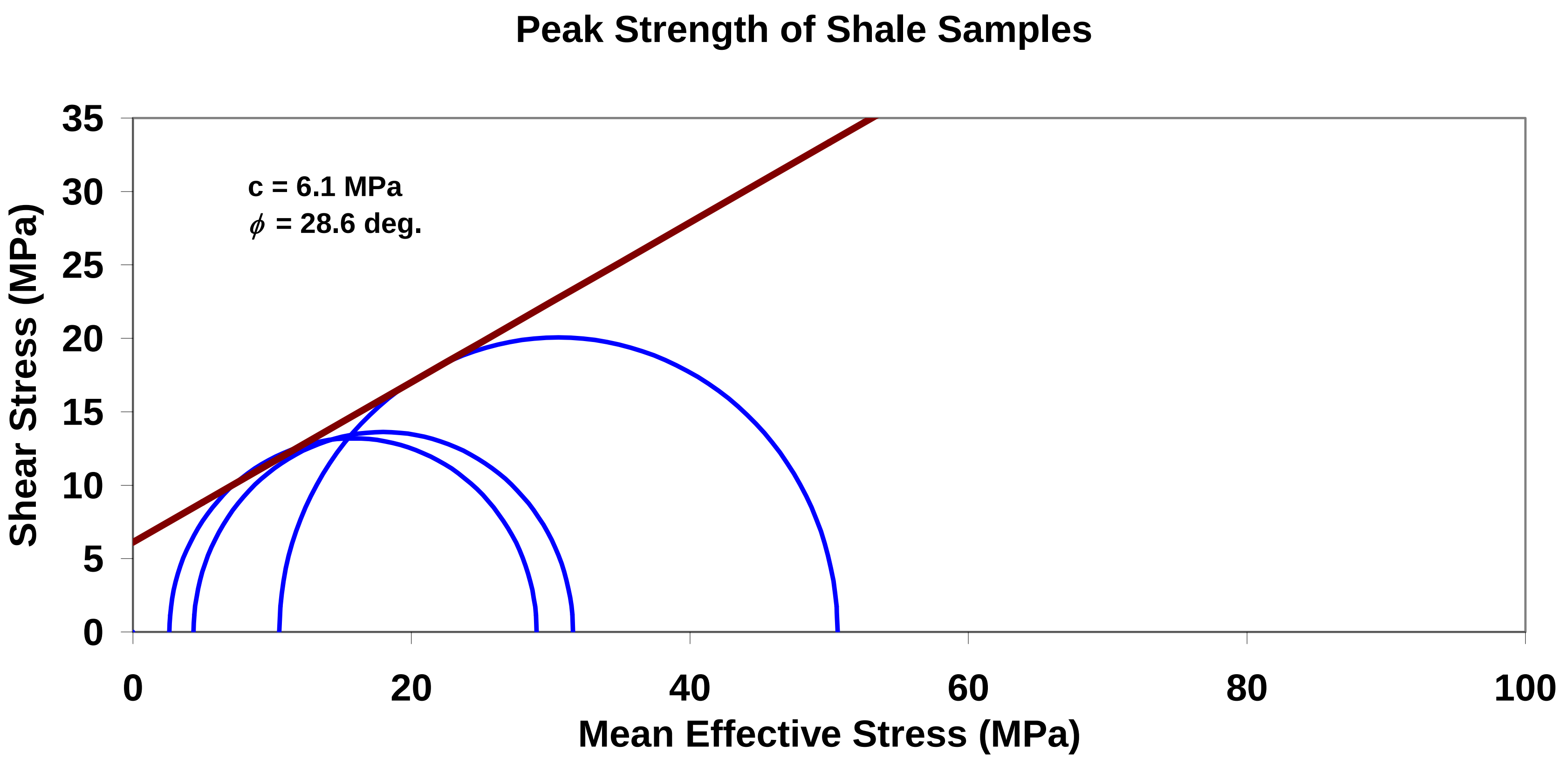

Figure 9. Mohr circles and Mohr-Coulomb strength criterion of peak strength for the consolidated undrained triaxial tests on shale samples.

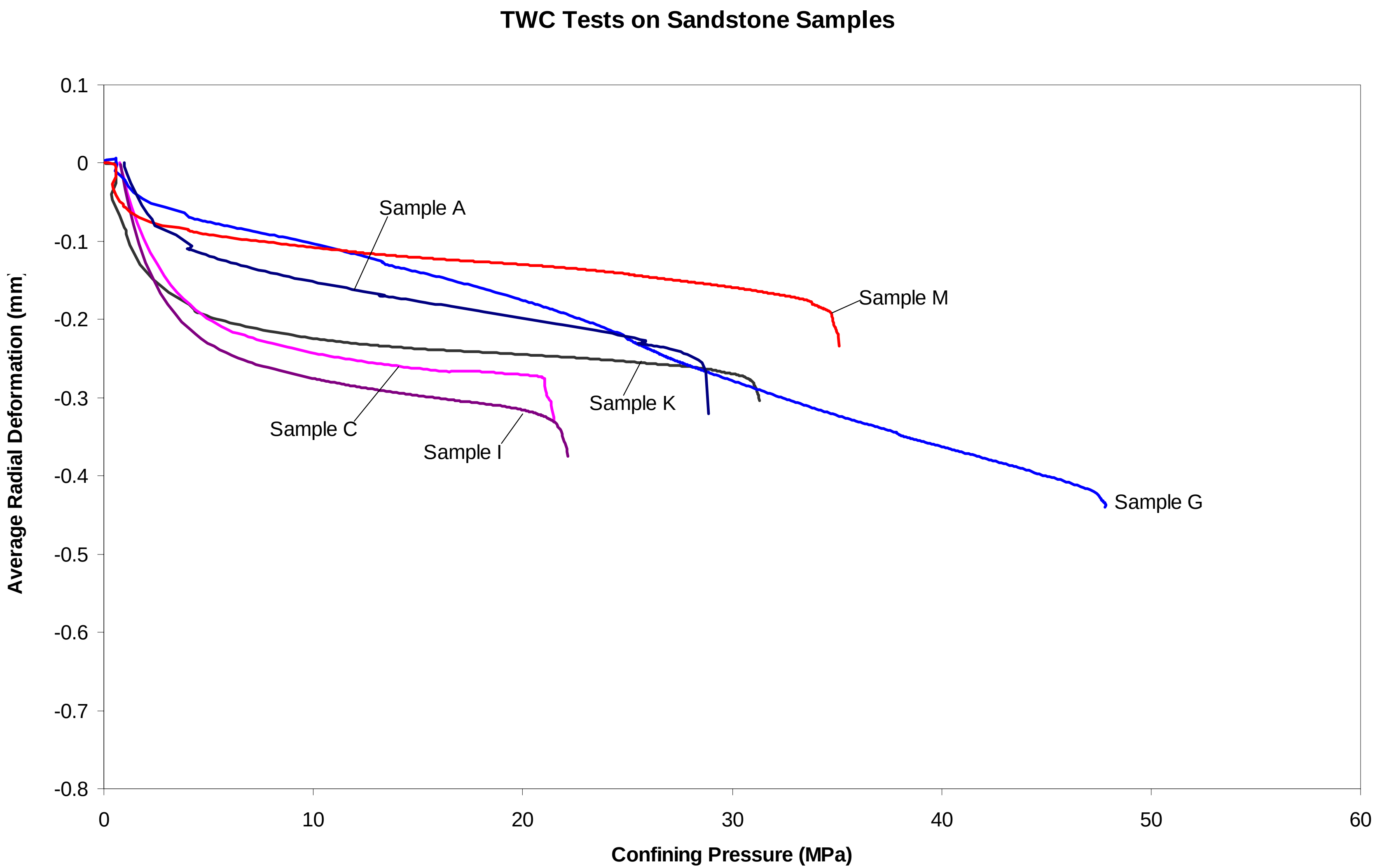

Figure 10. Average radial deformation versus confining pressure behaviour for TWC tests on sandstone samples.