

**Rut Depth Prediction for TNZ M4 1
Aggregate 1 –**

*(Predictions for dry (70%OMC) and wet
(100%OMC))*

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Disclaimer

This report predicts the rut depth that would occur if the aggregate was used at Transit New Zealand's accelerated pavement testing facility (CAPTIF) at the moisture and density content tested in the Repeated Load Triaxial apparatus. Rut depth predictions are therefore intended for comparative purposes with a Canterbury Greywacke commonly used at CAPTIF and they may not reflect the rut depth that would occur in the field.

Results Summary

Results Summary Comparing Rut Depth Prediction of TNZ M4 Aggregate 1 with CAPTIF 1 (Canterbury Greywacke - AP40 TNZ M4).

		CAPTIF Pavement 300mm Aggregate over 10CBR Subgrade		
		Total Pavement	Aggregate only	Aggregate only
Material	RLT Sample	N, ESAs to get 25mm rut	N, ESAs to get 10mm rut in aggregate.	Long term rate of rutting within aggregate
		<i>Million ESAs</i>	<i>Million ESAs</i>	<i>mm per 1 Million ESAs</i>
TNZ M4 Aggregate 1 (Dry)	90%MDD ($1.97 t/m^3$), 70%OMC (5.4%)	2.10	2.82	2.3
TNZ M4 Aggregate 1 (Wet)	91%MDD ($2.01 t/m^3$), 100%OMC (6.42%)	0.02	0.01	24
CAPTIF 1	TNZ M4, AP40, 70%OMC, 95%MDD, Pond Road, Christchurch	2.9	10.4	0.9
CAPTIF test	2001, Section 1A, 40kN Wheel Load	3.8	<i>Unknown</i>	<i>Unknown</i>

MDD = Maximum Dry Density from Vibrating Hammer Compaction Test (NZS 4402 : Test 4.1.3)

OMC = Optimum Moisture Content (NZS 4402 : Test 4.1.3).

ESAs = Equivalent Standard Axles from Austroads Pavement Design Manual (1ESA = 1 pass of 8.2 tonne dual tired axle).

Conclusion

The Aggregate 1 shows a lower life than that achieved by the high quality Canterbury Greywacke. If kept dry (<70%OMC) it is expected after 3 million ESAs (Heavy Axle passes) that pavement smoothing would be required due to rutting within the aggregate, while the long term rate of rutting of the dry (<70%OMC) Aggregate 1 is 2.3mm per 1 million ESAs. Should the in service moisture content of the Aggregate 1 exceed 100%OMC then it is expected that pavement failure in terms of rutting exceeding 25mm will occur very quickly within the first 1 million ESAs.

In comparison with other aggregates tested in the Repeated Load Triaxial apparatus and rut depth predicted the Aggregate 1 in the dry condition (rutting rate = 2.3mm per 1 million ESAs) is nearly as good as the better quality aggregates in the dry condition (rutting rate = 0.5 to 2mm per 1 million ESAs). In the wet condition the Aggregate 1 would be group in with the worst performing aggregates (rutting rate = 14 to 51mm per 1 million ESAs).

Scope

This report summarises the results of pavement rut depth modelling for TNZ M4 Aggregate 1 aggregate based on a typical pavement cross section used at Transit New Zealand's pavement testing facility CAPTIF from multi-stage permanent strain Repeated Load Triaxial (RLT) tests (*see Appendix A for a technical note on Repeated Load Triaxial testing*).

Aim

The aim is to compare the amount of rutting predicted using the TNZ M4 Aggregate 1 for a wet (100%OMC) and dry (70%OMC) condition with that achieved in an actual CAPTIF test using high quality Canterbury Greywacke TNZ M4 AP40 aggregate at CAPTIF in a dry condition (70%OMC).

RLT Aggregate Sample

The aggregate tested is a Greywacke aggregate from Aggregate 1, complying with TNZ M/4. Table 1 shows further details of this aggregate.

Table 1: Details of Aggregate 1

Name	Aggregate 1
Owner	?
Location	?
Rock Type	?
Gradings	TNZ M/4 – AP 40
Aggregate Properties	Compliance with TNZ M4

Density and moisture content achieved in compacted Repeated Load Triaxial sample are detailed in Table 2.

Table 2: Aggregate 1 Moisture Content and Densities Achieved in Repeated Load Triaxial Sample.

Aggregate 1			
RLT Test Number:		1 (dry)	2 (wet)
Test date		?	?
Lab moisture content	%	5	7
Optimum Moisture Content (OMC):	%	7	7
Lab Dry Density	t/m ³		
Max Dry Density (MDD)	t/m ³	MDD	MDD
Target OMC:	% of	70	100

	OMC		
Lab OMC:	% of OMC	70	100
Target Degree of Compaction:	% of MDD	95	95
¹Lab Specimen Degree of Compaction:	% of OMC	95	95

Note 1: Sample is compacted using a vibrating hammer complying with NZS 4402 : Test 4.1.3 with a surcharge weight of 35kg for 1 minute in 5 layers.

MDD = Maximum Dry Density from Vibrating Hammer Compaction Test (NZS 4402 : Test 4.1.3)

OMC = Optimum Moisture Content (NZS 4402 : Test 4.1.3).

The aggregate tested at two different moisture contents can be defined as:

RLT Test 1 (dry): Aggregate 1, 95%MDD, 70%OMC

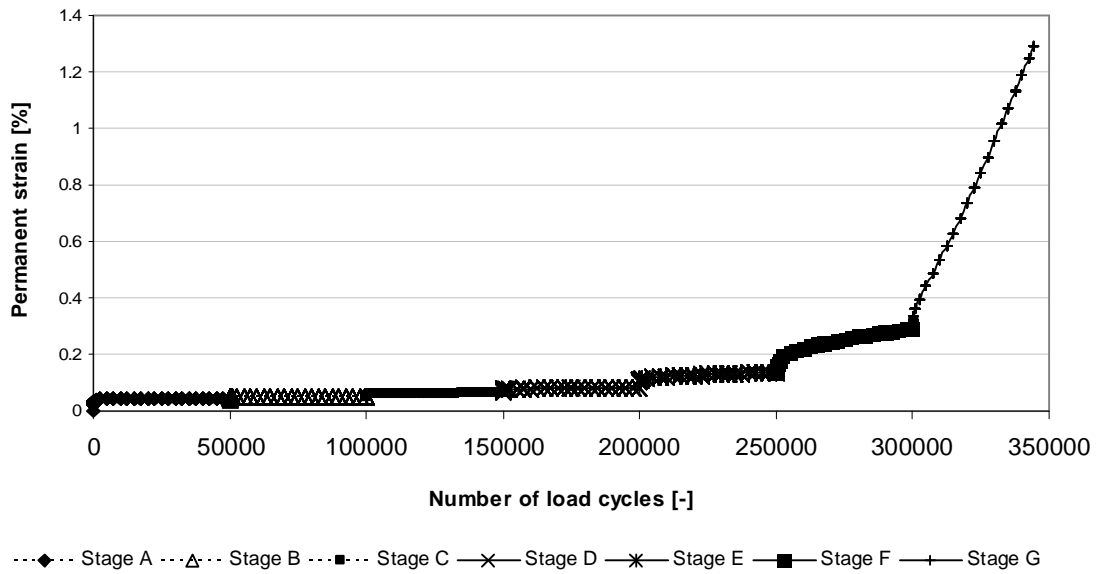
RLT Test 2 (wet): Aggregate 1, 95%MDD, 100%OMC

RLT Aggregate Test

Repeated Load Triaxial test conducted on the Aggregate 1 followed the same procedure developed from a current Transit New Zealand research project, *Performance Tests for Road Aggregates and Alternative Materials* funded by Land Transport New Zealand. This is a multi-stage permanent strain RLT test to test at a range of stresses present in a pavement for determining parameters required for an Equation that relates stress to permanent strain/deformation. Testing stresses and conditions conducted on the Aggregate 1 are detailed in Appendix B.

Results of RLT testing for the dry and wet samples are shown in Figure 1 for testing stresses detailed in Table 3.

Aggregate 1 Dry (70% OMC)



Aggregate 1 Wet (100% OMC)

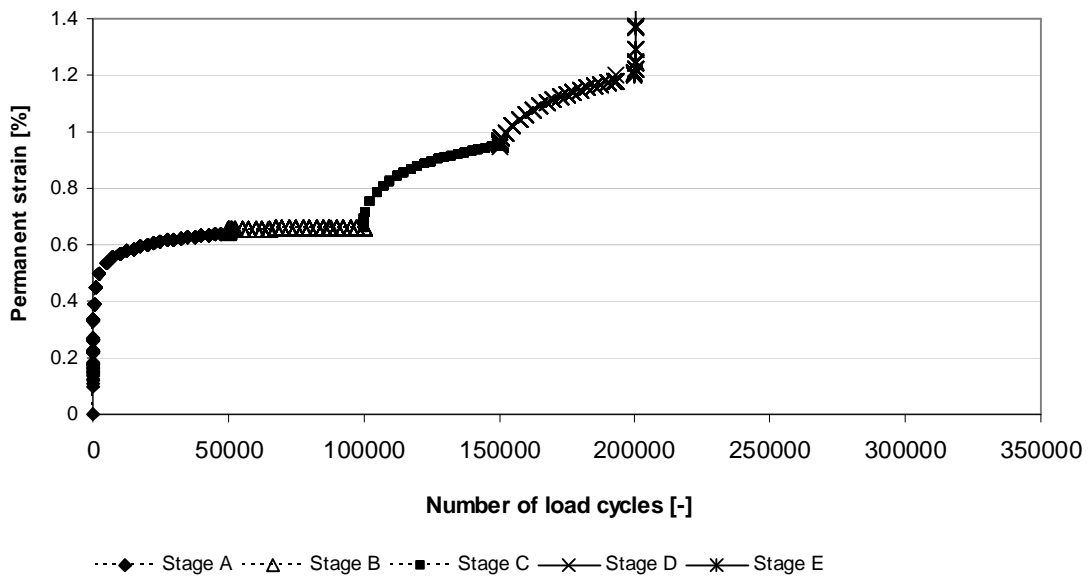


Figure 1: RLT Test Results for Aggregate 1.

Table 3: RLT Testing Stresses.

RLT Testing Stress Stage	A	B	C	D	E	F	G
Deviator stress - q (kPa) (cyclic vertical stress)	90.0	50.0	100.0	100.0	180.0	330.0	420.0
Mean stress - p (kPa)	150.0	75.0	100.0	75.0	150.0	250.0	250.0
Cell Pressure, s_3 (kPa)	120.0	58.3	66.7	41.7	90.0	140.0	110.0
Major Principal Vertical Stress, s_1 (kPa)	210.0	108.3	166.7	141.7	270.0	470.0	530.0
Cyclic Vertical Loading Speed	Sinusoidal at 4 Hz						
Number of Loads (N)	50,000						
Record and Report Data Electronically in Microsoft Excel	Permanent strain versus load cycles and resilient modulus versus load cycles						

Rut Depth Prediction from RLT Test

The method used to predict rutting is reported in Dr Arnold's thesis (Arnold, 2004). Following is a summary of the steps involved in order to predict the rutting of a 300mm deep pavement at CAPTIF.

Step 1: Extrapolation and Convert to Individual Results

The first step in rut depth prediction is to extrapolate the RLT results and individualise the RLT results to one test per stress stage. A power law model ($y=k1x^{k2}$) was used to extrapolate the results to 500,000 load cycles from the 50,000 load cycles. From 500,000 load cycles onwards a linear extrapolation following the same deformation rate from 100,000 to 500,000 is used. The linear extrapolation is considered a conservative approach and follows the same trend typically found from CAPTIF tests. Another assumption used to extrapolate the results relates to adding on an incremental permanent strain value to each new stress stage being the permanent strain value at 10,000 load cycles for the previous load cycle. Figure 2 illustrates the extrapolation method used (see Appendix C for full results).

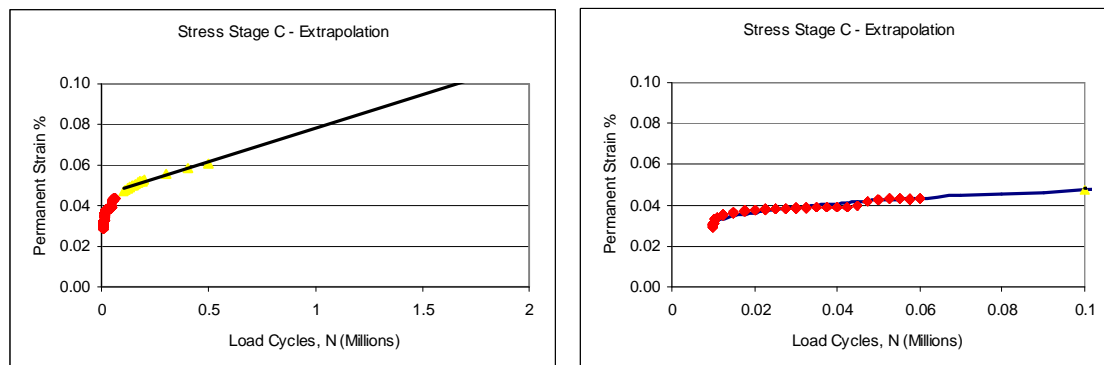


Figure 2: Example of extrapolation method used (full results see Appendix C)

Step 2: Permanent Strain Rates and Associates Stress

From the extrapolated RLT results permanent strain rates and associated stresses are determined (Tables 4 and 5 for the dry and wet RLT test respectively).

Table 4: Permanent strain rates and associated stresses for the RLT Test 1 (Dry) Aggregate 1, 70%OMC.

Stress (MPa)		Magnitude %	Slope %/1 Million Load Cycles			
p	q		First 25k	25k to 50k	50k to 100k	100k to 500k
0.150	0.090		0.023	0.059	0.030	0.009
0.075	0.050		0.029	0.000	0.000	0.000
0.100	0.100		0.038	0.184	0.100	0.033
0.075	0.100		0.046	0.144	0.077	0.025
0.150	0.180		0.066	0.401	0.210	0.066
0.250	0.330		0.145	1.997	1.038	0.322
0.250	0.420		0.462	22.588	24.982	30.307

p = mean principle stress ($1/3*(\sigma_1 + 2*\sigma_3)$)

q = principle stress difference ($\sigma_1 - \sigma_3$)

Table 5: Permanent strain rates and associated stresses for the RLT Test 2 (Wet) Aggregate 1, 100%OMC.

Stress (MPa)		Magnitude %	Slope %/1 Million Load Cycles		
p	q	First 25k	25k to 50k	50k to 100k	100k to 500k
0.150	0.090	0.515	1.771	0.902	0.270
0.075	0.050	0.474	0.115	0.060	0.018
0.100	0.100	0.643	4.210	2.224	0.707
0.075	0.100	0.761	3.778	2.026	0.661
0.150	0.180	Sample failed			
0.250	0.330				
0.250	0.420				

p = mean principle stress ($1/3*(\sigma_1 + 2*\sigma_3)$)

q = principle stress difference ($\sigma_1 - \sigma_3$)

Step 3: Equation Parameters to Predict Permanent Strain Rate from Stress

Equation 1 developed by Arnold in his doctorate studies (Arnold, 2004) is used to determine the permanent strain rate for any stress not tested. Parameters a , b and c are determined by using solver in Microsoft Excel to the actual measured values in the RLT test listed in Table 3.

$$\begin{aligned} \epsilon_{p(\text{rate or magn})} &= e^{(a)} e^{(bp)} e^{(cq)} - e^{(a)} e^{(bp)} \\ &= e^{(a)} e^{(bp)} (e^{(cq)} - 1) \end{aligned} \quad \text{Equation 1}$$

where,

$e = 2.718282$;

$\epsilon_{p(\text{rate or magn})}$ = secant permanent strain rate or can be just permanent strain magnitude;

a , b & c = constants obtained by regression analysis fitted to the measured RLT data;

p = mean principal stress (MPa); and

q = mean principal stress difference (MPa).

An example of the using Equation 1 to fit the measured data is detailed in Figure 3, where full results are shown in Appendix D.

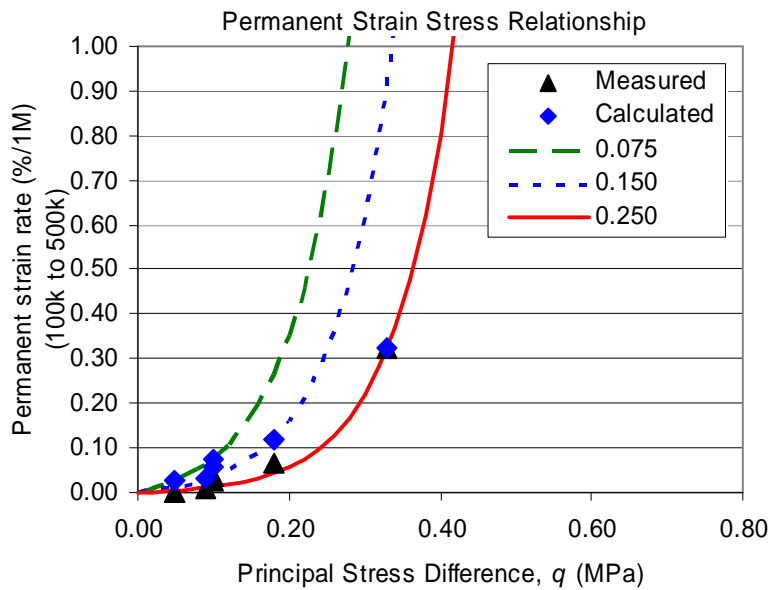


Figure 3: Example of Fitting Permanent Strain Rate Equation to RLT Data for Aggregate 1 (Dry-70%OMC) (full results in Appendix D).

Parameters a , b and c for Equation 1 are listed in Table 6 and 7.

Table 6: Parameters a , b and c (Equation 1) for RLT Test 1 (Dry, 70%OMC).

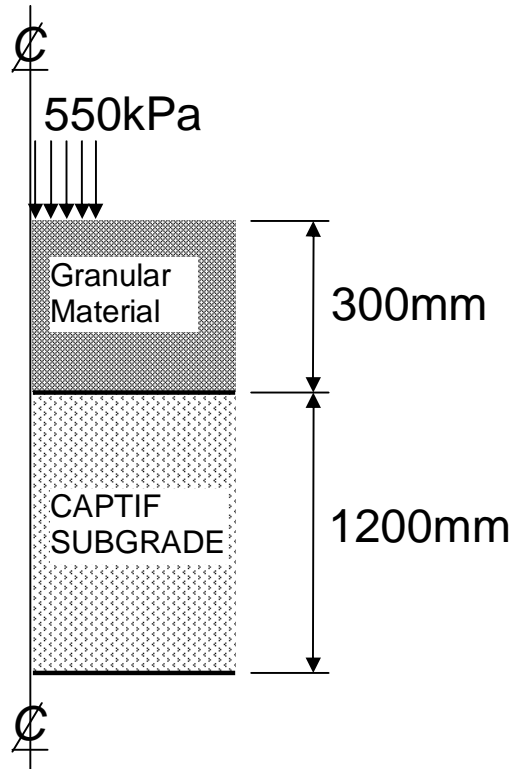
	Model Parameters (Arnold, 2004)			Mean error
	$\epsilon_{rate} = e^{(a)} e^{(bp)} e^{(cq)} - e^{(a)} e^{(bp)}$			
ϵ_{rate}	a	b	c	ϵ_{rate} (%/1M)
$\epsilon_{mgn(25k)}$	-3.048	-15.000	14.774	0.004
$\epsilon_{rate(25k-50k)}$	-1.781	-24.791	26.276	0.057
$\epsilon_{rate(50k-100k)}$	-3.065	-10.696	17.514	0.014
$\epsilon_{rate(100k-500k)}$	-2.788	-10.434	12.957	0.029

Table 7: Parameters a, b and c (Equation 1) for RLT Test 2 (Wet, 100%OMC).

	Model Parameters (Arnold, 2004)			Mean error
	$\epsilon_{rate} = e^{(a)} e^{(bp)} e^{(cq)} - e^{(a)} e^{(bp)}$			
ϵ_{rate}	a	b	c	$\epsilon_{rate} (\%/1M)$
$\epsilon_{mgn(25k)}$	-0.481	-11.972	13.920	0.140
$\epsilon_{rate(25k-50k)}$	-0.118	-10.382	17.863	1.100
$\epsilon_{rate(50k-100k)}$	-0.118	-10.382	17.863	0.336
$\epsilon_{rate(100k-500k)}$	-0.665	-9.343	12.781	0.099

Step 4: Finite Element Modelling to Calculate Stress and Deformation

An axisymmetric finite element model, ROSTRA, was used to calculate stresses in a typical CAPTIF pavement under a standard 8 tonne axle (40kN). The wheel load was simulated as a circular load of 550kPa. Pavement depth used was 300mm of aggregate over a silty clay subgrade (CBR =10) as detailed in the pavement cross-section (Figure 4). The FEM was validated by showing a good match with actual measured strains and surface deflections within the CAPTIF pavement.

**Figure 4: Pavement Cross Section used in Finite Element Modelling.**

Elastic modulus relationships are required for input into the finite element model. The relationship for the Aggregate 1 was found from the RLT results (Table 8).

Table 8: Elastic Modulus from RLT results for Aggregate 1.

					Dry (70% OMC)	Wet (100% OMC)
Single test	s_3	s_1	q	p	E-Modulus	E-Modulus
	[kPa]	[kPa]	[kPa]	[kPa]	[MPa]	[MPa]
A	120	210	90	150	184	112
B	58	108	50	75	183	94
C	67	167	100	100	203	123
D	42	142	100	75	184	127
E	90	270	180	150	217	<i>failed</i>
F	140	470	330	250	268	
G	110	530	420	250	220	

ROSTRA FEM requires the elastic modulus to be inputted in tabular or Equation form as detailed in Table 8 and Figure 5. Elastic modulus used for a typical aggregate used at CAPTIF (Canterbury Greywacke, TNZ M/4 AP40) is shown for comparison.

Table 6. Elastic Modulus for Aggregate 1 used in FEM.

σ_1 (kPa)	E (CAPTIF AP40)	E (Aggregate 1, 70%OMC) - Dry	E (Aggregate 1, 100%OMC) - Wet
1	40	72	33
100	159	176	102
200	196	201	121
300	221	217	134
500	258	239	152

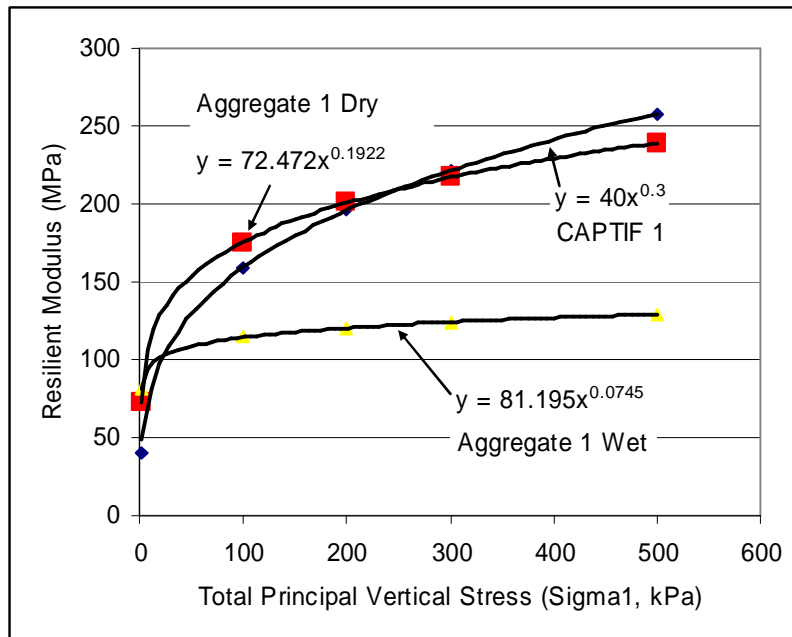


Figure 5: Elastic Modulus Relationship for Aggregate 1 used in FEM.

Running the FEM for the Aggregate 1 material yielded stresses under the wheel which were then used to calculate permanent strain from Equation 1 with Table 4 parameters. Table 7 detail the results of the rut depth prediction for the Aggregate 1 and CAPTIF Subgrade (note: Equation 1 Parameters for CAPTIF materials from Arnold's 2004 thesis). Figure 6 illustrates the result of the rut depth prediction.

Table 7: FEM and Rut Depth Prediction for Aggregate 1 Dry (70%OMC) Aggregate for CAPTIF Cross-Section.

Total Pavement	Aggregate only	Aggregate only
N, ESAs to get 25mm rut	N, ESAs to get 10mm rut in aggregate.	Long term rate of rutting within aggregate
Million ESAs	Million ESAs	mm per 1 Million ESAs
2.10	2.82	2.3

Rate of Rutting mm/1Million

Aggregate	-66.9	-67.2	-9.8	-2.3
Subgrade	-64.4	-22.0	-22.0	-6.7
Total	-131.4	-89.2	-31.8	-9.0

Rut Depth

Aggregate	-1.67	-3.35	-3.84	-4.75
Subgrade	-1.61	-2.16	-3.26	-5.94
Total	-3.28	-5.52	-7.11	-10.69

Aggregate 1 Dry 70% OMC

Depth	FEM Results (MPa)		Subgrade	Rutting (mm)			
	p	q		N, Millions:	0.025	0.05	0.1
-22	0.5774	0.5776		-0.0092	-0.0022	-0.0264	-0.0233
-43	0.4247	0.5429		-0.0519	-0.0371	-0.0702	-0.0698
-75	0.2983	0.4865		-0.2287	-0.2948	-0.1540	-0.1912
-97	0.2212	0.4277		-0.2095	-0.2926	-0.0863	-0.1369
-118	0.1492	0.3557		-0.2024	-0.2505	-0.0503	-0.1083
-150	0.0924	0.2906		-0.2740	-0.2821	-0.0448	-0.1267
-172	0.0549	0.2430		-0.1614	-0.1407	-0.0198	-0.0681
-193	0.0154	0.1944		-0.1318	-0.0992	-0.0121	-0.0502
-225	-0.0168	0.1552		-0.1738	-0.1185	-0.0126	-0.0607
-247	-0.0439	0.1295		-0.1165	-0.0800	-0.0071	-0.0373
-268	-0.0714	0.1080		-0.1142	-0.0834	-0.0059	-0.0332
-300	0.0490	0.0932		-0.0918	-0.0334	-0.0669	-0.1888
-330	0.0442	0.0849		-0.0847	-0.0305	-0.0611	-0.1673
-358	0.0396	0.0762		-0.0763	-0.0272	-0.0543	-0.1448
-400	0.0364	0.0690		-0.1087	-0.0383	-0.0765	-0.1998
-430	0.0343	0.0637		-0.0738	-0.0258	-0.0515	-0.1328
-458	0.0315	0.0581		-0.0657	-0.0227	-0.0454	-0.1151
-500	0.0283	0.0516		-0.0921	-0.0316	-0.0632	-0.1570
-559	0.0259	0.0457		-0.1185	-0.0403	-0.0805	-0.1971
-616	0.0212	0.0399		-0.1086	-0.0368	-0.0735	-0.1752
-700	0.0181	0.0351		-0.1483	-0.0500	-0.1000	-0.2338
-759	0.0163	0.0319		-0.0972	-0.0326	-0.0653	-0.1511
-816	0.0146	0.0286		-0.0868	-0.0290	-0.0580	-0.1329
-900	0.0133	0.0260		-0.1182	-0.0394	-0.0788	-0.1791
-959	0.0126	0.0241		-0.0778	-0.0259	-0.0517	-0.1170
-1016	0.0120	0.0220		-0.0692	-0.0229	-0.0459	-0.1034
-1100	0.0118	0.0192		-0.0888	-0.0292	-0.0585	-0.1315
-1233	0.0064	0.0130		-0.1045	-0.0343	-0.0687	-0.1498
-1683	0.0020	0.0052		-0.1534	-0.0500	-0.1000	-0.2126

Table 8: FEM and Rut Depth Prediction for Aggregate 1 Wet (100%OMC) Aggregate for CAPTIF Cross-Section.

Total Pavement	Aggregate only	Aggregate only
N, ESAs to get 25mm rut	N, ESAs to get 10mm rut in aggregate.	Long term rate of rutting within aggregate
<i>Million ESAs</i>	<i>Million ESAs</i>	<i>mm per 1 Million ESAs</i>
0.02	0.01	24.4

Rate of Rutting mm/1Million

Aggregate	-1100.3	-282.9	-282.9	-24.4
Subgrade	-65.2	-22.4	-22.4	-6.9
Total	-1165.5	-305.3	-305.3	-31.2

Rut Depth

Aggregate 1 Wet 100% OMC

Aggregate	0	-27.51	-34.58	-48.73	-58.47
Subgrade	0	-1.63	-2.19	-3.31	-6.06
Total	0	-29.14	-36.77	-52.04	-64.52

Depth	FEM Results (MPa)		N, Millions:	Rutting (mm)			
	p	q		0	0.025	0.05	0.1
-22	0.5511	0.5776	0	-0.5754	-0.4844	-0.9688	-0.4223
-43	0.4057	0.5452		-1.9931	-1.1720	-2.3439	-1.0356
-75	0.2845	0.4906		-6.0629	-2.3721	-4.7442	-2.4365
-97	0.2133	0.4340		-4.4365	-1.2412	-2.4824	-1.5761
-118	0.1493	0.3644		-3.4460	-0.6638	-1.3275	-1.1180
-150	0.0987	0.3003		-3.9105	-0.5430	-1.0860	-1.1910
-172	0.0669	0.2539		-2.0319	-0.2253	-0.4505	-0.5979
-193	0.0340	0.2064		-1.4413	-0.1275	-0.2550	-0.4082
-225	0.0070	0.1670		-1.6766	-0.1238	-0.2477	-0.4594
-247	-0.0143	0.1412		-0.9908	-0.0650	-0.1299	-0.2628
-268	-0.0444	0.1194		-0.9422	-0.0550	-0.1099	-0.2353
-300	0.0546	0.1035	Subgrade	-0.0933	-0.0345	-0.0691	-0.2017
-330	0.0476	0.0935		-0.0889	-0.0325	-0.0651	-0.1823
-358	0.0409	0.0831		-0.0824	-0.0298	-0.0595	-0.1603
-400	0.0362	0.0743		-0.1189	-0.0424	-0.0849	-0.2221
-430	0.0333	0.0680		-0.0813	-0.0288	-0.0575	-0.1478
-458	0.0303	0.0614		-0.0716	-0.0251	-0.0501	-0.1264
-500	0.0274	0.0538		-0.0982	-0.0339	-0.0678	-0.1679
-559	0.0242	0.0469		-0.1263	-0.0432	-0.0864	-0.2097
-616	0.0213	0.0403		-0.1095	-0.0371	-0.0742	-0.1768
-700	0.0186	0.0350		-0.1464	-0.0493	-0.0986	-0.2312
-759	0.0161	0.0315		-0.0961	-0.0323	-0.0645	-0.1492
-816	0.0139	0.0278		-0.0851	-0.0285	-0.0569	-0.1299
-900	0.0124	0.0247		-0.1143	-0.0381	-0.0761	-0.1721
-959	0.0115	0.0225		-0.0741	-0.0246	-0.0492	-0.1106
-1016	0.0105	0.0202		-0.0650	-0.0215	-0.0430	-0.0962
-1100	0.0093	0.0172		-0.0834	-0.0275	-0.0550	-0.1219
-1233	0.0074	0.0122		-0.0959	-0.0314	-0.0628	-0.1376
-1683	0.0024	0.0055		-0.1598	-0.0521	-0.1042	-0.2218

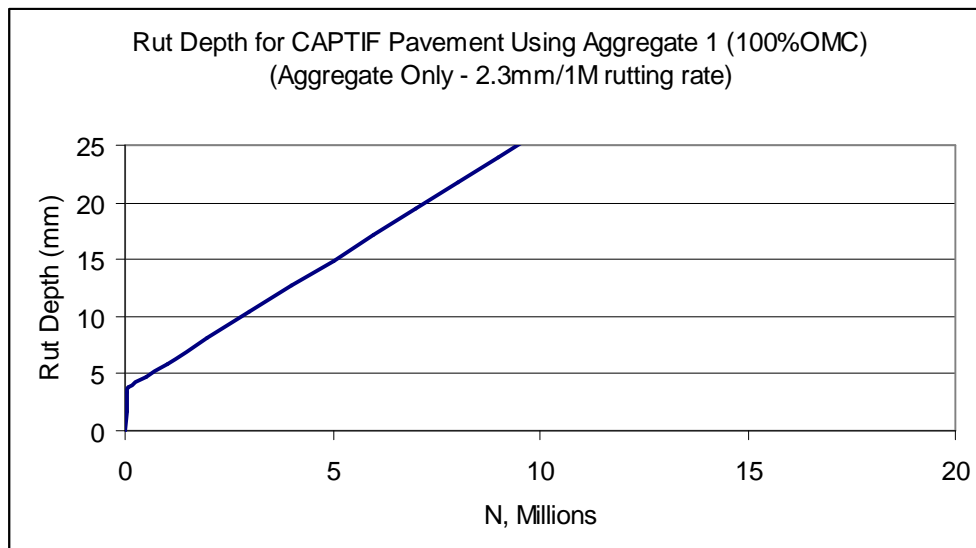
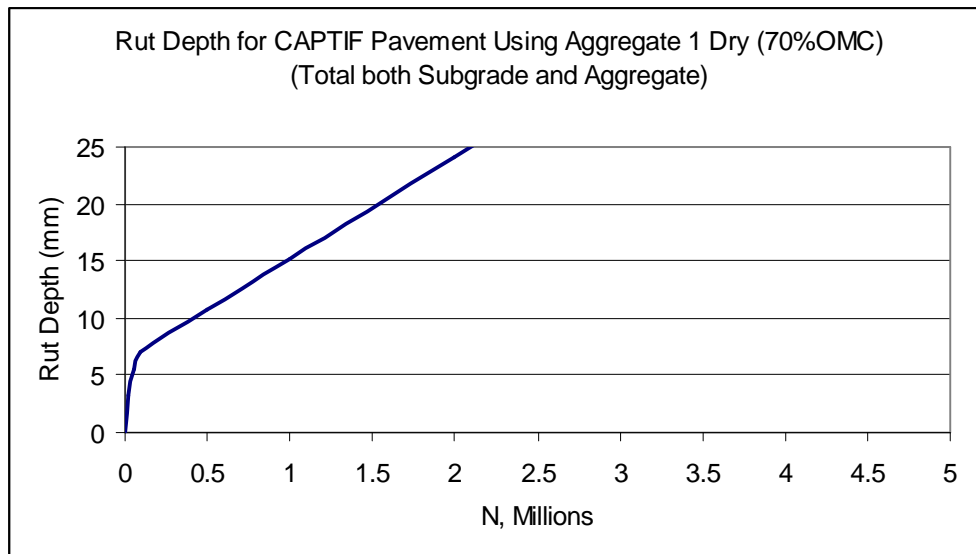


Figure 6: Results of Rut Depth Prediction for Aggregate 1 – Dry (70%OMC) (N = Equivalent Standard Axles, ESAs).

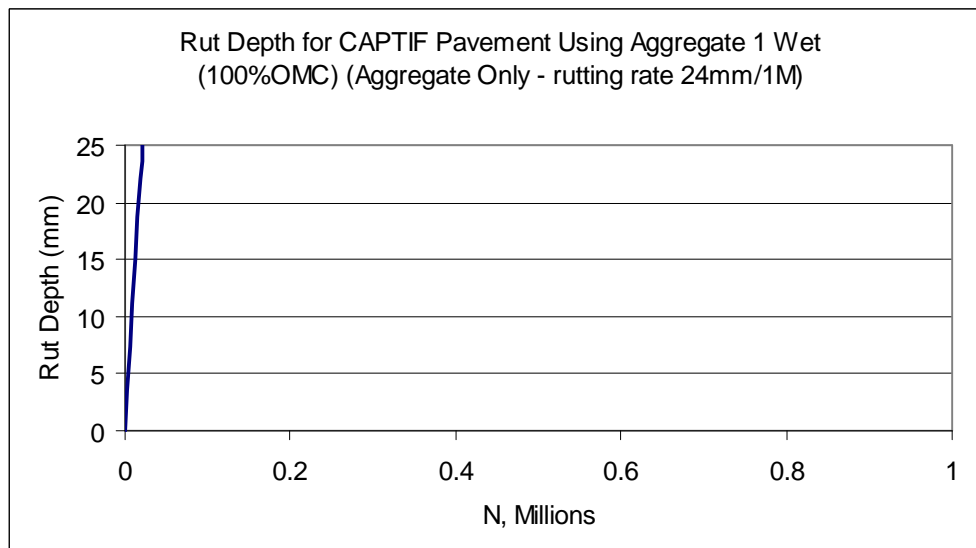
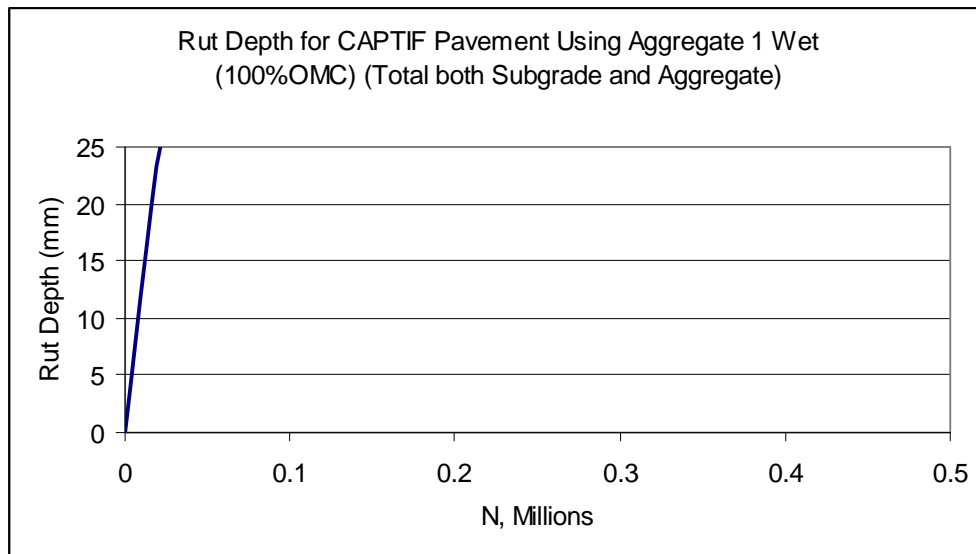


Figure 7: Results of Rut Depth Prediction for Aggregate 1 – Wet (100%OMC) (N = Equivalent Standard Axles, ESAs).

Comparison of Results to CAPTIF

There are many assumptions required throughout the analysis of RLT results to predict rut depth. To give confidence in the predictions a comparison with results at CAPTIF was undertaken and the assumptions used were on the conservative side (ie. calculated deformations are generally higher than those actually measured). The same assumptions and analysis method used for the Aggregate 1 is applied to a commonly used aggregate in accelerated pavement tests at CAPTIF. This CAPTIF aggregate is an AP40 complying with TNZ M4 Canterbury Greywacke from Ponds Road in Christchurch. In Arnold's thesis, the Canterbury AP40 aggregate is referred to as CAPTIF 1. Arnold's thesis reports a total of three multi-stage permanent strain RLT tests were conducted on the

CAPTIF 1 aggregate and the Subgrade material for determining the parameters for Equation 1 (Table 9). It should be noted that the CAPTIF 1 aggregate was tested at CAPTIF and in the RLT apparatus at dry conditions (70%OMC @ 95%MDD) and therefore good performance is expected.

Table 9: Equation Parameters for CAPTIF Aggregate and Subgrade

Material	ϵ_{rate}	Model Parameters (Arnold, 2004)			Mean error
		a	b	c	
		$\epsilon_{rate} = e^{(a)} e^{(bp)} e^{(cq)} - e^{(a)} e^{(bp)}$			
					$\epsilon_{rate} (\%/1M)$
CAPTIF 1 (AP40, 70%OMC, 95%MDD)	$\epsilon_{mgn}(25k)$	-4.369	-13.05	14.41	
	$\epsilon_{rate}(25k-50k)$	-1.548	-18.937	14.993	0.220
	$\epsilon_{rate}(50k-100k)$	-1.548	-18.937	14.993	0.220
	$\epsilon_{rate}(100k-500k)$	-3.100	-13.578	12.203	0.100
	$\epsilon_{rate}(500k-1M)$	-3.100	-13.578	12.203	0.100
CAPTIF Subgrade	$\epsilon_{mgn}(25k)$	0.401	-20.243	4.479	
	$\epsilon_{rate}(25k-50k)$	2.125	-22.583	9.564	0.050
	$\epsilon_{rate}(50k-100k)$	2.125	-22.583	9.564	0.050
	$\epsilon_{rate}(100k-500k)$	0.8	-17.434	10.328	0.070
	$\epsilon_{rate}(500k-1M)$	0.8	-17.434	10.328	0.070

The elastic modulus relationships used in the FEM for the CAPTIF 1 aggregate and subgrade are shown in Figure 8.

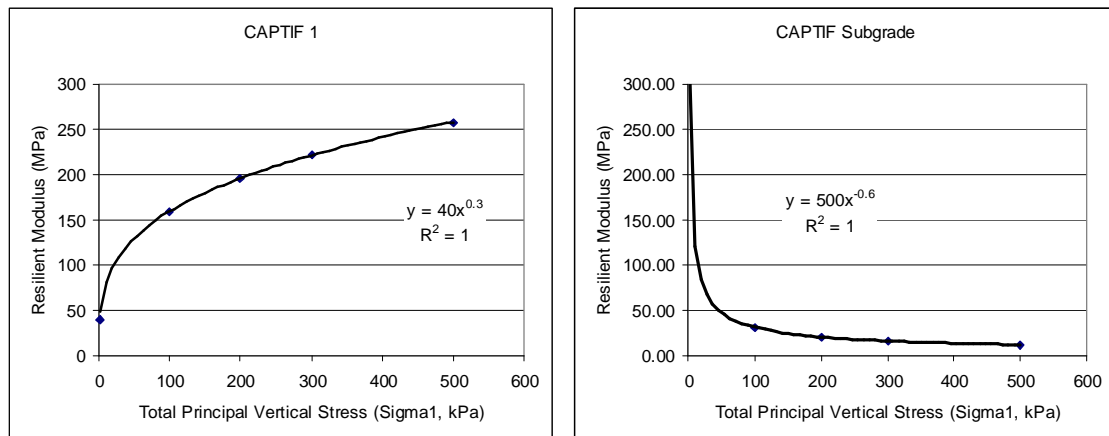


Figure 8: Elastic Modulus Relationships used in FEM.

Applying the same assumptions as used for the Aggregate 1 the results of the FEM and rut depth prediction using the CAPTIF 1 aggregate at 300mm thick over the CAPTIF subgrade CBR are shown in Table 10 and Figure 9.

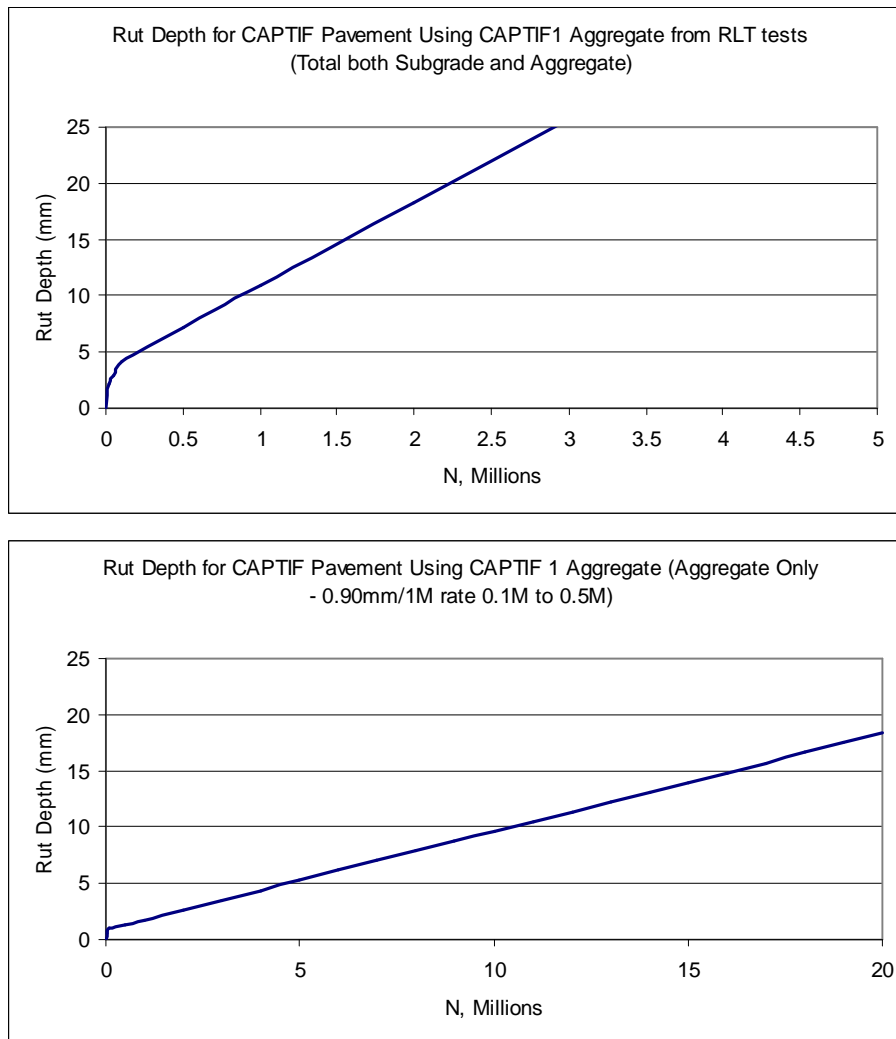


Figure 9: Results of Rut Depth Prediction for CAPTIF 1 Aggregate (N = Equivalent Standard Axles, ESAs).

Actual rut depth measured at CAPTIF for a 300mm deep pavement is shown in Figure 10. It can be seen that the RLT rut depth prediction method under estimates the actual life. It is likely that this is due to the rutting in the subgrade being predicted higher than actually occurred. However, the results do indicate that the RLT prediction method is conservative.

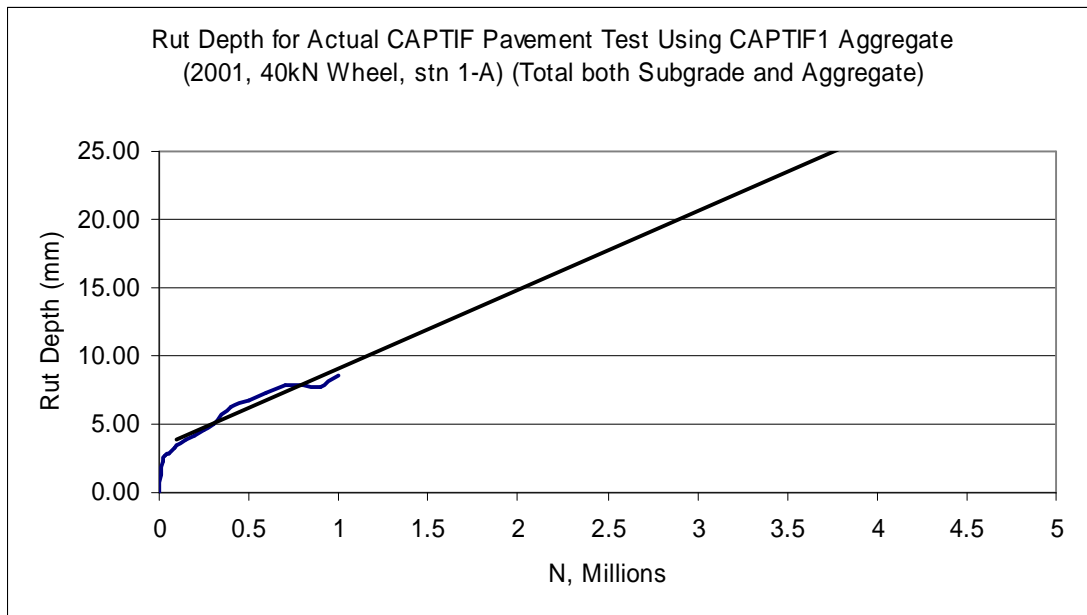


Figure 10: Actual Rutting From Accelerated Pavement Test at CAPTIF.

Table 10: FEM and Rut Depth Prediction for CAPTIF 1 (AP40, TNZ M4, 70%OMC) Aggregate for CAPTIF Cross-Section.

FEM Results (MPa)			Rate of Rutting mm/1Million				
Depth	p	q	Aggregate	Subgrade	Total		
			-21.1	-5.9	-5.9	-0.9	
			-63.4	-21.6	-21.6	-6.6	
			-84.6	-27.6	-27.6	-7.4	
FEM Results (MPa)			Rut Depth				
Depth	p	q	Aggregate	Subgrade	Total		
			-0.53	-0.68	-0.97	-1.32	
			-1.59	-2.13	-3.21	-5.84	
			-2.11	-2.80	-4.18	-7.16	
FEM Results (MPa)			Rutting (mm)				
Depth	p	q	N, Millions:	0.025	0.05	0.1	0.5
-22	0.5794	0.5774	CAPTIF 1	-0.0060	-0.0001	-0.0002	-0.0017
-43	0.4211	0.5411		-0.0265	-0.0013	-0.0026	-0.0092
-75	0.2892	0.4834		-0.0985	-0.0100	-0.0200	-0.0413
-97	0.2100	0.4231		-0.0797	-0.0125	-0.0249	-0.0398
-118	0.1376	0.3498		-0.0677	-0.0155	-0.0310	-0.0411
-150	0.0814	0.2843		-0.0828	-0.0255	-0.0509	-0.0594
-172	0.0457	0.2369		-0.0451	-0.0167	-0.0334	-0.0363
-193	0.0091	0.1892		-0.0337	-0.0151	-0.0302	-0.0303
-225	-0.0183	0.1515		-0.0405	-0.0209	-0.0418	-0.0395
-247	-0.0408	0.1268		-0.0248	-0.0144	-0.0288	-0.0255
-268	-0.0675	0.1062		-0.0232	-0.0157	-0.0314	-0.0251
-300	0.0480	0.0918	Subgrade	-0.0920	-0.0335	-0.0670	-0.1879
-330	0.0430	0.0837		-0.0852	-0.0307	-0.0614	-0.1672
-358	0.0382	0.0752		-0.0773	-0.0275	-0.0550	-0.1456
-400	0.0348	0.0681		-0.1105	-0.0389	-0.0779	-0.2016
-430	0.0326	0.0629		-0.0753	-0.0263	-0.0526	-0.1344
-458	0.0303	0.0573		-0.0662	-0.0229	-0.0458	-0.1154
-500	0.0271	0.0508		-0.0927	-0.0318	-0.0637	-0.1571
-559	0.0243	0.0449		-0.1201	-0.0409	-0.0817	-0.1983
-616	0.0215	0.0391		-0.1054	-0.0356	-0.0712	-0.1698
-700	0.0182	0.0346		-0.1453	-0.0489	-0.0978	-0.2289
-759	0.0163	0.0313		-0.0954	-0.0320	-0.0640	-0.1480
-816	0.0144	0.0279		-0.0848	-0.0283	-0.0567	-0.1296
-900	0.0130	0.0251		-0.1146	-0.0382	-0.0763	-0.1732
-959	0.0121	0.0230		-0.0748	-0.0248	-0.0497	-0.1121
-1016	0.0112	0.0207		-0.0659	-0.0218	-0.0436	-0.0978
-1100	0.0100	0.0177		-0.0844	-0.0278	-0.0556	-0.1238
-1233	0.0071	0.0120		-0.0953	-0.0312	-0.0624	-0.1365
-1683	0.0024	0.0056		-0.1621	-0.0529	-0.1057	-0.2251

In summary, results comparing Aggregate 1 with a Canterbury Greywacke compliant TNZ M4 material are shown in Table 9.

Table 9: Results Summary Comparing Rut Depth Prediction of Aggregate 1 with CAPTIF 1 (Canterbury Greywacke - AP40 TNZ M4).

		CAPTIF Pavement 300mm Aggregate over 10CBR Subgrade		
		Total Pavement	Aggregate only	Aggregate only
Material	RLT Sample	N, ESAs to get 25mm rut	N, ESAs to get 10mm rut in aggregate.	Long term rate of rutting within aggregate
		<i>Million ESAs</i>	<i>Million ESAs</i>	<i>mm per 1 Million ESAs</i>
TNZ M4 Aggregate 1 (Dry)	95%MDD, 70%OMC	2.10	2.82	2.3
TNZ M4 Aggregate 1 (Wet)	95%MDD 100%OMC	0.02	0.01	24
CAPTIF 1	TNZ M4, AP40, 70%OMC, 95%MDD, Pond Road, Christchurch	2.9	10.4	0.9
CAPTIF test	2001, Section 1A, 40kN Wheel Load	3.8	<i>Unknown</i>	<i>Unknown</i>

MDD = Maximum Dry Density from Vibrating Hammer Compaction Test (NZS 4402 : Test 4.1.3)

OMC = Optimum Moisture Content (NZS 4402 : Test 4.1.3).

ESAs = Equivalent Standard Axles from Austroads Pavement Design Manual (1ESA = 1 pass of 8.2 tonne dual tyred axle).

Conclusion

The Aggregate 1 shows a lower life than that achieved by the high quality Canterbury Greywacke. If kept dry (<70%OMC) it is expected after 3 million ESAs (Heavy Axle passes) that pavement smoothing would be required due to rutting within the aggregate, while the long term rate of rutting of the dry (<70%OMC) Aggregate 1 is 2.3mm per 1 million ESAs. Should the in service moisture content of the Aggregate 1 exceed 100%OMC then it is expected that pavement failure in terms of rutting exceeding 25mm will occur very quickly within the first 1 million ESAs.

In comparison with other aggregates tested in the Repeated Load Triaxial apparatus and rut depth predicted the Aggregate 1 in the dry condition (rutting rate = 2.3mm per 1 million ESAs) is nearly as good as the better quality aggregates in the dry condition (rutting rate = 0.5 to 2mm per 1 million ESAs). In the wet condition the Aggregate 1 would be group in with the worst performing aggregates (rutting rate = 14 to 51mm per 1 million ESAs).

Spread Sheet File References

- *RLT test Aggregate 1 100%OMC 5_7_06 v1.xls*
- *RLT test Aggregate 1 70%OMC 5_7_06 v1.xls*
- *Rut Depth Aggregate 1 70%OMC 5_7_06 v1.xls*
- *Rut Depth Aggregate 1 100%OMC 5_7_06 v1.xls*

Appendix A

Repeated Load Triaxial Testing and Rut Depth Modelling Technical Note

Repeated Load Triaxial Testing and Rut Depth Modelling for Pavement Materials (granular, modified, local, recycled, waste, stabilised, subgrade)

Dr Greg Arnold, PaveSpec Ltd (email: greg.arnold@pavespec.co.nz)

What is Repeated Load Triaxial (RLT) Testing?

The RLT (Repeated Load Triaxial) apparatus applies repetitive loading on cylindrical materials for a range of specified stress conditions, the output is deformation (shortening of the cylindrical sample) versus number of load cycles (usually 50,000) for a particular set of stress conditions. Multi-stage RLT tests are used to obtain deformation curves for a range of stress conditions to develop models for predicting rutting.

Resilient Modulus information can also be obtained for pavement design in CIRCLY and Finite Element Models.



Fig 1. RLT Apparatus and Setup.

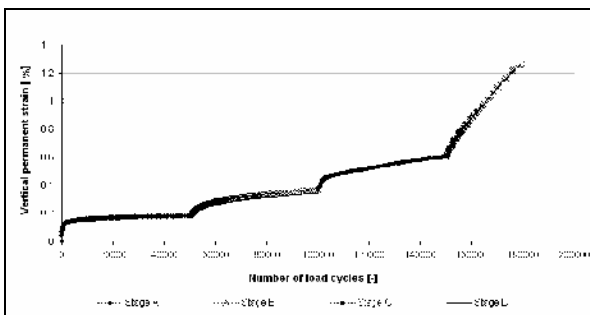


Fig 2. Typical Output from Permanent Strain RLTT.

Analysis of RLTT Results – Rut Depth Modelling.

The method developed by Dr Arnold in his Doctorate studies at the University of Nottingham, UK is used to interpret the results to predict the rut depth in a pavement. First step is to develop a

mathematical relationship between stress (both vertical and horizontal) with permanent strain rate (slope of each deformation curves (Fig 2), e.g % deformation per 1 Million Loads Cycles).

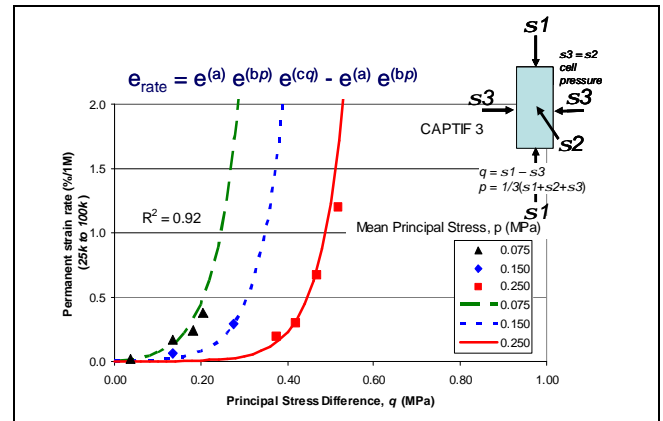


Fig 3. Fitting the Permanent Strain Rate Model to RLTT Results.

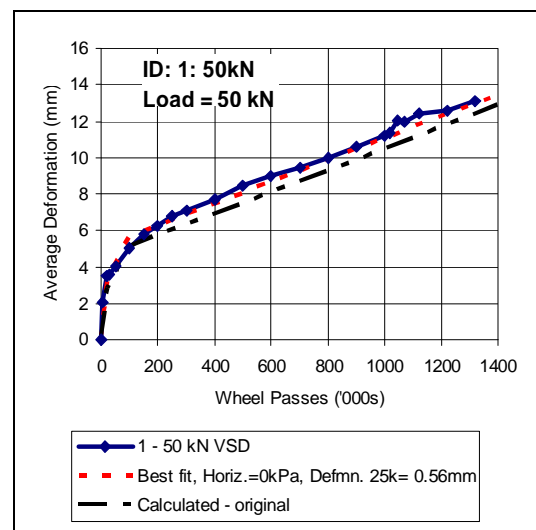


Fig 4. Rut Depth Prediction from RLTT for CAPTIF (Accelerated Pavement Test) Trial.

Next step is to use a finite element model (to model the non-linear elastic behaviour of a pavement material and to avoid discontinuities as occurs in CIRCLY which results in high tensile stresses) to compute the stresses (both vertical and horizontal) underneath a standard axle load (8.2 tonne dual tyred axle or higher if designing for ports etc). Stresses are exported into a spreadsheet to calculate

the deformation rate at depth increments in the pavement from the permanent strain model (Fig 3.). Results showed very good predictions of rutting that occurred at CAPTIF (Fig 4.) (Arnold, 2004).

Applications for RLTT and Rut Depth Modelling

Preventing Early Failure

Recent research has shown that even if your aggregate complies with M4 that they do not perform equally. The aggregate may fail by shear (Fig 5) within 6 months after the pavement has been constructed especially if it gets wet. The RLTT can quickly identify aggregates where there may be a risk of this occurring as often the sample fails before the completion of all the stress stages (Fig 2).

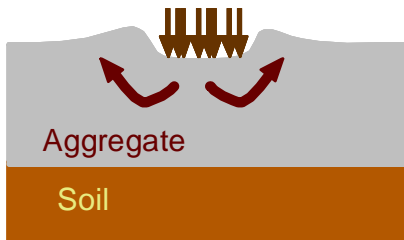


Fig 5. Shear Failure in Aggregate Layer.

Modified/Stabilised Materials for High Trafficked Roads

Small quantities of cement, lime or other additive are classified as a modified aggregate in the Transit New Zealand Supplement to the Austroads Pavement Design Guide. Modified aggregates are recommended in the NZ Supplement for use for high trafficked state highways as an economical alternative to structural asphalt. Using the RLTT will identify the most appropriate amount of additive and using rut depth modelling can predict the amount of extra life that can be obtained through modification compared with the source aggregate.

Modified/Stabilised Marginal Local Materials as a Lower Cost to TNZ M4 (and may perform better!)

RLTT and rut depth modelling allow any material that does not comply with a current specification to be assessed as suitable or not for the chosen application in the pavement. This allows a local material non-compliant with the specifications to be modified by say adding cement to be approved for use. Transit New Zealand are in the process to

develop a RLTT method and associated analysis to approve use of other materials on State Highways.

Local Materials for Local Roads

Footpaths, tennis courts, cul-de-sacs, low trafficked local roads do not need to use TNZ M/4 Basecourse Aggregate meant for State Highways. In fact M4 is difficult to lay and compact for these small local jobs. RLTT and rut depth prediction for the required application can allow say a local but dirty aggregate to be assessed as suitable for low trafficked situations and footpaths.

Waste and Recycled Materials

Waste or recycled materials like glass and reclaimed asphalt mixed with aggregate or otherwise can be tested in the RLT apparatus with rut depth modelling to determine appropriate applications as pavement base material.

PaveSpec Ltd

Dr Greg Arnold is the Director of PaveSpec Ltd which along with offering specialist pavement advice and design is a company that has just recently purchased a state of the art Repeated Load Triaxial apparatus for testing Pavement Materials.

Please contact Dr Greg Arnold if you would like to conduct any Repeated Load Triaxial tests and / or you would like to learn more with a visit at your office by Dr Greg Arnold as he is travelling the country in the next few months:

Dr Greg Arnold
PaveSpec Ltd
26 Copeland St
Lower Hutt 5011

Phone (04) 586 7434
Mobile 021 0323 117

Email: greg.arnold@pavespec.co.nz

References

ARNOLD, G. (2004) Rutting of Granular Pavements. PhD. University of Nottingham, England, UK. (If interested email: greg.arnold@pavespec.co.nz for a copy).

Appendix B

Repeated Load Triaxial (RLT) Multi-Stage Permanent Strain Test.

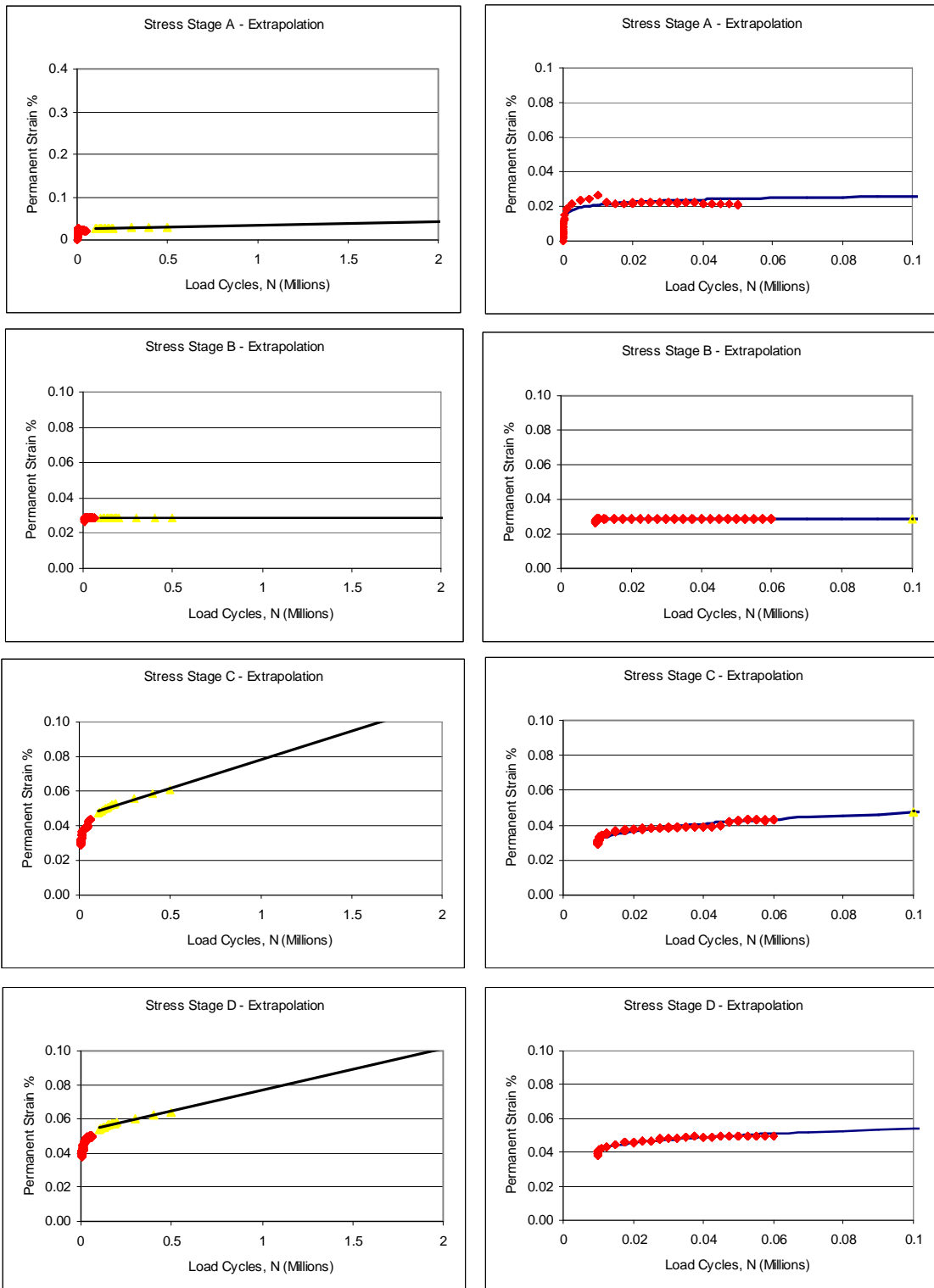
Features	Simplified Arnold Rut Depth Model
Material type	Maximum particle size less than 30 mm (usually remove > 26.5mm)
Sample Size	150 mm diameter and 300 mm length
Sample Preparation	Vibratory Hammer Compaction test in NZS 4402
Target Density-	95% Vibratory MDD (TNZ B/2:1997) or Specified field dry density
Moisture Condition	Fully saturated condition or optimum moisture content (OMC) or Specified field operating moisture content (70% OMC)
1-DI RLT test apparatus (vertical loading pulse)	To suit available RLT pneumatic equipment and control software in New Zealand Sinusoidal pulse at 4 times a second (4 hertz) using pneumatic equipment*
Triaxial Cell and Instrumentation	External load cell and 2 external displacement transducers mounted between loading caps to measure whole -sample strain.
Drainage Condition	Drained condition (no pore pressure measurement)
Stress conditions for permanent strain testing	7 stages on one specimen (see Table B1)
Number of specimens required	1 specimen per 7 stress stages per target density and moisture condition
Number of loading cycles	50,000 cycles per stress stage
Interpretation of test results	Rut depth and permanent strain modelling following the procedure developed by Arnold during his doctorate studies (Arnold, 2004).
Assessment methods	Compare predicted aggregate rate of rutting for a pavement at CAPTIF and compare with actual CAPTIF results using high quality TNZ M4 Canterbury Grey Wacke aggregate.

Table B1: RLT permanent strain testing for base deformation prediction

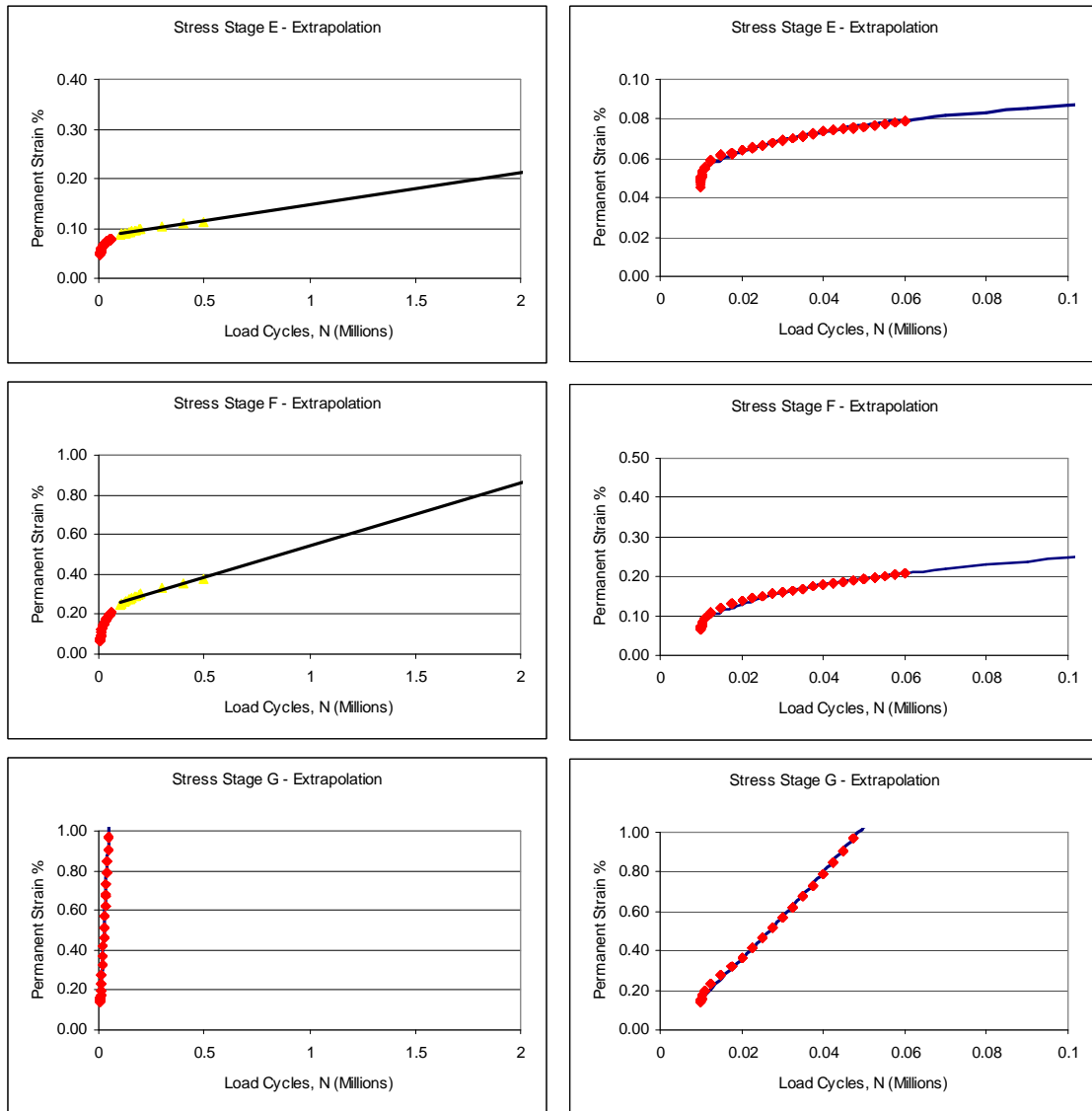
RLT Testing Stress Stage	A	B	C	D	E	F	G
Deviator stress - q (kPa) (cyclic vertical stress)	90.0	50.0	100.0	100.0	180.0	330.0	420.0
Mean stress - p (kPa)	150.0	75.0	100.0	75.0	150.0	250.0	250.0
Cell Pressure, s_3 (kPa)	120.0	58.3	66.7	41.7	90.0	140.0	110.0
Major Principal Vertical Stress, s_1 (kPa)	210.0	108.3	166.7	141.7	270.0	470.0	530.0
Cyclic Vertical Loading Speed	Sinusoidal at 5 Hz						
Number of Loads (N)	50,000						
Record and Report Data Electronically in Microsoft Excel	Permanent strain versus load cycles and resilient modulus versus load cycles						

Appendix C

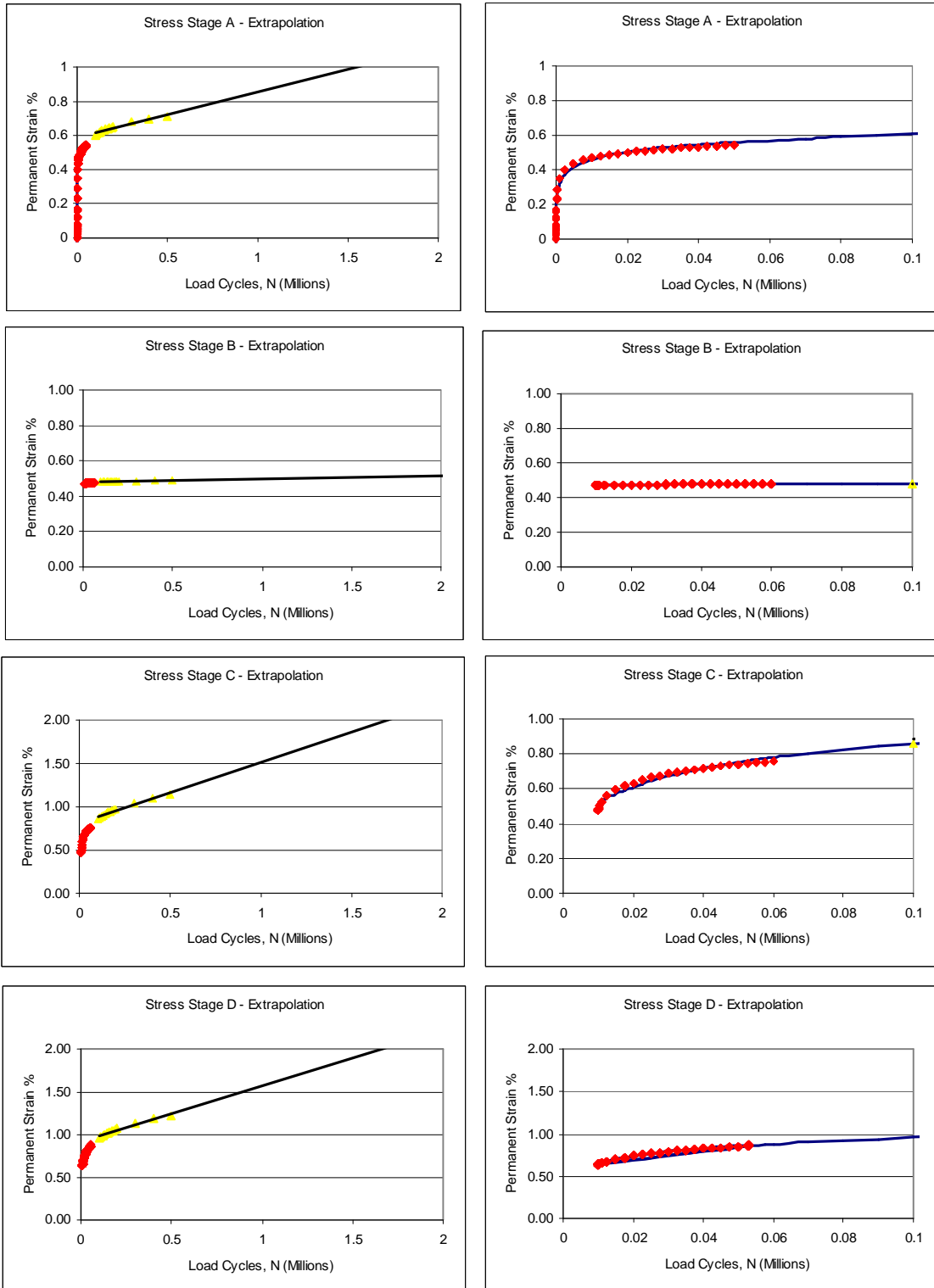
Extrapolation of Repeated Load Triaxial Results for RLT Test 1: Aggregate 1 Dry (70% OMC) and RLT Test 2: Aggregate 1 Wet (100% OMC)



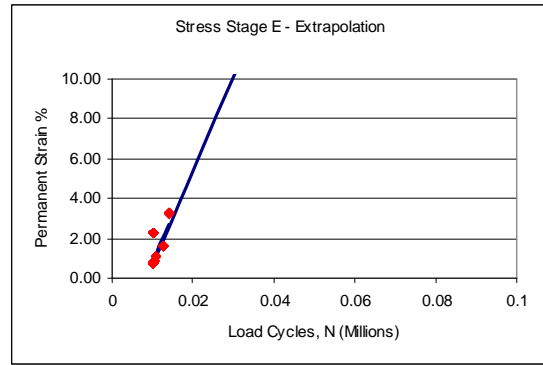
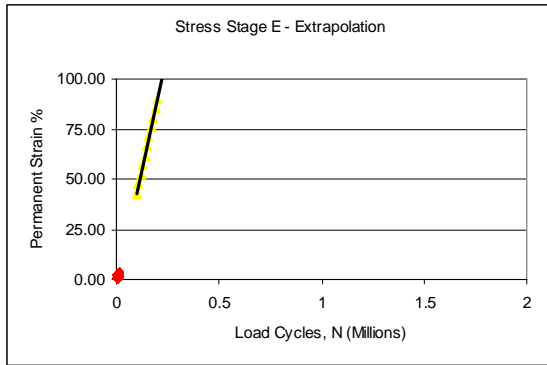
Aggregate 1 Dry (70%OMC) RLT Test – stages A to D



Aggregate 1 Dry (70%OMC) RLT Test – stages E to G



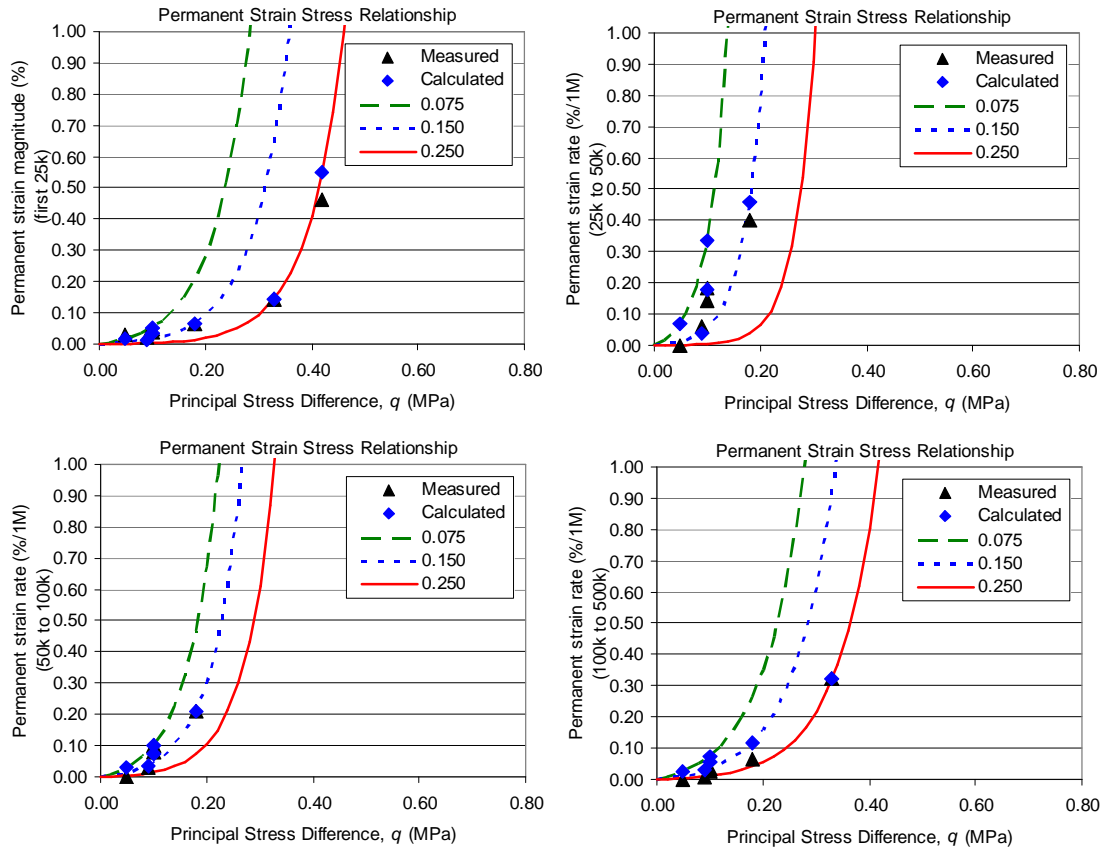
Aggregate 1 Wet (100%OMC) RLT Test – stages A to D



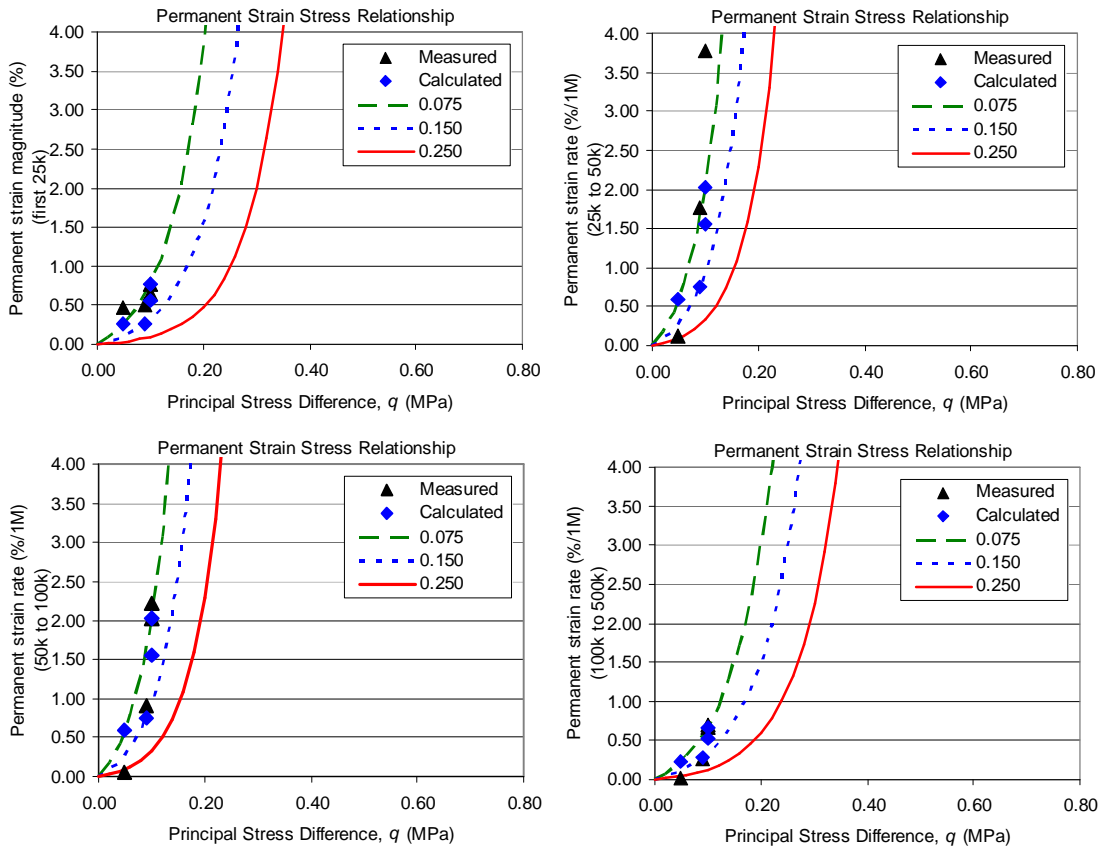
Aggregate 1 Wet (100%OMC) RLT Test – stages E to G

Appendix D

Fitting Equation to Predict Permanent Strain Rate from Stresses for Aggregate 1 Dry (70% OMC) and Wet (100% OMC)



Fitting Equation to RLT Data for Aggregate 1 Dry (70%OMC)



Fitting Equation to RLT Data for Aggregate 1 Wet (100%OMC)