Characterisation of Pavements Materials from Accelerated Model Pavement Testing and Back-analysis

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Pavement materials can be characterised using accelerated model testing, which allows pavement materials to be tested under field performance conditions. The tests can be conducted directly in the field or on model pavements in the laboratory. This report aims to describe experiments conducted on pavement materials using an accelerated model testing method, and how the materials were characterised using back-analysis. The aim of the thesis is to characterise the pavement materials. A design pavement was tested in a pavement model tank using cyclic loading and then, from the results, the materials were characterized using back-analysis. The 'design pavement' consisted of a lightly stabilised bound granular base material and a clay subgrade. The results of the accelerated model testing were then compared to triaxial tests conducted on elements of the base material using similar stress conditions to those experienced in the model pavement. It was found that the results obtained from the accelerated model pavement testing were not able to be replicated in a triaxial test under similar stress conditions.

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Nomenclature

ε = Strain
ε_r = Recoverable strain
σ_d = Deviatoric Stress (MPa)
M_r = Resilient modulus (MPa)

[1] LT, School of Engineering & Information Technology. ZEIT4501

I. Introduction

Pavement materials are subjected to many different stress variables, such as traffic loading and weather conditions. The stresses induced from these variables are complex in nature. Excessive exposure to these stresses cause the pavement to deteriorate, which reduces the performance of the pavement and thus its safety for users. Rutting, or permanent deformation of a pavement along a wheel path, is a prominent deterioration mechanism. Prediction of rutting has become a concern in the M-E approach to design. Accelerated model pavement testing (AMPT) has become one of the more recent ways to model permanent deformation in pavements [1].

AMPT provides an adequate indication of probable field performance for a design pavement. The test is able to evaluate the field performance of a design pavement across the pavement structure as a whole. Field tests generally give a good indication of how a pavement will behave across its design life, however long term trials can take many years and are therefore not suitable in the design pavement process [2].

AMPT uses a cyclic loading facility that can study the fatigue and permanent deformation in a material. A model pavement is constructed in a testing tank, the tank is then placed under a loading cell which simulates the traffic loading on the pavement. One of the outputs from AMPT is the resilient modulus of a material, which can be used in the characterisation of the material. The resilient modulus quantifies the stiffness of the material, as it is the ratio of deviatoric stress to recoverable strain [3].

II. Procedure Accelerated Model Pavement Tank Testing

The accelerated model pavement tank testing was conducted at the University of New South Wales Australian Defence Force Academy campus. The testing was conducted using a lightly stabilised granular material for a base layer, and a clay for the subgrade layer. The base layer thickness was 150 mm and the thickness of the subgrade was 600 mm. The schematic of the testing facility is shown in figure 1.

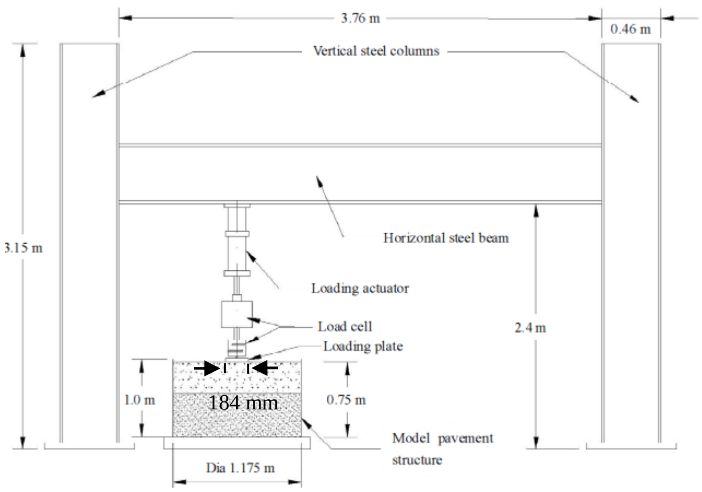

Figure 1 - Schematic of Accelerated Model Pavement Tank Testing facility

A. Model pavement

The preparation of materials for laboratory experiments is generally straightforward. However, for AMPT a large amount of material is required to construct the model pavement. The pavement was constructed in 25 mm layers. To ensure a consistent moisture content of the layers all of the materials were oven dried at 105°C. The oven dried materials were then divided into batches and placed in separate containers to cool down to room temperature. The batches each contained enough material for one layer, 36 Kg for the subgrade and 55 Kg for the base.

The subgrade layers were prepared by mixing the oven dried materials in a concrete mixing machine. After approximately ten minutes of mixing, 11.9 Kg of water was slowly added. After, the material was mixed with the water for another ten minutes. Once the layer was thoroughly mixed it was placed and compacted in the tank. Each batch was compacted to 25 mm to ensure that the compaction of the material was consistent throughout the subgrade. The interior wall of the tank had been marked in increments of 25 mm to ensure that the required compaction was achieved. This ensured that the density of the subgrade was consistent throughout the entire subgrade layer.

The base layer consisted of 55 Kg of oven dried granular material, 0.62 Kg of cement, 0.21 Kg of fly ash and 4.88 Kg of water. Initially the granular material was mixed in a concrete mixed for approximately ten minutes. The cement, fly ash and water were then slowly added, and the material was mixed for another ten minutes. As with the subgrade, each batch was placed and compacted in the tank in 25 mm layers.

Compaction was achieved with a vibratory compactor/jack hammer. The vibratory compactor consisted of a rectangular cross section steel head of 15 cm length, 10 cm width and 1 cm thickness. A square thin rubber mat of 25 x 25 x 0.5 cm was placed between the compactor and the layer, to evenly distribute the force and give a smoother finish to the top of the layer.

Two of the base layers were mixed with a slightly higher amount of material. The percentage of water, cement and fly ash remained the same. The extra material was used to conduct unconfined compression testing (UCS) on the materials, to ensure that the mixes had similar properties. The testing was conducted in accordance with AS 5101.4 – 2008 Unconfined Compressive Strength of compacted materials. The results of the testing are located in table 1.

Table 1 – UCS testing conducted on layer samples

Layer	Sample	Load (KN)	Average Load (KN)	Stress (KPa)	Average Stress (KPa)
1	1	-19.131	-19.8	-2209.315	-2289.656
1	2	-20.272		-2341.114	
1	3	-20.076		-2318.541	
6	1	-22.286	-21.8	-2573.766	-2522.793
6	2	-25.206		-2910.910	
6	3	-18.043		-2083.704	

As can be seen in table 1, the UCS testing showed that the compressive properties of the base layer mixes were similar. This shows that even though the mixes were conducted separately the properties of the base layers were fairly consistent.

After the model pavement was constructed it was cured for 28 days. Curing is an important stage for a cementitiously stabilised material (D. Paul, 2011). By curing for 28 days the material was able to reach its final strength. The pavement was covered with plastic sheeting during the duration of the curing process to prevent moisture loss.

B. Instrumentation

Instrumentation was installed at various levels in the model pavement to measure its response at different points of interest. These points were the top of the pavement, the mid height of the base layer and the interface between the base layer and the subgrade.

Six pressure cells were installed into the model pavement to measure the pressure applied at the points of interest. Four pressure cells were placed horizontally throughout the mid height of the base layer. These were used to measure the horizontal pressure in the base layer, so that the results could be compared to a triaxial test. The remaining pressure cells were placed vertically at the mid height of the base layer and at the base/subgrade interface, to measure the pressure exerted on these points.

Eight linear variable differential transducers (LVDTs) were used to measure displacements. Four were placed equidistantly on the load plate to measure the displacement at the top of the model pavement. Two were placed equidistantly at the mid height of the base layer and the remaining two were placed at the base/subgrade interface.

MP306 moisture sensors were to be used to measure the volumetric moisture content at the top of the model pavement, the interface of the base and subgrade layers and at 100mm below the interface in the model pavement. The moisture probes were calibrated to ensure that their results would accurately reflect the moisture content present in the model pavement. This was achieved by using the moisture probes to record the moisture content of sample subgrade materials at varying moisture contents. The samples were then weighed and oven dried at 105°C for over 24 hours and the gravimetric moisture content was measured. The volumetric moisture content was then calculated based on the containers used, table 2 contains the results.

Table 2 – Calibration of Moisture Probes for Subgrade Material

MP 1	MP 2	MP 3	MP 4	Avg (Measured)	Gravimetric Moisture content	Avg	VWC(%)
15.34	15.34	15.73	15.96	**15.59**	10.15	11.27	**15.62**
					12.39		
					11.28		
39.72	39.40	38.56	38.92	**39.15**	36.66	38.86	**48.47**
					38.98		
					40.96		
22.24	22.85	23.2	22.58	**22.72**	23.14	22.26	**30.75**
					21.79		
					21.84		
31.82	29.99	30.05	31.69	**30.89**	28.96	30.35	**41.53**
					32.64		
					29.46		
42.33	42.90	41.90	43.65	**42.70**	49.77	48.47	**54.92**
					48.31		
					47.33		
14	13.8	13.76	13.3	**13.72**	7.68	8.00	**11.20**
					7.95		
					8.38		
17.4	17.06	17.2	17.8	**17.37**	17.74	18.09	**22.14**
					19.86		
					16.67		

This data was then used to calibrate the moisture probes so that accurate results during testing could be obtained. Due to time constraints, multiple AMPT was not conducted, and the moisture content was not varied. As such, the moisture probes were not utilised to collect data.

The set up for the instrumentation is detailed in figures 2 and 3. The instruments was installed into the positions as the pavement layers were placed in the tank.

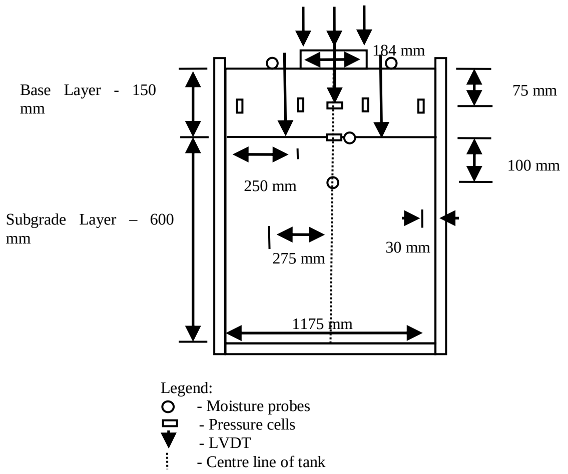

Figure 2 - Cross section of instrumentation setup

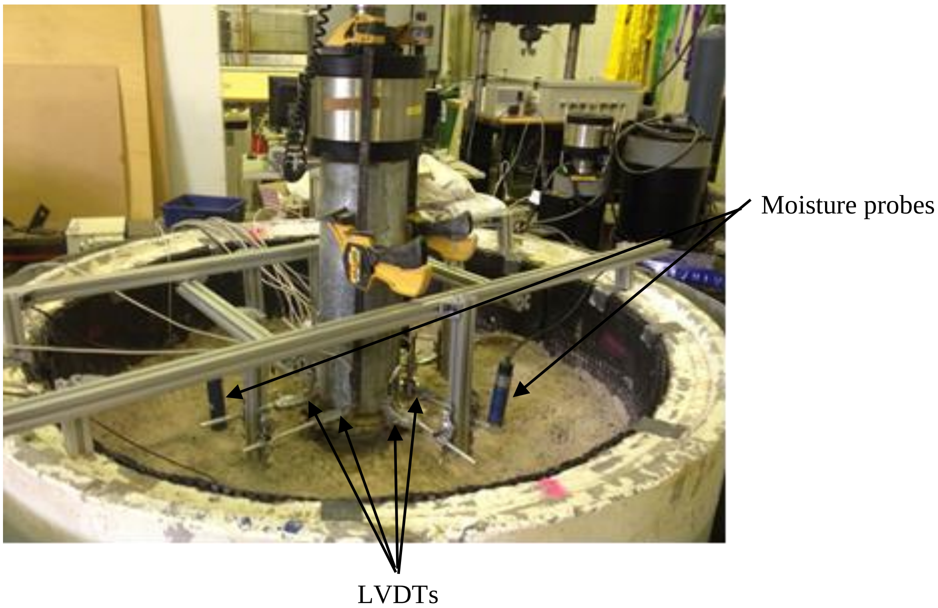

Figure 3 - Top view of instrumentation setup

C. Conduct of testing

Once curing was completed a load plate of 184 mm diameter was placed at the center of the model pavement. The loading plate was set onto the surface of the pavement with a thin layer of grout, to prevent its movement during the test, the grout was given approximately 24 hours to set before testing was conducted. The loading actuator was then positioned such that the actuator and the loading plate lay on the same vertical axis. This can be observed in figure 4.

Figure 4 – AMPT setup

The load plate used had four aluminum plates, of approximately 3 mm thickness, bolted to the top of the load plate. These were placed at right angles to each other, as shown in figure 5.

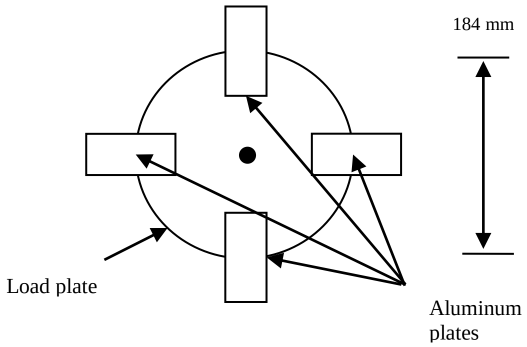

Figure 5 - Diagram of load plate

As outlined previously, four LVDTs were placed on these plates to measure displacements on the surface of the model pavement. All LVDTs were supported by a metal frame, as shown in figure 3. The pressure cells and LVDTs were then connected to the data acquisition system through a signal conditioner before testing commenced.

A National Instruments (NI) data acquisition system connected to a computer was used to collect the data. It consisted of a portable, shielded SCC module carrier data acquisition board and signal conditioner. Inputs from the Instron hydraulic controller, eight LVDT outputs and six pressure cell outputs from the model pavement were continuously stored at a rate of 50 Hz in the computer as ASCII files through a Labview 10.0.1 program.

The loading was applied as a sinusoidal stress pulse of frequency 1 Hz with a rest period between cycles. Four loading pressure were applied, 750 KPa, 1000 KPa, 1250 KPa and 1500 KPa. Each load pressure was applied to the model pavement for approximately 10^5 cycles. Due to time and equipment constraints, only one test was conducted using the previously mentioned pressures and the moisture content was not varied. The model pavement undertook approximately 5 x 10^5 cycles. The deflection obtained for one cycle for each loading case is located in appendix A

III. Results from testing

Due to the large amount of data output during the testing, MATLAB was used to analyse the data. The MATLAB code used is located in appendix B. The MATLAB code used took the pressure and LVDT data inputs and output the resilient modulus, stress, strain and permanent deformation. The full data obtained has not been included in an appendix due to the large size of the data.

A. Resilient Modulus

The resilient modulus of the base and subgrade were calculated using the LVDT data and stresses. The stress was calculated using equation 1.

Equation 1:

$$\varepsilon = \Delta length/length$$

The change in length was calculated using the LVDT data, and since the height of the base and subgrade layers are known the strain was calculated.

Equation 2:

$$M_r = \frac{\sigma_d}{\varepsilon_r}$$

Once the strain was calculated the resilient modulus could be calculated using equation 2. The results were then graphed, as shown in figures 6 and 7.

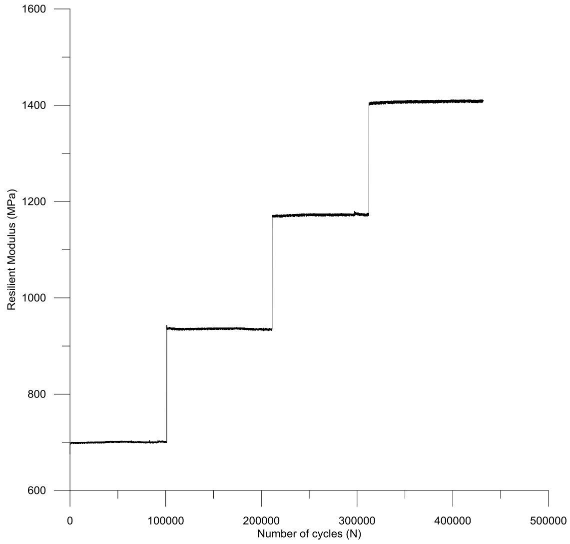

Figure 6 - Resilient modulus of the base layer

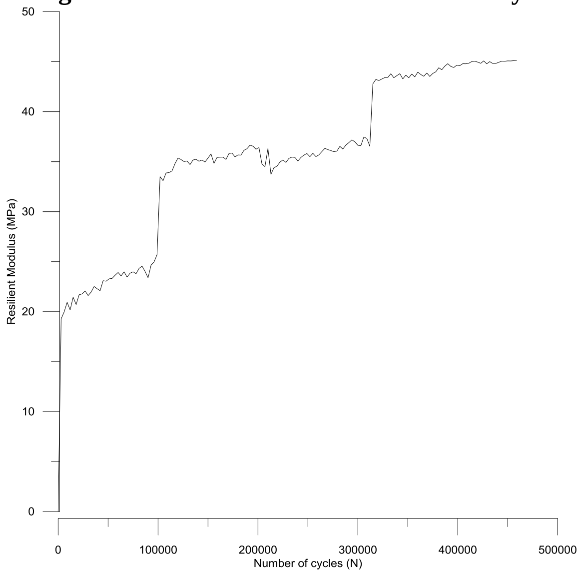

Figure 7 - Resilient modulus of the subgrade layer

B. Permanent deformations

The permanent deformations were calculated using the LVDT data for each measured point. This was done by subtracting the LVDT reading when the deformation was maximum from the LVDT reading at the beginning of the test. Figures 8 and 9 contain the results.

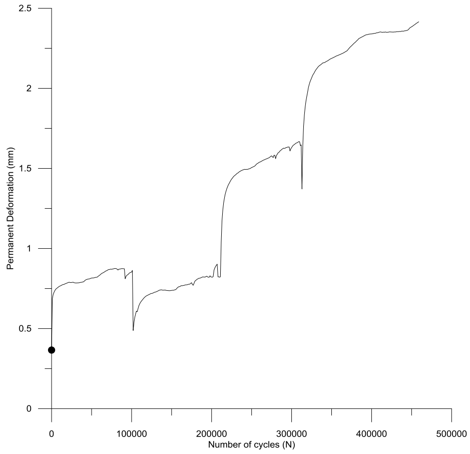

Figure 8 - Permanent deformation of the base layer

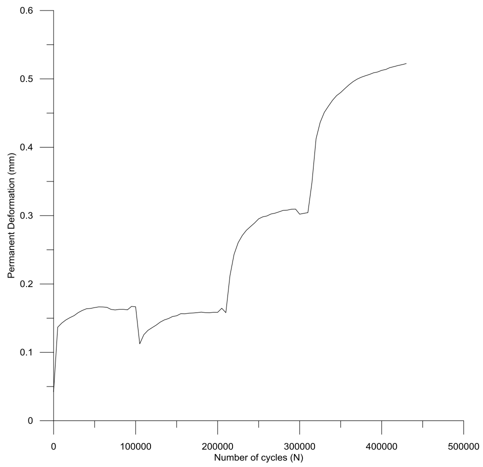

Figure 9 - Permanent deformation of the subgrade layer

IV. Triaxial testing

To compare the results of the AMPT, triaxial tests were conducted on the base layer material using similar a similar deviator stress and confinement pressure. Since the stress applied in triaxial testing must be uniform, the stresses measured in the AMPT testing were used to calculate an equivalent uniform load. This was achieved by using the pressure cell values at the mid height of the base layer and the interface of the base and subgrade. These pressures, in conjunction with the pressure applied by the load cell allowed for an equivalent uniform pressure to be calculated. The confinement pressure used was the data obtained by the central horizontal pressure cells. Table 3 outlines the results used from the AMPT and the resultant uniform pressures calculated.

Table 3 – Pressures used from AMPT and resultant uniform pressures

Stress values from AMPT Testing (MPa)						
Top	Mid - layer	Interface	Boundary Wall	Horizontal (Confinement Pressure)	Representative Stress (MPa)	Number of cycles
750	93	49	3	**27**	**250**	5000
1000	117	104	3	**41**	**330**	5000
1250	149	141	3	**42**	**427**	5000
1500	174	201	4	**69**	**478**	5000

The table also shows the confining pressure and stress used in the triaxial testing as well as the number of cycles conducted at each pressure. Only 5×10^3 cycles were conducted due to time constraints. The tests were conducted using MTS Test Star control software and Test Ware SX data acquisition software. The resulting data was processed using MATLAB code similar to that used for the AMPT. The results obtained are shown in figures 10 and 11.

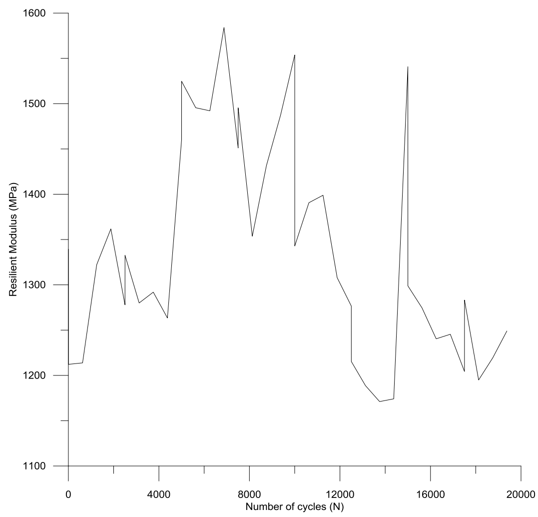

Figure 10 - Resilient modulus from triaxial testing

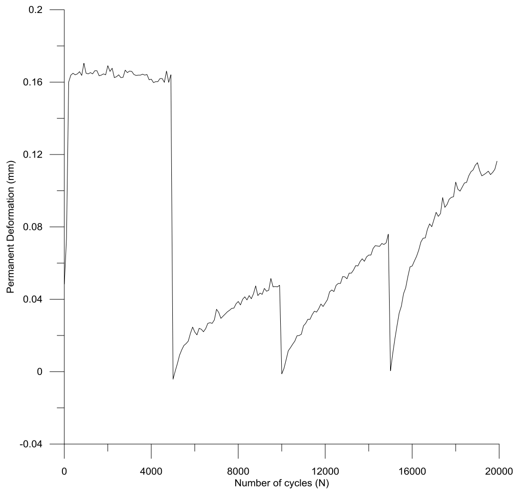

Figure 11 - Permanent deformation from triaxial testing

V. Discussion of results

A. Resilient modulus

As can be seen in figure 6, the results obtained from the AMPT show that as the number of cycles increase during a load pressure, the resilient modulus of the base remained constant. They also showed that as the load increased the resilient modulus also increased. appendix C shows the resilient modulus comparisons between the equivalent loadings. As can be seen in appendix C, the resilient modulus obtained from the AMPT is approximately constant over the 5000 cycles, while the triaxial testing resilient modulus varies. These results show that there is a clear difference between the results obtained from the two tests. The AMPT results show that the recoverable strain for each load is constant, as the deviatoric stress is constant for each load. As the load is increased the recoverable strain decreases resulting in the increase in resilient modulus. For the triaxial testing the recoverable strain varies throughout each cycle, resulting in the varied resilient modulus. As can be seen in figure7, as the number of cycles increase, the recoverable strain decreases, resulting in an increase in resilient modulus.

A possible reason for the difference between the results is that AMPT uses a scaled down version of a design pavement structure. While in a triaxial test only one element of the pavement is tested in isolation. Thus the increased number of variables from AMPT may have an effect on the modulus results. Since the resilient modulus of the base material is calculated using the pressure at the top of the pavement, which is higher than the deviatoric pressure used in the triaxial testing, this may explain the difference between the resilient moduli obtained. Since the resilient moduli is directly proportional to deviatoric stress, as per equation 2, higher results are not unreasonable.

From the results it can be seen that the triaxial tests conducted do not accurately reflect the results of the AMPT. The AMPT resulted in resilient moduli of 697 MPa, 935 MPa, 1173 MPa and 1408 MPa for the loading cases of 750 KPa, 1000 KPa, 1250 KPa and 1500 KPa respectively.

The resilient modulus of the subgrade layer increased with the number of cycles. Thus the recoverable strain was decreasing with each cycle.

B. Permanent deformation

The base layer of the pavement is permanently deforming to a greater level when compared to the subgrade layer. As the base layer experienced the highest load from the actuator, as demonstrated in table 3, this is to be expected.

As can be seen in figure C5, appendix C, initially the graphs of permanent deformation are similar, with the AMPT material deforming less than the triaxial testing results. However, it was observed that for most load cases the base material deformed less than the AMPT results. Since the permanent deformations were measured at the top of the base layer, and this is where the highest stress occurred, it is possible that this greater deformation is a result of the lower equivalent deviatoric stress applied to the triaxial test. Another possible source for the discrepancies is that the material in the AMPT have undergone a significantly larger amount of cycles, 10^5 compared to 5000. This may have altered the characteristics of the material as it was subjected to a larger amount of loads. The comparison of permanent deformations from both test can be seen in appendix C.

Since the triaxial test is conducted on the base material in isolation the differences between the two tests are not unexpected.

VI. Conclusion

It was found that the AMPT results acquired differed from those acquired through triaxial testing. The permanent deformation was found to be higher in the majority of load cases for AMPT, while the resilient modulus calculated from triaxial testing was found to be generally higher. These results reflect that the AMPT results could not be replicated in triaxial testing.

It was found that the resilient moduli of the base material from AMPT was 697 MPa, 935 MPa, 1173 MPa and 1408 MPa, for the loading cases of 750 KPa, 1000 KPa, 1250 KPa and 1500 KPa respectively.

VII. Recommendations

Based on the conclusions and limitations of this thesis, it is recommended that future research into the following areas is conducted.

- Due to time constraints, multiple AMPT was not conducted. By varying the moisture content of the pavement, the effects on resilient modulus and permanent deformation could be further explored. Allowing for a better comparison with other laboratory testing.

- Further AMPT should be conducted with differing base layer materials to further explore the effect the base layer has on the properties of the subgrade material.

- Further triaxial tests should be conducted with similar parameters to those found in AMPT. This will allow better comparison with the AMPT data, and allow triaxial tests to be conducted that have results similar to those found in AMPT. By discovering the relationship, triaxial tests, which are quicker and easier to run, can have more accurate results similar to those achieved by AMPT.

Acknowledgements

I would like to express gratitude to Dr R. Gnanendran for his guidance and advice throughout the course of this study. I am also extremely grateful for the support and advice from Mathanraj Theivakularatnam during the conduct of testing and his help with analyzing the data. I would also like to thank the UNSW@ADFA laboratory staff, J. Baxter and D. Smith, for helping me throughout the conduct of my studies and for the tireless efforts.

References

[1] A.W. Ahmed, S. Erlingsson, “Evaluation of permanent deformation models for unbound granular materials using accelerated pavement tests”, Road Materials and Pavement Design, 2013.

[2] J. Piratheepan, “Characterisation of Lightly Cementitiously Stabilised Granular Materials for Pavement Design”, University of New South Wales, 2009.

[3] A. Taylor , “Mechanistic Characterization of Resilient Moduli for Unbound Pavement Layer Materials”, Auburn University, 2008.

Appendices

Appendix A - Deflections for one cycle for each loading case

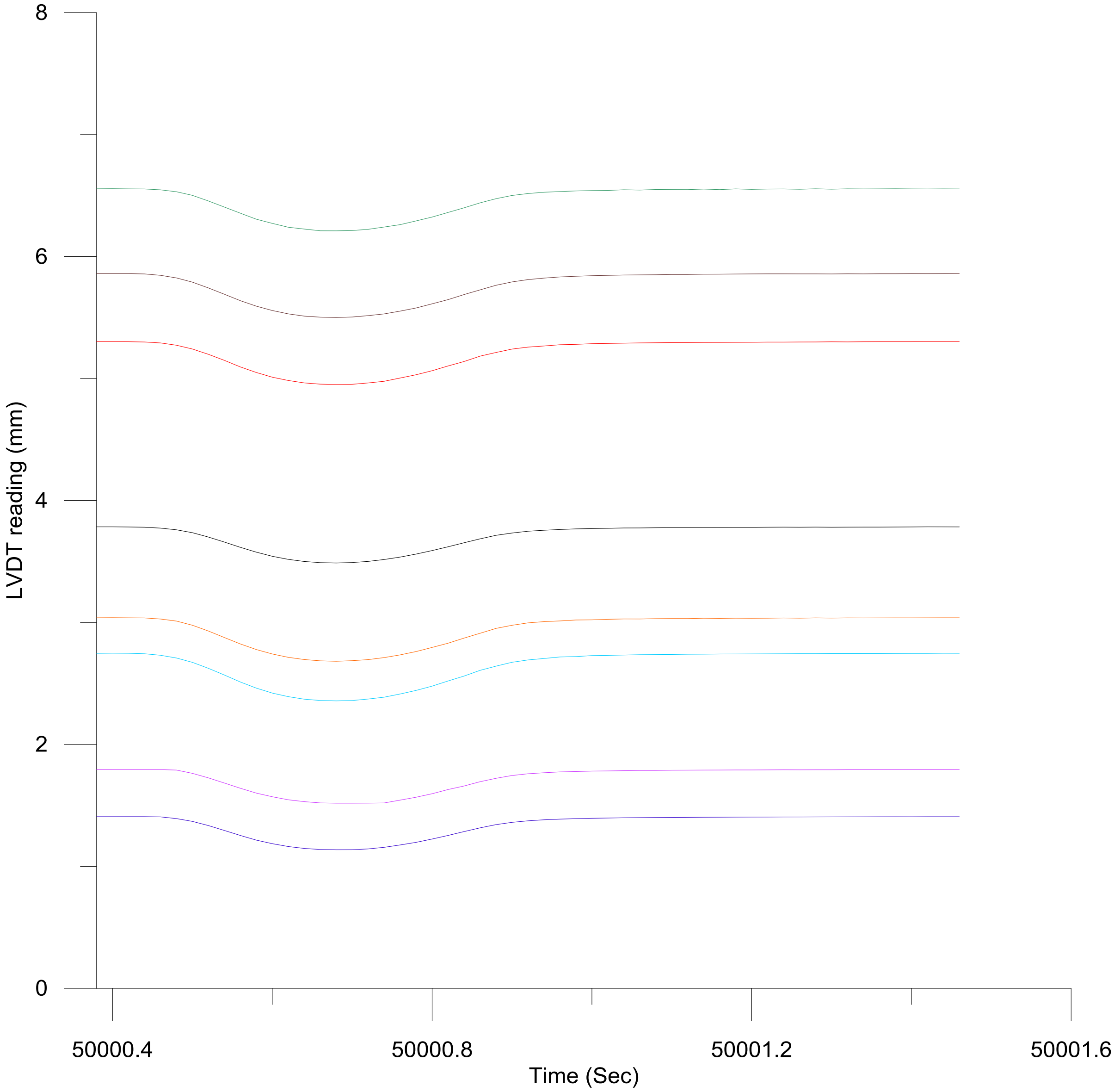

Figure A1 – LVDT readings for one cycle at 750 KPa

A1

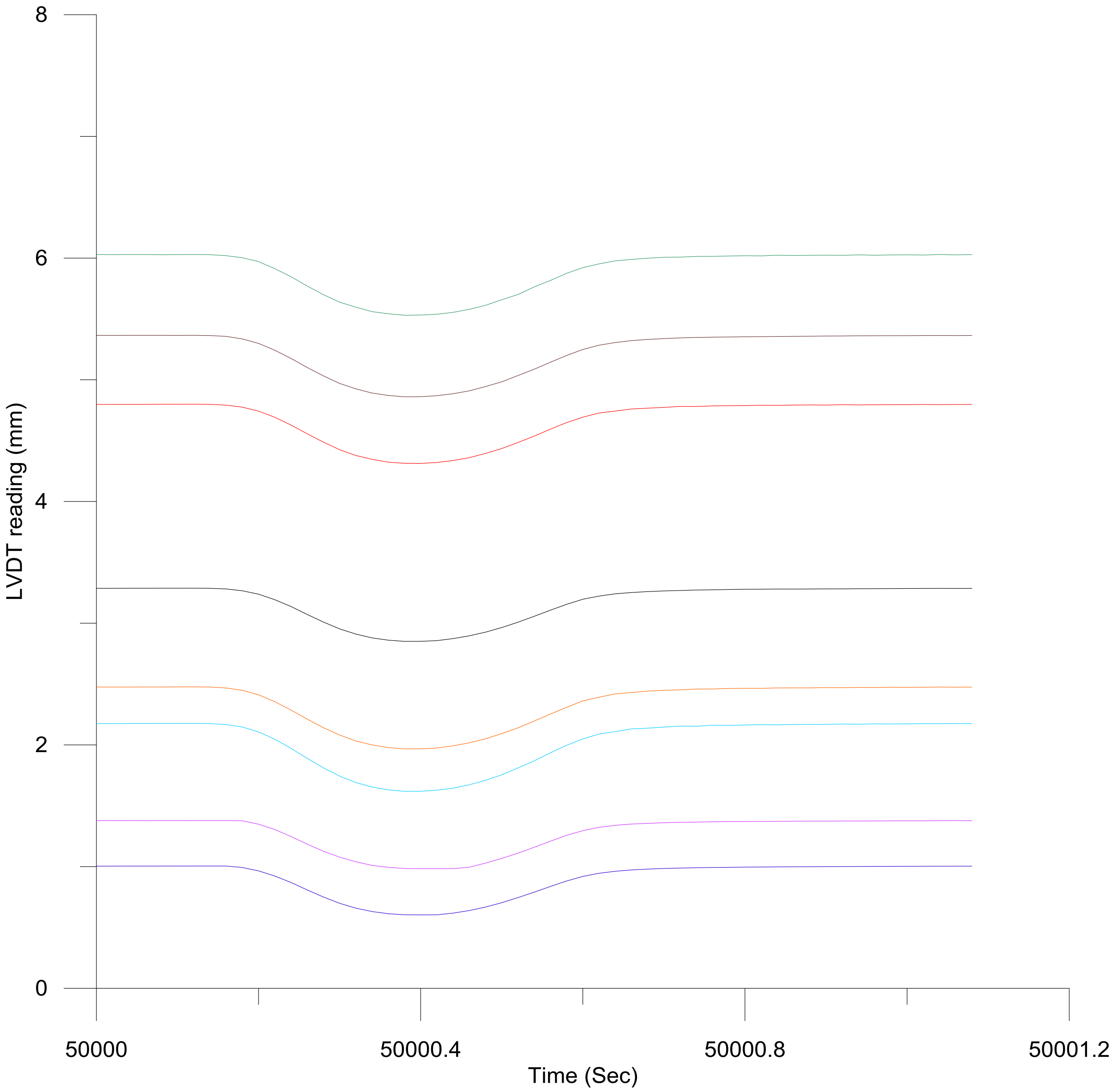

Figure A2 - LVDT readings for one cycle at 1000 KPa

A2

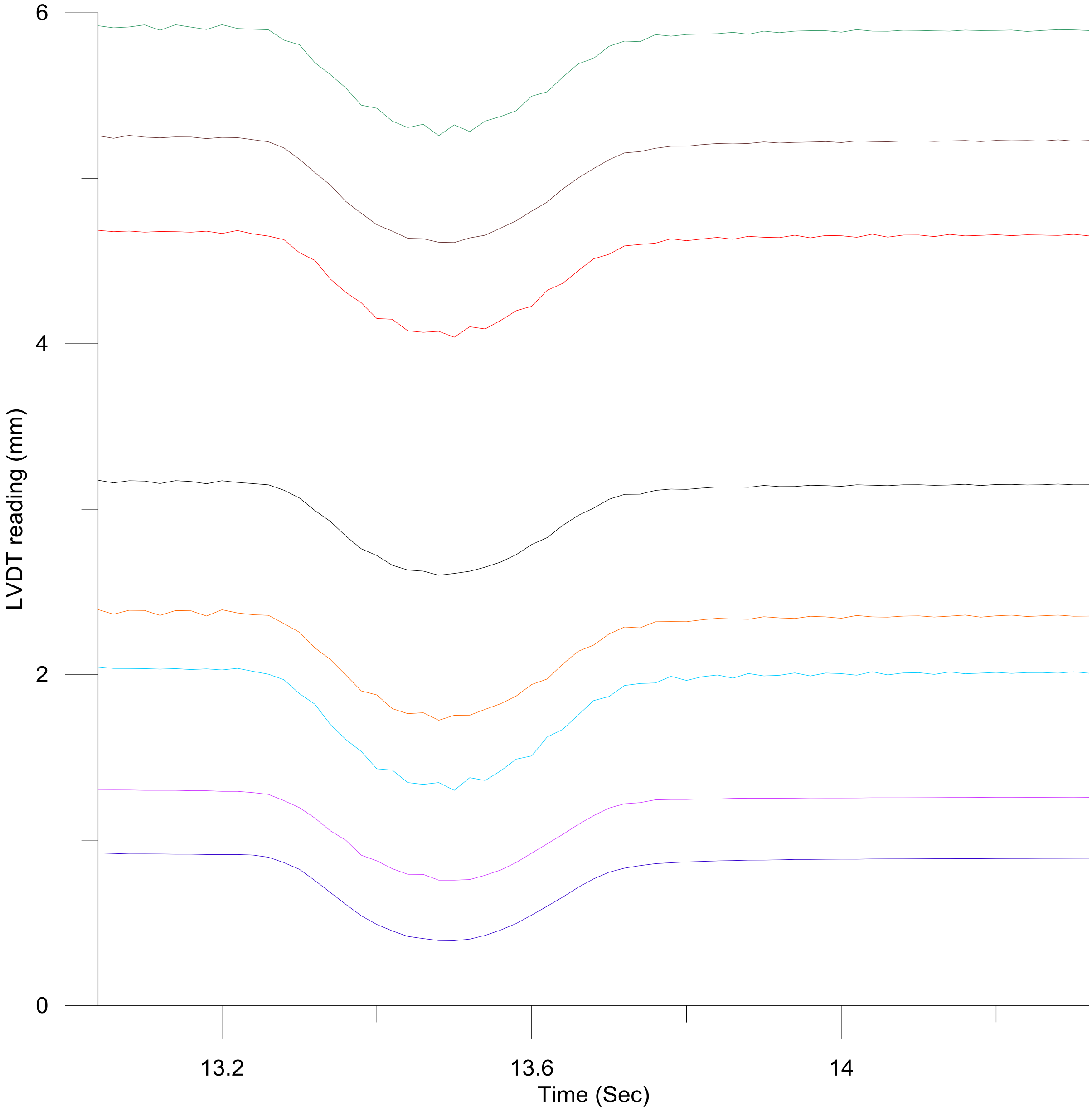

Figure A3 - LVDT readings for one cycle at 1250 KPa

A3

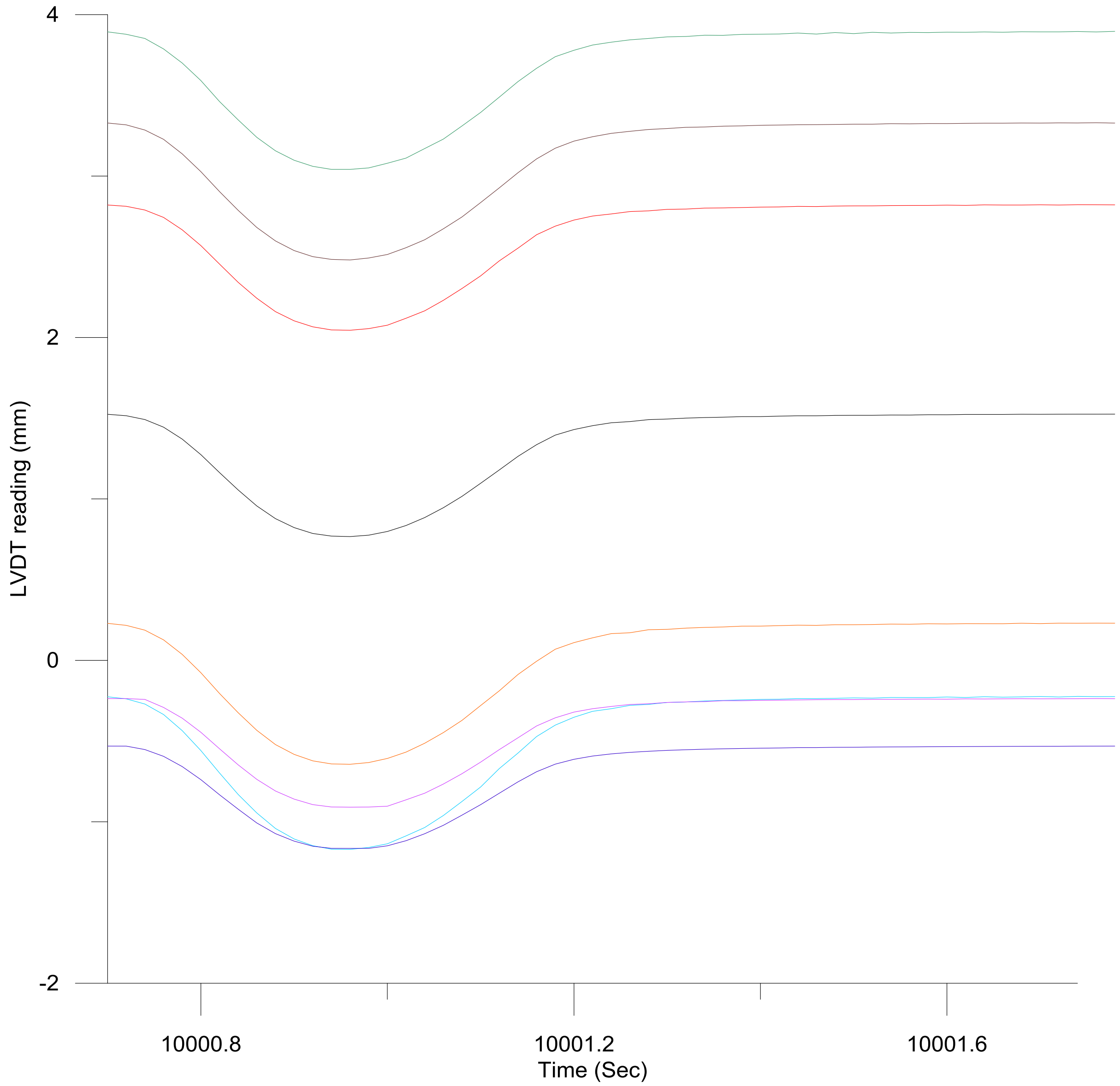

Figure A4 - LVDT readings for one cycle at 1500 KPa

A4

Appendix B - MATLAB code used for analysis of data

```
%MATLAB code developed to analyse AMPT data
clear all;close all;clc;
tic
file=[1:11];
j =27; % number of rows to be captured
incr = 60;
store_data = [];
A1 =2.393452;
A2 = 3.17531;
A3 =4.685716;
A4 =2.047519;
A5 = 5.921878;
A6 = 5.256502;
A7 = 1.30317;
A8 =0.922692;
for i=1:length(file);
     f=file(i);
    file_name_a = sprintf('%d',f');
    file_name_b = '.xlsx';
    file_name = [file_name_a, file_name_b];
%
sheet = 1;
[A]  = xlsread(file_name, sheet);
[nr,nc] = size(A);
c=0;
cycle=1;
while (incr+c)<=nr
    B = A(c+1:incr+c,:);
    [r,k]=min (B(:,2));
    data = [];
    if ((k-j)<=0)
        data = B(1:k+j,:);
    else
        data = B(k-j:k+j,:);
    end

    %%%% Stress %%%%
    Deviator_Stress_top(cycle,1)= -(min(data(:,2)-data(1,2))/(pi*0.092^2));
    Deviator_Stress_middle(cycle,1)= max(data(:,8)) - min(data(:,8));
    Deviator_Stress_bottom(cycle,1)= max(data(:,5)) - min(data(:,5));
    %Deviator_Stress_middle(cycle,1)= -(min(data(:,2))/(pi*0.092^2));
    %Deviator_Stress_bottom(cycle,1)= -(min(data(:,2))/(pi*0.092^2));
    %maxload(cycle,1) = min(data(:,2));
    %
    %%% Permanent Deformation %%%
    Perm_LVDT0(cycle,1) = -min(data(:,10)) + A1;
    Perm_LVDT1(cycle,1) = -min(data(:,11)) + A2;
    Perm_LVDT2(cycle,1) = -min(data(:,12)) + A3;
    Perm_LVDT3(cycle,1) = -min(data(:,13)) + A4;
    Perm_LVDT4(cycle,1) = -min(data(:,14)) + A5;
    Perm_LVDT5(cycle,1) = -min(data(:,15)) + A6;
    Perm_LVDT6(cycle,1) = -min(data(:,16)) + A7;
    Perm_LVDT7(cycle,1) = -min(data(:,17)) + A8;
    average_perm_middle(cycle,1) = (Perm_LVDT1(cycle,1) +
Perm_LVDT6(cycle,1))/2;
    average_perm_bottom(cycle,1) = (Perm_LVDT7(cycle,1) +
Perm_LVDT2(cycle,1))/2;
```

B1

```
    average_perm_top(cycle,1) = ((Perm_LVDT0(cycle,1)+
Perm_LVDT3(cycle,1)+Perm_LVDT4(cycle,1)+Perm_LVDT5(cycle,1))/4)-
average_perm_bottom(cycle,1);
    %%% Resilient Deformation %%%
    Resil_LVDT0(cycle,1) = -min(data(:,10)) + data(1,10);
    Resil_LVDT1(cycle,1) = -min(data(:,11)) + data(1,11);
    Resil_LVDT2(cycle,1) = -min(data(:,12)) + data(1,12);
    Resil_LVDT3(cycle,1) = -min(data(:,13)) + data(1,13);
    Resil_LVDT4(cycle,1) = -min(data(:,14)) + data(1,14);
    Resil_LVDT5(cycle,1) = -min(data(:,15)) + data(1,15);
    Resil_LVDT6(cycle,1) = -min(data(:,16)) + data(1,16);
    Resil_LVDT7(cycle,1) = -min(data(:,17)) + data(1,17);
    average_resil_top(cycle,1) = (Resil_LVDT0(cycle,1)+
Resil_LVDT3(cycle,1)+Resil_LVDT4(cycle,1)+Resil_LVDT5(cycle,1))/4;
    average_resil_middle(cycle,1) = (Resil_LVDT1(cycle,1) +
Resil_LVDT6(cycle,1))/2;
    average_resil_bottom(cycle,1) = (Resil_LVDT7(cycle,1) +
Resil_LVDT2(cycle,1))/2;
    %%% Strain %%%
    strain_top(cycle,1) = average_resil_top(cycle,1)/ (150);
    strain_middle(cycle,1) = average_resil_middle(cycle,1)/ (150);
    strain_bottom(cycle,1) = average_resil_bottom(cycle,1)/ (150);
    %%% Resilient Modulus %%%

Resilient_Modulus_top(cycle,1)=Deviator_Stress_top(cycle,1)/strain_top(cycl
e,1)/1000;

Resilient_Modulus_middle(cycle,1)=Deviator_Stress_middle(cycle,1)/strain_mi
ddle(cycle,1)/1000;

Resilient_Modulus_bottom(cycle,1)=Deviator_Stress_bottom(cycle,1)/strain_bo
ttom(cycle,1)/1000;
    %
    c = c+k+j;
    Index(cycle,1)=[c-j];
    cycle=cycle+1;
end
output_data=[Resilient_Modulus_top,Resilient_Modulus_middle,Resilient_Modul
us_bottom,Deviator_Stress_top,Deviator_Stress_middle,Deviator_Stress_bottom
,strain_top,strain_middle,strain_bottom,average_perm_top,average_perm_middl
e,average_perm_bottom];
store_data = [store_data; output_data];
end
new_file_name = 'results_final2';
xlswrite(new_file_name,store_data);
toc
```

B2

Appendix C – Comparison of AMPT and Triaxial testing results

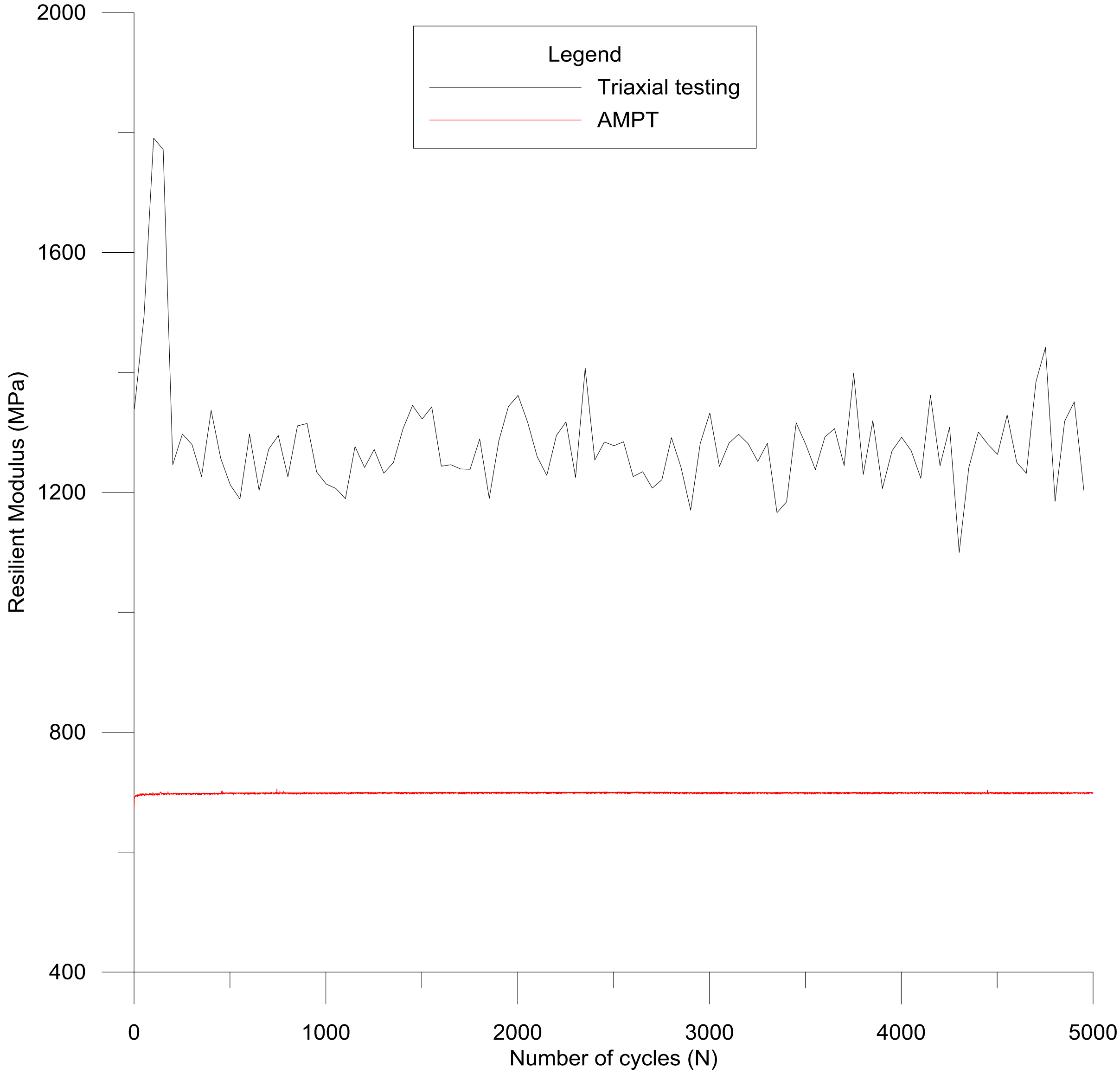

Figure C1 – Comparison of resilient modulus over the same number of cycles for the first loading

C1

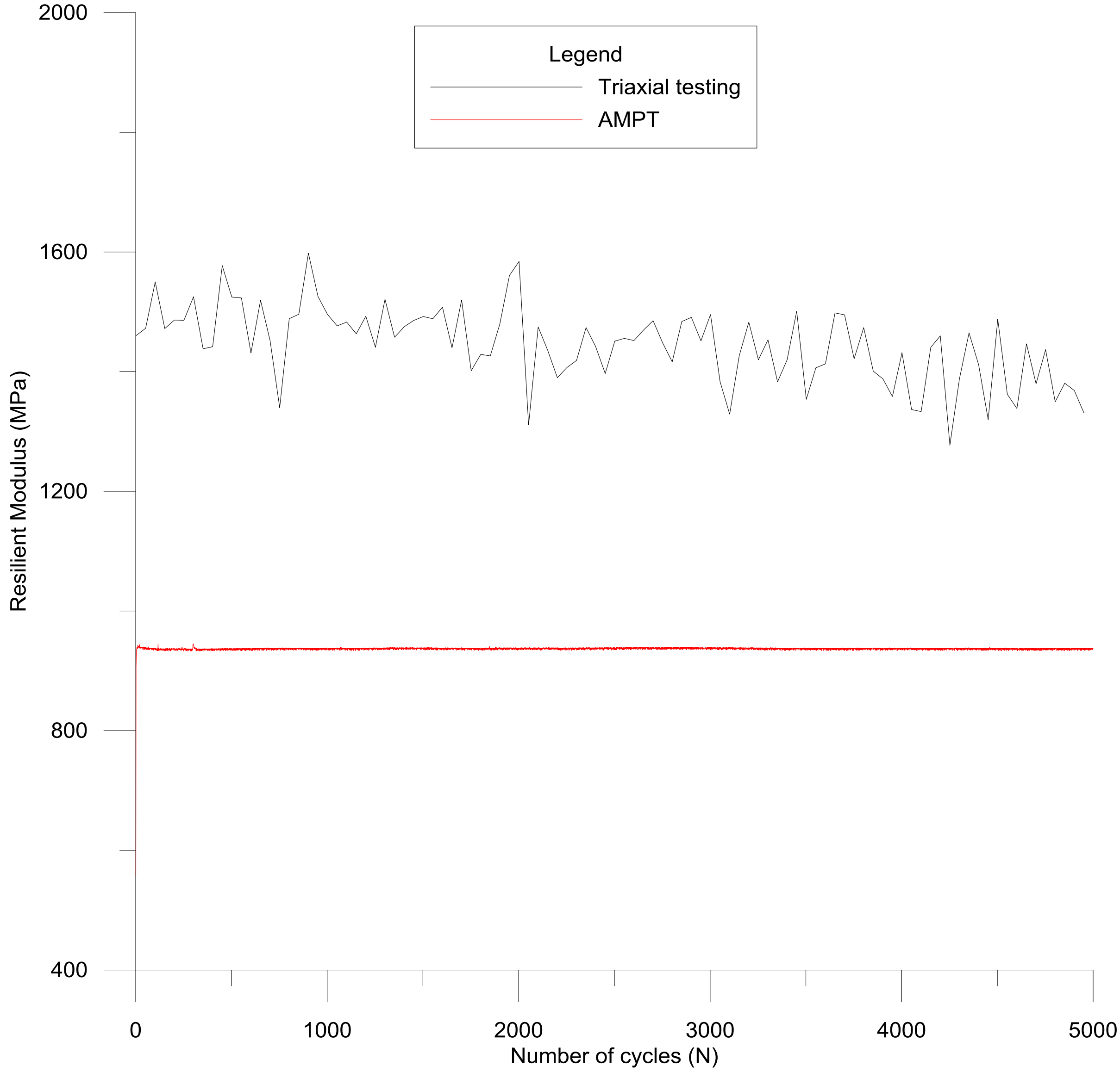

Figure C2 – Comparison of resilient modulus over the same number of cycles for the second loading

C2

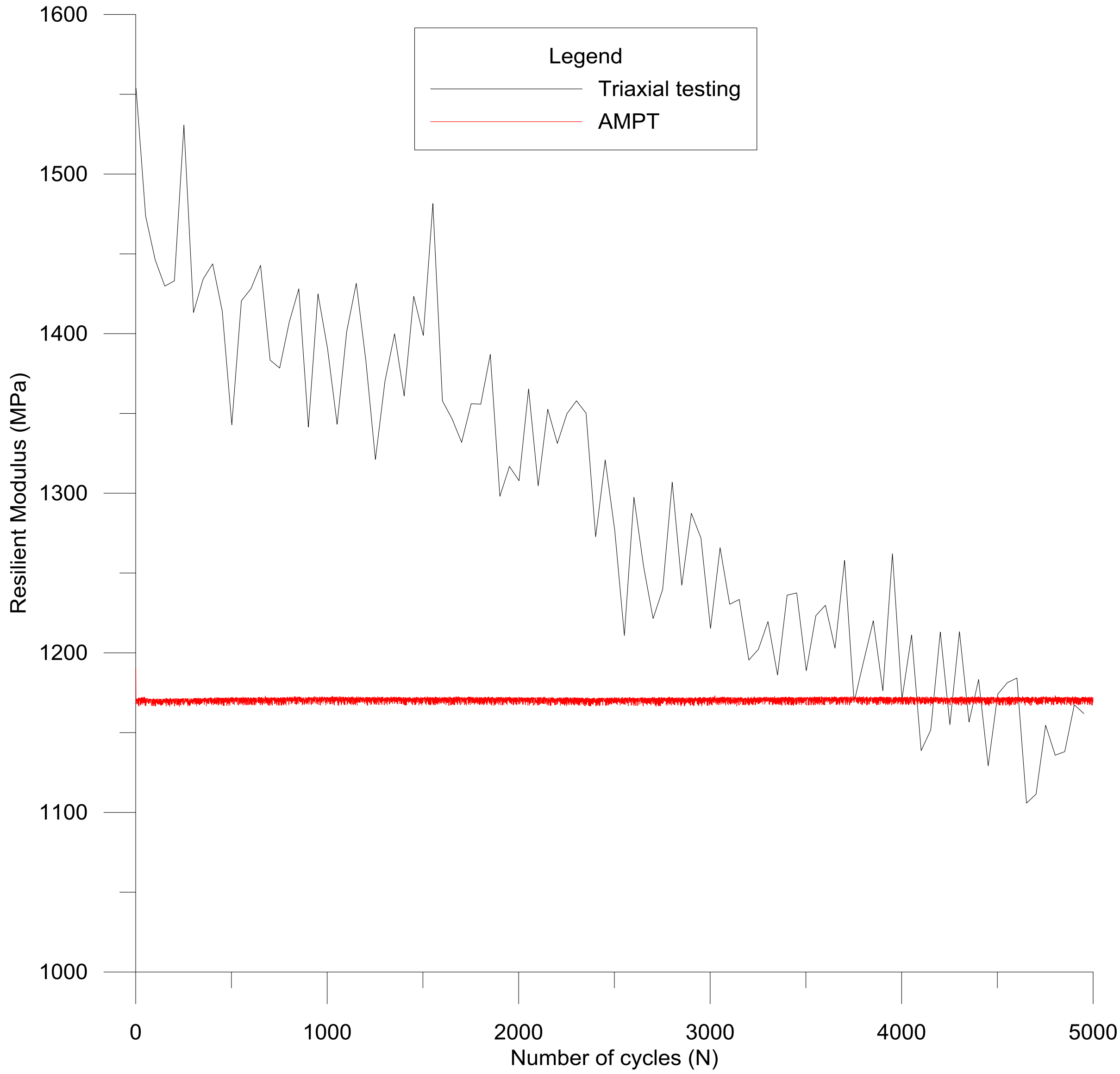

Figure C3 – Comparison of resilient modulus over the same number of cycles for the third loading

C3

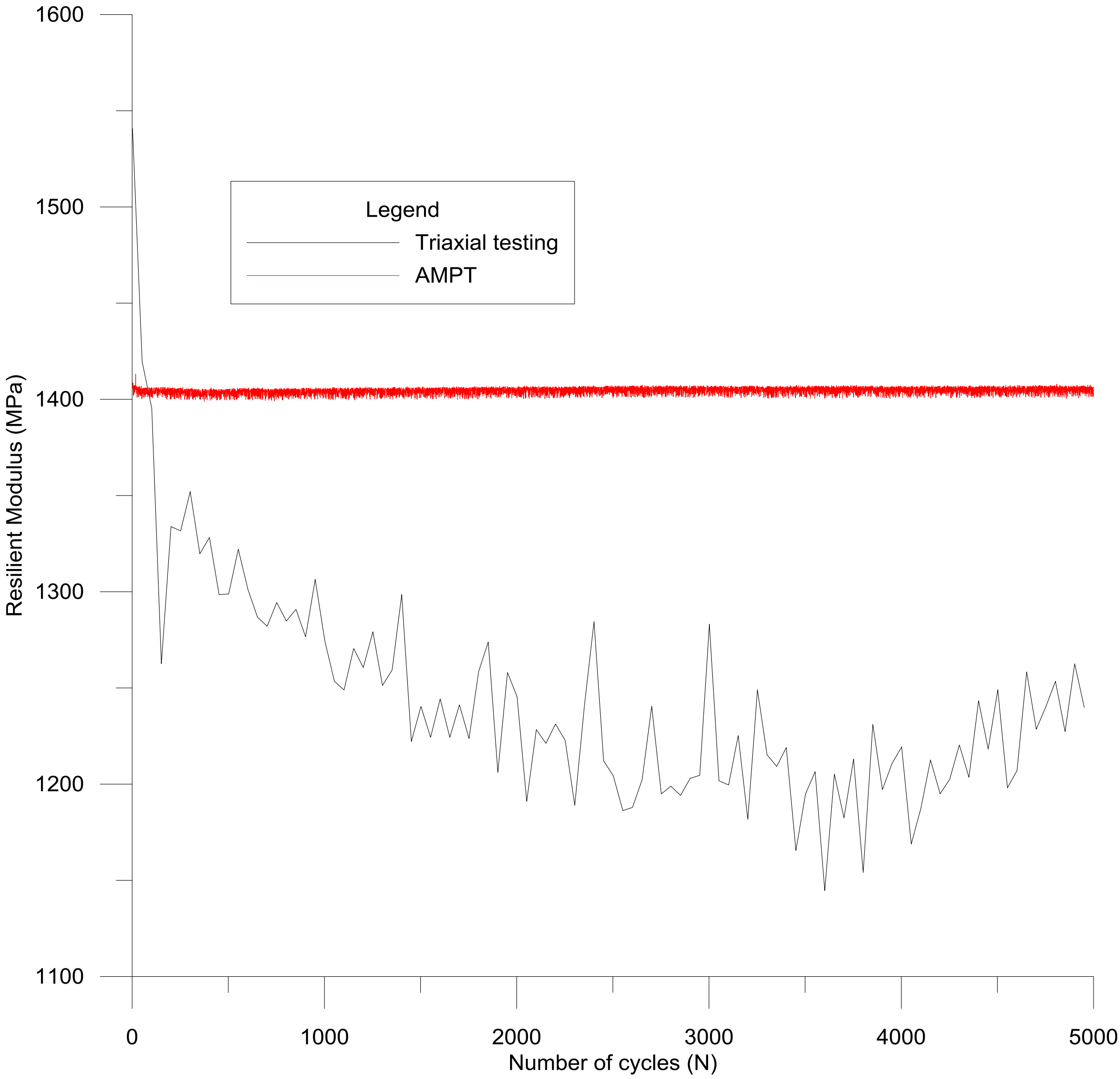

Figure C4 – Comparison of resilient modulus over the same number of cycles for the fourth loading

C4

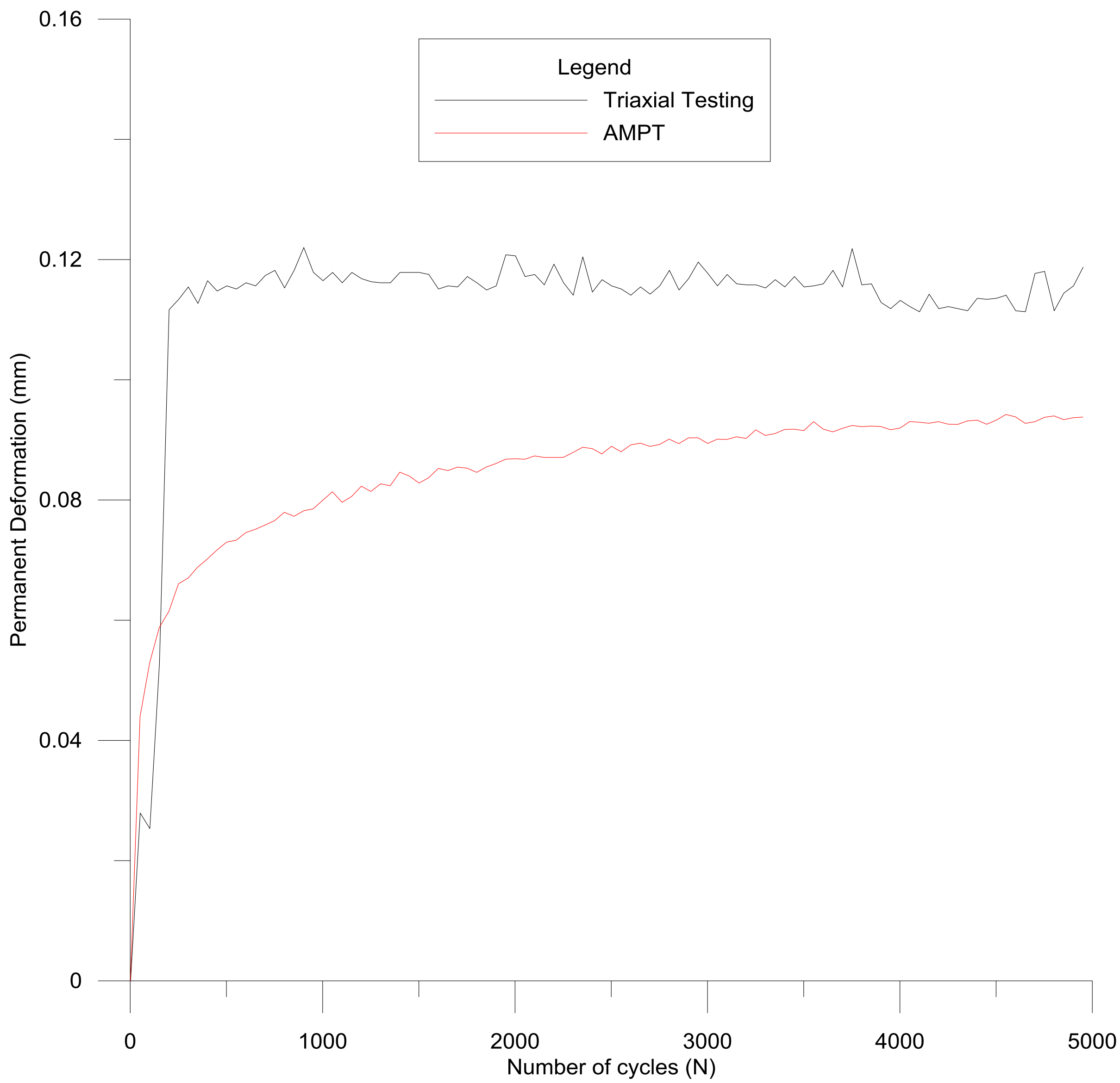

Figure C5 – Comparison of permanent deformation over the same number of cycles for the first loading

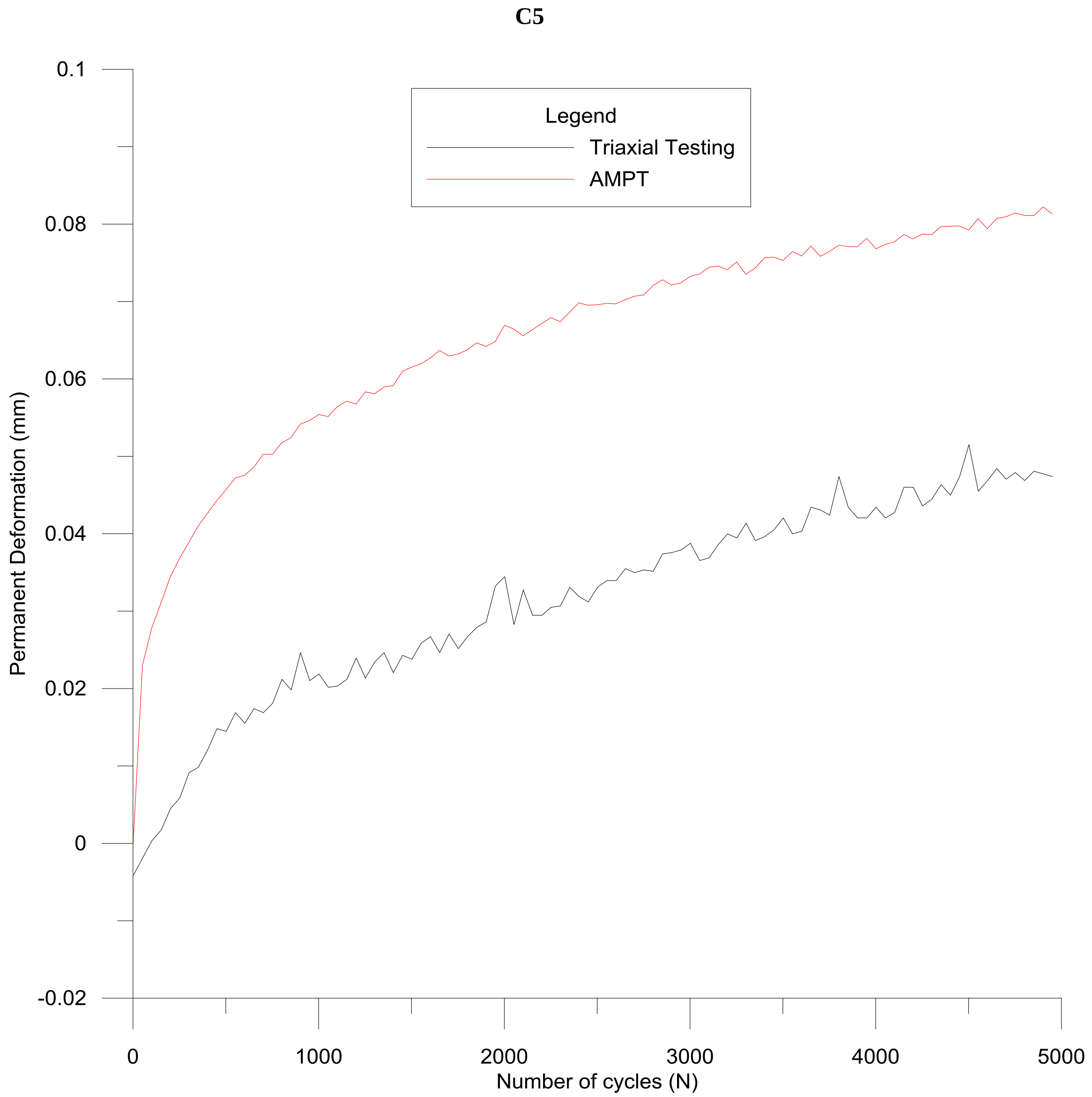

Figure C6 – Comparison of permanent deformation over the same number of cycles for the second loading

C6

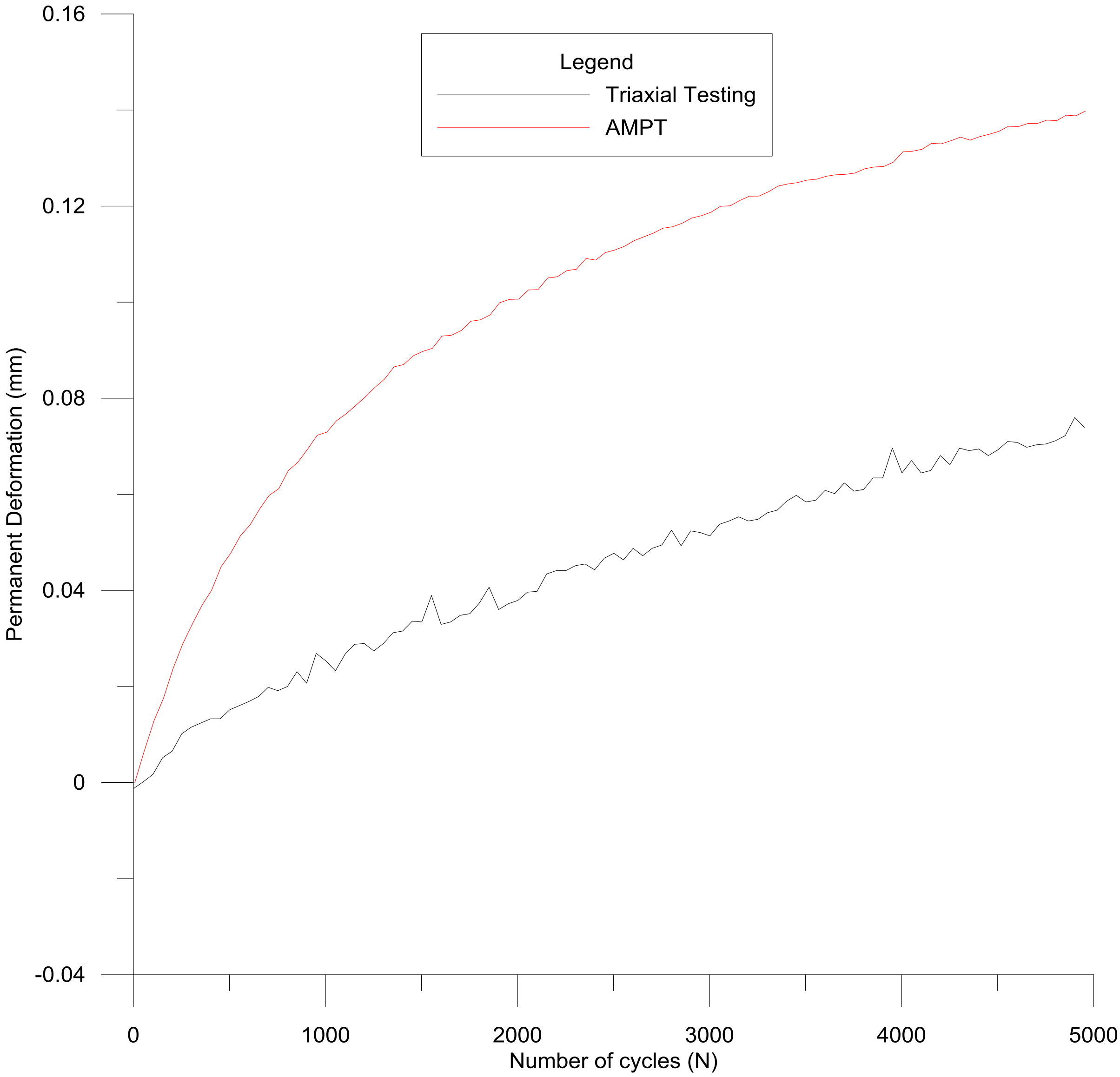

Figure C7 – Comparison of permanent deformation over the same number of cycles for the third loading

C7

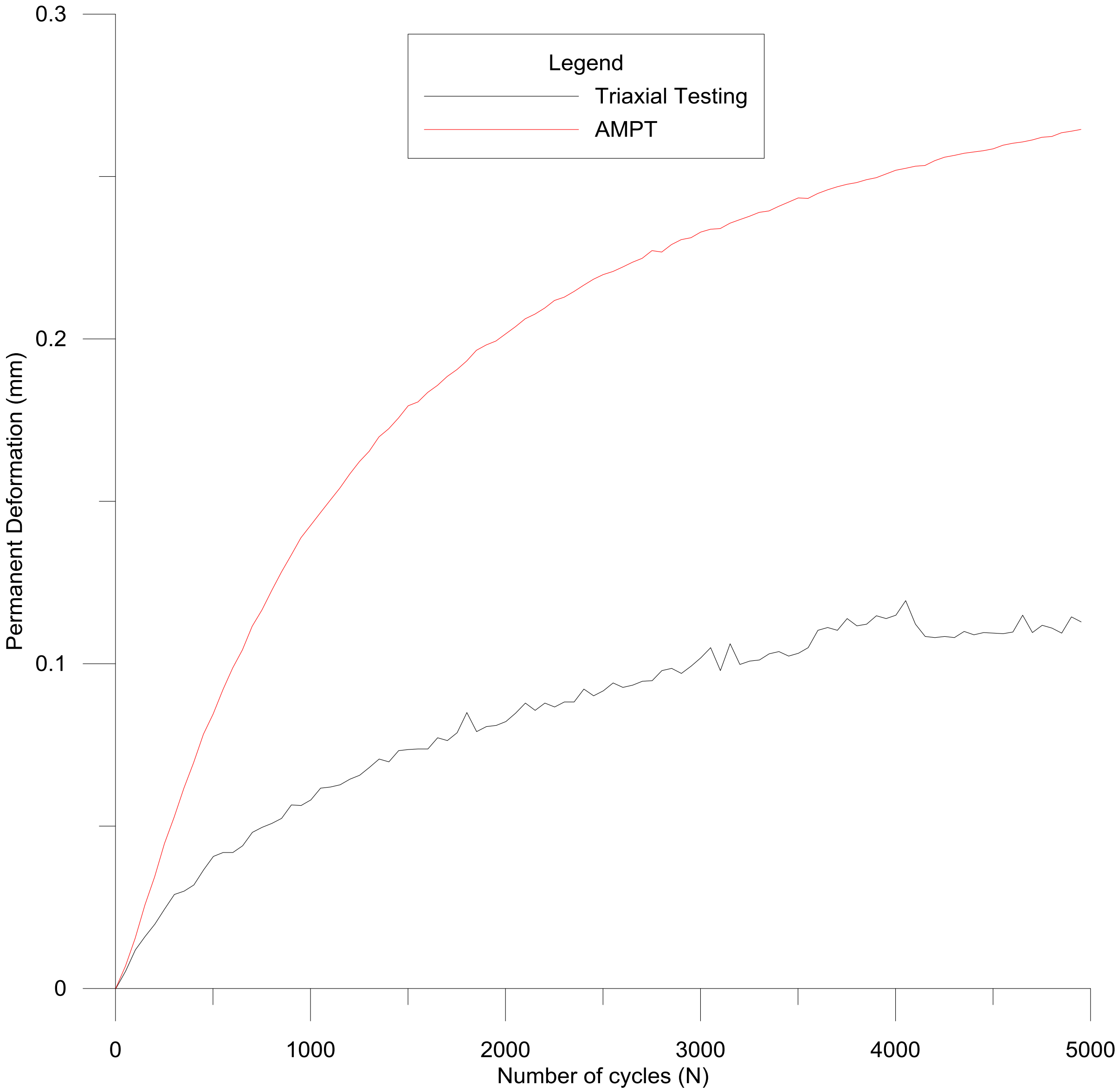

Figure C8 – Comparison of permanent deformation over the same number of cycles for the fourth loading

C8