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DEVELOPMENT OF A DYNAMIC DRTT K-MOULD SYSTEM

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SUMMARY

The paper briefly describes the K-mould and the dynamic loading and data acquisition system that was developed for the Division of Roads and Transport Technology (Transportek) K-mould. The loading system allows for the selection of the loading curve, the maximum load to be applied, the speed of application, the interval between load repetitions and the number of load repetitions required. The data acquisition system allows for the continuous recording of data during loading cycles, the selection of the number of data points per second as well as the interval (number of load cycles) between different data "windows". Some interesting results obtained with this system are then discussed.

OPSOMMING

Die referaat beskryf kortliks die K-druksel en die dinamiese belading- en dataversamelingsisteem wat vir die Divisie vir Pad- en Vervoertegnologie K-druksel ontwikkel is. Die belading sisteem maak voorsiening vir die seleksie van die beladingskromme, die maksimum aangewende las, die snelheid van aanwending, die tyd-interval tussen las-aanwendings, en die aantal las-aanwendings verlang. Die dataversamelingsisteem maak voorsiening vir die kontinue registrasie van data gedurende belading, die seleksie van die aantal data punte per sekonde asook vir die interval (die aantal lasherhalings) tussen opeenvolgende data "vensters". Sommige interessante resultate wat met die sisteem vasgelê is, word kortliks bespreek.

INTRODUCTION

The K-mould may be described as any of several mechanical devices that automatically increase the lateral restraint on a soil specimen as it is being vertically loaded. The result is a confined compression test but with a constant or controlled horizontal elastic modulus E_3 rather than a constant or controlled horizontal stress. The stiffness (i.e. elastic modulus) of the radial springs of the K-mould was chosen to simulate the lateral stiffness of roadbuilding materials in general ($E_3 = \pm 61250$ kPa) (somewhere between totally constrained and unconfined in the radial direction). An advantage over the conventional triaxial stress path method is that the horizontal stress need not be calculated in advance on the basis of elastic theory and an assumed K_o, but seeks its own value. The radial stress σ_3 depends on the amount of lateral strain ε_3 caused by the vertical stress σ_1 against the radial springs of the K-mould (i.e. $\sigma_3 = -E_3.\varepsilon_3$). Another advantage is that axially rigid but laterally flexing walls distribute strain uniformly through the specimen rather than to allow bulging in the middle, as typically occurs in the triaxial test[1].

A unique feature of a K-test system is that by following along either a K_o consolidation stress path or K_f shear failure stress path or something in between, a travelling Mohr circle is obtained that traces the entire envelope from one test on a single specimen[1].

The original concept of the K-mould was developed at the Iowa State University under the guidance of professor R L Handy. The current American version consists of a 100 mm (4 inch) internal diameter single-split mould (with a greater wall thickness at the back, in the zone of maximum bending moment) which takes normal Proctor samples. Since local practice uses 152,4 mm diameter samples, it was felt that the right approach would be to develop a K-mould of similar diameter so that the sample used to determine moisture-density curves can also be utilized to determine the parameters E_1, $E_d(M_R)$, ν, c and ϕ (see list of symbols at end of paper). Professor Handy was kind enough to send some design drawings for the basic manufacture of a 152,4 mm diameter K-mould. This is a larger version of the prototype 100 mm diameter K-mould.

The second prototype K-mould (see Figure 1) developed at Transportek consists of an internal thick-walled cylinder (with an internal diameter of 152,4 mm) made up to eight equal casehardened circular segments. Each segment is mounted on two horizontal shafts which fit into two radially mounted linear ball bearings to allow each segment to move freely in a radial direction. The linear bearings are mounted on an outer thick-walled cylinder which also support sixteen mountings housing the disc springs which apply radial forces to the internal segmented cylinder.

The dynamic loading and data recording system which has now been developed, makes it possible to simulate traffic loading and determine the elastic properties (E, c, ϕ and ν) of roadbuilding materials under these condition.

The system basically consists of two computers (286 or faster) and an Instron (or equivalent) load frame. The one computer is used to drive the load frame by means of a function generated by the computer (eg haversine wave). The response of the loadframe loadcell is fed back to this computer to ensure the correct response. Apart from the shape of the load curve, the maximum load can be specified (between 1 and 200 kN) and the speed of loading (from 25 ms to 60 s or greater). The speed of loading is however also dependant on the loadframe configurations (ie the pump may be too small

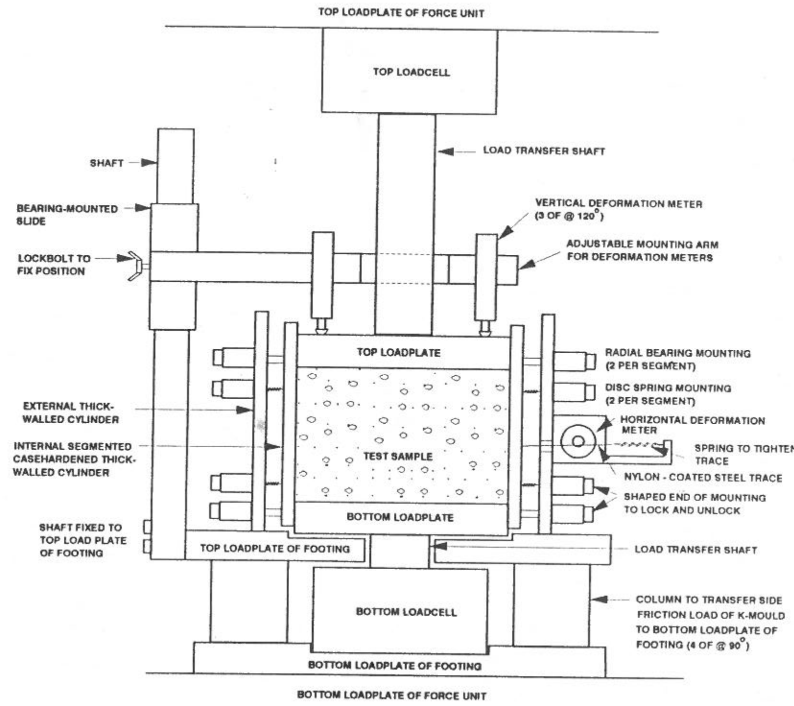

FIGURE 1: Schematic side view of K-mould set-up

to allow loading in 25 ms). Most of the dynamic tests sofar have been successfully run at a loading time of 100 ms. The number of load repetitions required (eg five to several million) as well as the time interval between consecutive load pulses (≥ 100 ms) can also be set. At a loading rate of 0,1 s and recovery time interval of 0,2 s it is possible to apply 250 000 load applications in 24 hours.

The second computer is used as the data acquisition system and is connected to the first computer to synchronise the two systems. Data of the Instron load cell, the average measured load of the K-mould load cells, the average vertical deformation and the total horizontal expansion are presently recorded continuously. The rate of data collection can vary from 10 points per second to 7 000 points per second per channel. Data "windows" are collected for every n th load repetition where n is a variable (2 or greater). The size of the window (ie 1 000 points per channel) is also variable.

The system therefore allows for the dynamic as well as quasi static testing of materials. From the measured average load of the K-mould, the average vertical deformation and horizontal expansion all the elastic properties (E, ϕ, c and ν) of roadbuilding materials are determined (see ATC Research Forum, Volume 1[2] for more detailed discussion of the theory of the K-mould).

DISCUSSIONS OF SOME RESULTS OF THE DYNAMIC K-MOULD SYSTEM

Figure 2 shows a typical stress-strain curve for a weathered dolerite as recorded by the system. Contra to a perfect elastic material the weathered dolerite does not follow the same curve during the "loading" and "unloading" phase. It is therefore necessary to treat these two phases separately. Where the elastic modulus is actually the slope of these curves it is clear to see why the maximum E-value during the unloading phase is often greater than the maximum E-value during the loading phase. This may be one of the factors which support the finding that the deflection bowl under a moving load is asymmetrical.

The elastic modulus further depends on the stress state (see Figure 3). The increase in stress state ($\theta = \sigma_1 + \sigma_2 + \sigma_3$) is more dependant on the internal friction and rate of loading than on the increase in density during loading (see Figures 4 and 5). Figure 4 shows the relation between the derived dynamic E-values (see Appendix) and the rate of loading for a single weathered dolerite sample. The speed of travel of a vehicle therefore also has a potential effect on the elastic and shear properties (provisional results indicate that E, c, ϕ and υ are all dependent on the speed of loading), indicating that slow moving vehicles normally do more damage than fast moving vehicles. The dynamic loads applied by fast moving vehicles on uneven pavements could however be larger than for slow traffic, offsetting the advantage of speed to some extent. This also proves why up-hill lanes are normally more

damaged than down-hill lanes. Figure 5 clearly shows that the increase in the density during dynamic loading is very slight compared to the change in E-value.

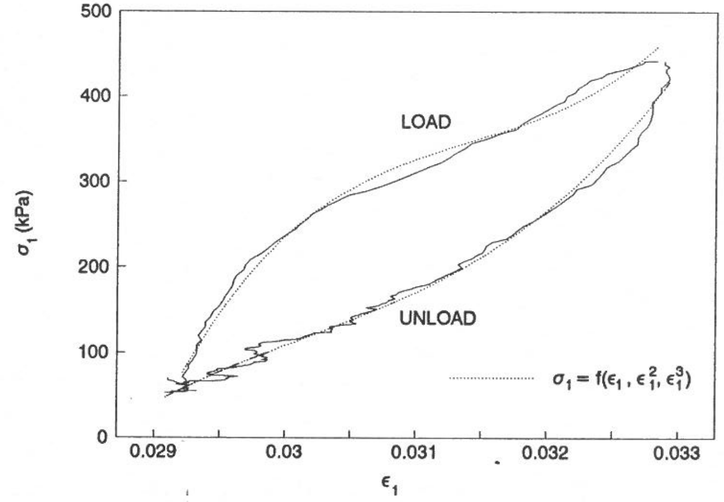

FIGURE 2: A typical example of σ_1 against ε_1 for a weathered dolerite (loading time = 100 ms)

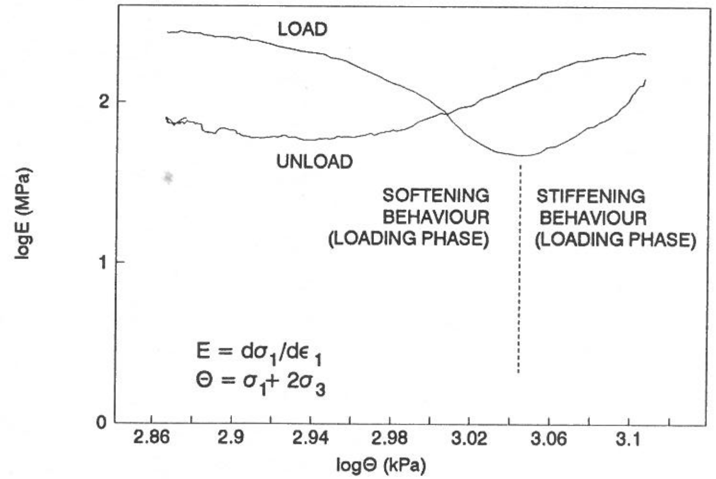

FIGURE 3: A typical curve of log E against log θ where $\theta = \sigma_1 + 2\,\sigma_3$ for a weathered dolerite (loading time = 100 ms)

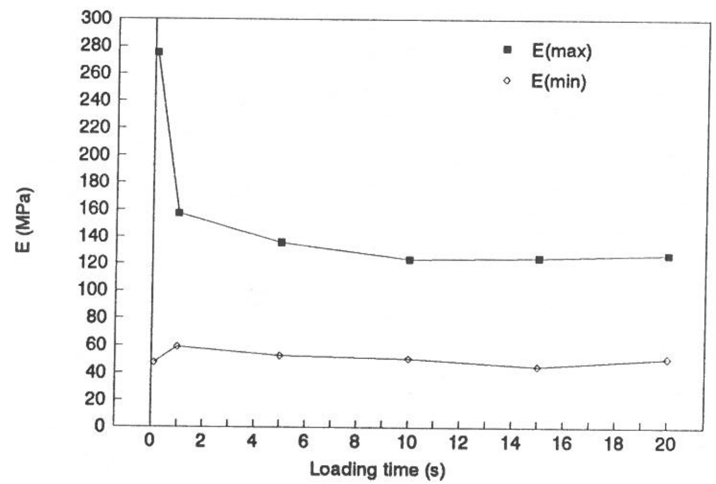

FIGURE 4: The derived values for E for different loading rates for weathered dolerite (same sample throughout)

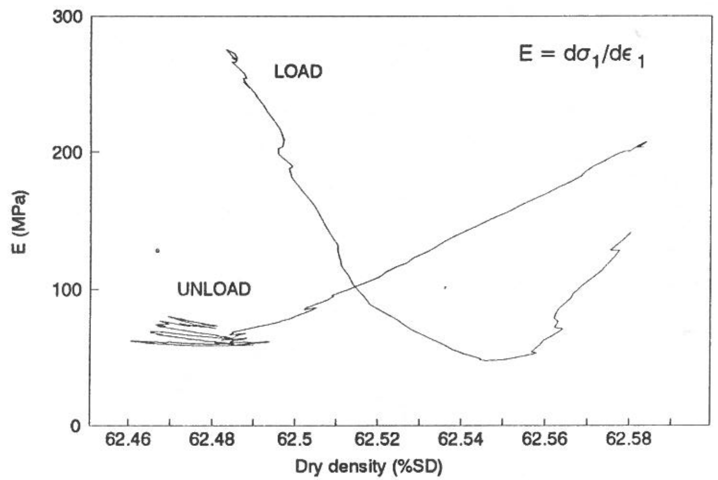

FIGURE 5: The relation between E and dry density (% SD) for the weathered dolerite during the same loading cycle (loading time = 100 ms)

Although the plots of log E against log θ are sometimes close to a straight line (see Figure 6), this is more the exception than the rule (see Figure 3). This means that the standard approach that

$$E = k_1\theta^{k2} \text{ (or } \log E = \log k_1 + k_2.\ \log \theta) \qquad (1)$$

is only applicable to a limited stress range.

A function which seems to cover the full stress range, seems to be

$$\log E = k_1.\ (\log \theta) + k_2.\ (\log \sigma_1) + k_3.\ (\log \theta)^2 + k_4.\ (\log \sigma_1)^2 + k_5 \qquad (2)$$

(See appendix for results of both the weathered dolerite and the crushed G1 dolerite. Note the high r^2-values generally found. An r^2-value close to one indicates that the chosen function accurately describes the relation between the different properties. In civil engineering and r^2-value of 0,7 is already deemed to indicate a relationship).

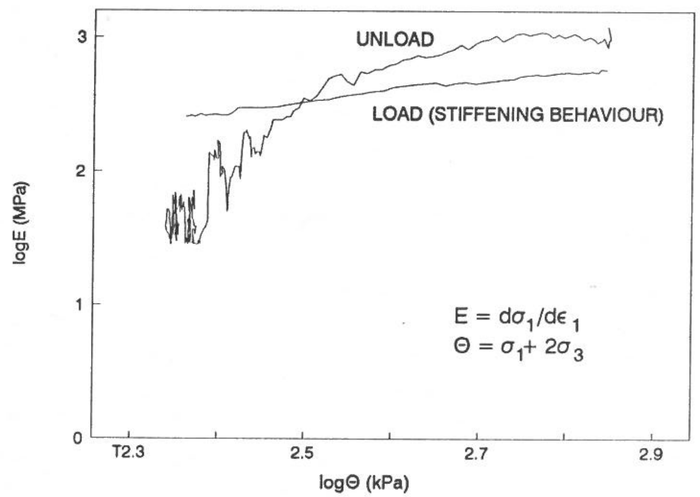

FIGURE 6: Log E against log θ for a crushed G1 dolerite (loading time = 100 ms)

The values of the friction angle, ϕ, for the normal stress range experienced in the pavement seem to be much higher than is presently being reflected by the static loading test to failure in the triaxial loading test (see results in Appendix). Lower ϕ-values comparing reasonably with those measured by the static triaxial loading test are only measured at extremely high stress levels ((ie load above 100 kN for crushed stone) (θ > 6 000 kPa)) It should be pointed out that the high negative values of c (= a.secϕ) (indicated in the Appendix) are due to the fact that the data used in both examples apply to the 200th load cycle. Both materials had at that stage expanded slightly in the horizontal direction leading to positive σ_3 when σ_1 is virtually nil, which implies a relatively high negative c-value. In the static triaxial test however, the sample is only loaded for one cycle to failure from which "static" c and ϕ values are determined. When this is done with K-mould samples the negative c-values are much smaller and even positive in some cases, comparable with those measured with the static triaxial test.

Assuming isotropic, homogenous, linear elastic conditions, Poisson's ratio υ was calculated with the following equation (see list of symbols at end of paper):

$$\upsilon = (\varepsilon_1.\sigma_3 - \varepsilon_3.\sigma_1)/(\varepsilon_1.(\sigma_1 + \sigma_3) - 2.\varepsilon_3.\sigma_3) \quad \ldots\ldots (3)$$

It is interesting to note that the value of Poisson's ratio is not constant, but also varies with the stress state (see Figure 7). Conventional triaxial tests by Sweere[4] showed that Poisson's ratio varies with the applied stress level. Note that the value can actually be greater than 0,5. According to the linear-elastic theory (assuming that the material is isotropic, homogeneous and linear elastic (Hooke's Law)) it can be proved that the value of Poisson's ratio cannot be greater than 0,5 (i.e. constant volume)[3]. Furthermore although the value of Poisson's ratio can be as low as 0,1 (concrete) and as high as 0,5 (rubber), it is normally fixed for a particular material in current practice. The fact that the value of Poisson's ratio was found to be greater than 0,5 as well as changing with the stress state with the K-mould tests, probably indicates that granular roadbuilding materials are actually an-isotropic in nature. The degrees of an-isotropy as expressed by the ratio E_1/E_3 where E_3 is the horizontal elastic stiffness of the K-mould springs, is as high as 17 for the crushed dolerite and 3,75 for the weathered dolerite. However, the degree of an-isotropy is highly dependent on the stress state and probably the moisture content as well (i.e. effective stresses).

The E-values of roadbuilding materials also vary with dry density (% SD) and moisture content, reaching a peak value at a particular moisture content (see Figure 8). In compactability research it was found that the bearing capacity in terms of CBR has similar tendencies (see Figure 8)[5].

CONCLUSIONS AND RECOMMENDATIONS

The results of the dynamic K-mould testing are extremely promising. Considering that no recorded results were deleted as "outliers" the r^2-values are extremely high, pointing to accurate prediction of relations. The authors are confident that the accurate determination of the actual elastic properties of roadbuilding materials, as made possible by dynamic K-mould testing, can play a very important role in the more optimal design of pavement structures in future. Apart from being relatively accurate it is also a fairly rapid test. It is further believed that with the improved constitutive laws for material behaviour (static and dynamic), improvements in back-calculation of layer (material) properties from field measured response data like the surface and subsurface deflection basins are possible.

The K-mould has great advantages, both as a routine design tool as well as research tool. If is far more productive than the conventional triaxial test in that it only requires one sample instead of a family of similarly prepared samples to determine the Mohr-Colomb feature envelope. Furthermore all the elastic and shear properties can be determined for each sample. It also uses standard size density samples (e.g. CBR mould size) instead of requiring special prepared samples with a height to diameter ratio of at least two as required by the conventional triaxial test. Because all the data is determined from one sample, the measured properties can also be related to the actual sample conditions (i.e. dry density, moisture content, etc.) Apart from this the actual testing time is also reduced (easier to handle, as well as less samples to test). It also does not require a sophisticated pressure cell. The high r^2-values of the results in general also point to very good relations, between the different properties, which therefore give an accurate reflection of the elastic and shear properties of roadbuilding materials.

No direct comparison has been done with the conventional triaxial test, as this would be an expensive exercise. However, a limited comparison was done with the back-calculated E-values from the HVS experiments. Material samples from the different layers from some HVS sites were compacted to the same density and air-dried to approximately the same moisture content as the field measurements; after which the samples were tested with the K-mould. In general there seems to be good agreement between K-mould measured E-values and the back-calculated E-values for the HVS.

Future K-mould research will concentrate on development of constitutive laws for various material types (i.e. asphaltic, granular and cemented) for both static and dynamic road behaviour.

Recent research showed that the spring stiffness E_3 may possibly have some effect on the values of c, ϕ and υ. This will also be researched in the next year.

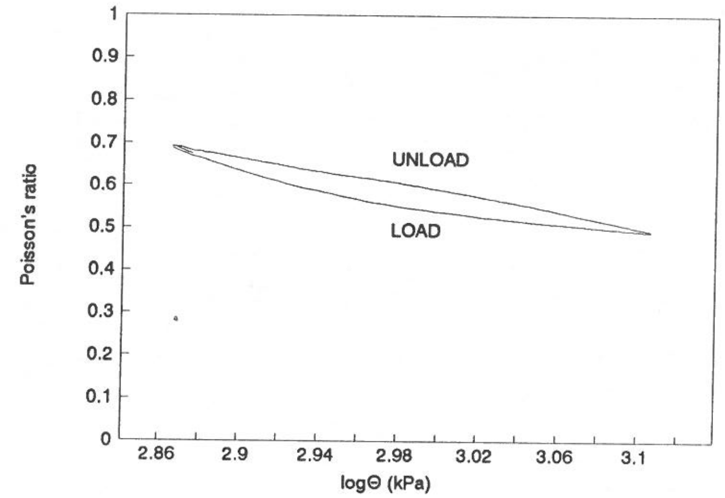

FIGURE 7: Poisson's ratio, ν, against log θ for weathered dolerite

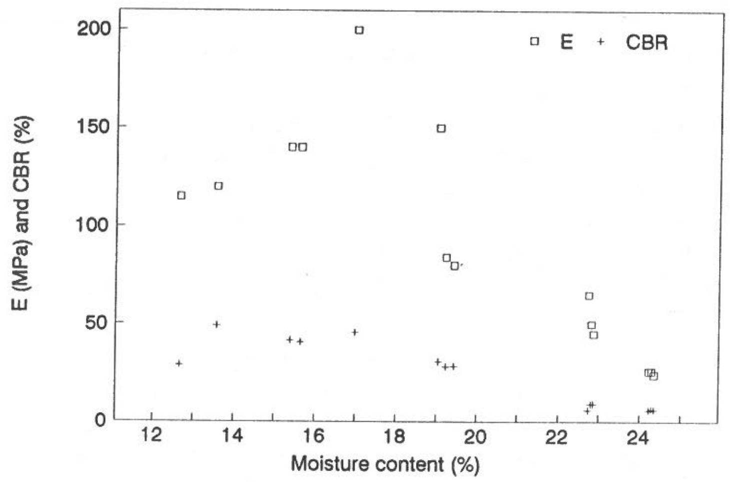

FIGURE 8: E and CBR against moisture content for weathered dolerite

LIST OF SYMBOLS

E_1	=	elastic modulus of soil = $d\sigma_1/d\varepsilon_1$
E_d (M_R)	=	modulus of resilience = $d\sigma_d/d\varepsilon_i$
υ	=	Poisson's ratio (see equation 3)
c	=	Adhesion component of shear force of soil
ϕ	=	friction angle of soil (= phi in Appendix)
σ_1	=	main axial stress (i.e. vertical stress)(= Sigma-1 in Appendix)
σ_3	=	secondary axial stress (i.e. radial stress)
σ_d	=	deviator stress = $\sigma_1 - \sigma_3$
ε_1	=	vertical strain
ε_3	=	radial strain
q	=	$(\sigma_1 - \sigma_3)/2$
p	=	$(\sigma_1 + \sigma_3)/2$
θ	=	$\sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3$ (= Theta in Appendix)
E_3	=	spring stiffness of K=mould = 61250 x 104/h
h	=	sample height (mm)

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APPENDIX

B124 - Weathered dolerite(0.1sec) 200

Sigma-1 vs Epsilon-1 (load)

Regression Output:					
Constant	-487708.				
Std Err of Y Est	11.65372				
R Squared	0.992004				
No. of Observations	82				
Degrees of Freedom	78				
				Emax	Emin
X Coefficient(s)	46506374	-1.5E+09	1.6E+10	275.0546	47.42789
Std Err of Coef.	3634775.	1.2E+08	1.3E+09		

Sigma-1 vs Epsilon-1 (unload)

Regression Output:					
Constant	-177030.				
Std Err of Y Est	8.448872				
R Squared	0.993138				
No. of Observations	260				
Degrees of Freedom	256				
				Emax	Emin
X Coefficient(s)	17513826	-5.8E+08	6.4E+09	207.2109	58.50880
Std Err of Coef.	1415454.	45838675	4.9E+08		

Phi and c (total range)(load)

Regression Output:			
Constant	-255.450		
Std Err of Y Est	6.149407		
R Squared	0.985198		
No. of Observations	82		
Degrees of Freedom	80		
		phi	c
X Coefficient(s)	0.640143	39.80250	-332.507
Std Err of Coef.	0.008772		

Phi and c (total range)(unload)

Regression Output:			
Constant	-267.822		
Std Err of Y Est	8.507427		
R Squared	0.951408		
No. of Observations	260		
Degrees of Freedom	258		
		phi	c
X Coefficient(s)	0.591926	36.29384	-332.289
Std Err of Coef.	0.008328		

B124 - Weathered dolerite(0.1sec) 200

Phi and c (total range)(load + unload)

Regression Output:			
Constant	-280.746		
Std Err of Y Est	13.33275		
R Squared	0.927980		
No. of Observations	341		
Degrees of Freedom	339		
		phi	c
X Coefficient(s)	0.665194	41.69721	-375.997
Std Err of Coef.	0.010064		

log(E)(MPa) vs A,B,A^2,B^2(A=logTheta,B=logSigma-1)(load)

Regression Output:				
Constant	1291.763			
Std Err of Y Est	0.046332			
R Squared	0.969634			
No. of Observations	82			
Degrees of Freedom	77			
X Coefficient(s)	-794.015	-32.2946	122.8613	10.96292
Std Err of Coef.	31.18540	2.865088	4.702394	0.854212

log(E)(MPa) vs A,B,A^2,B^2(A=logTheta,B=logSigma-1)(unload)

Regression Output:				
Constant	-7.90505			
Std Err of Y Est	0.027472			
R Squared	0.965951			
No. of Observations	260			
Degrees of Freedom	255			
X Coefficient(s)	11.23890	-6.42445	-1.96643	1.622497
Std Err of Coef.	26.13682	1.433498	4.617923	0.417773

log(E)(MPa) vs A,B,A^2,B^2(A=logTheta,B=logSigma-1)(load + unload)

Regression Output:				
Constant	647.1251			
Std Err of Y Est	0.122194			
R Squared	0.638334			
No. of Observations	341			
Degrees of Freedom	336			
X Coefficient(s)	-440.477	16.38277	72.89003	-3.32103
Std Err of Coef.	23.47131	1.119535	3.932793	0.258997

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OFS51 - OFS crushed dolerite(0,1sec)                                200
Sigma-1 vs Epsilon-1 (load)
             Regression Output:
Constant                        11500.71
Std Err of Y Est                17.27622
R Squared                       0.989625
No. of Observations                   62
Degrees of Freedom                    58
                                                       Emax      Emin
X Coefficient(s)       -3923535  4.0E+08 -1.0E+10 583.2570 253.6820
Std Err of Coef.       14323227  1.8E+09  7.6E+10

Sigma-1 vs Epsilon-1 (unload)
             Regression Output:
Constant                        -109403.
Std Err of Y Est                32.24276
R Squared                       0.946056
No. of Observations                  270
Degrees of Freedom                   266
                                                       Emax      Emin
X Coefficient(s)       44881590 -6.1E+09  2.8E+11 1209.652 28.21365
Std Err of Coef.       8056435.  1.0E+09  4.5E+10

Phi and c (total range)(load)
             Regression Output:
Constant                        -91.6316
Std Err of Y Est                0.549946
R Squared                       0.999956
No. of Observations                   62
Degrees of Freedom                    60
                                              phi         c
X Coefficient(s)       0.994755           84.12962  -895.906
Std Err of Coef.       0.000849

Phi and c (total range)(unload)
             Regression Output:
Constant                        -92.4955
Std Err of Y Est                0.854424
R Squared                       0.999846
No. of Observations                  270
Degrees of Freedom                   268
                                              phi         c
X Coefficient(s)       0.991404           82.48215  -706.963
Std Err of Coef.       0.000751
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OFS51 - OFS crushed dolerite(0,1sec)                                200
Phi and c (total range)(load + unload)
             Regression Output:
Constant                        -92.6100
Std Err of Y Est                0.960469
R Squared                       0.999838
No. of Observations                  331
Degrees of Freedom                   329
                                              phi         c
X Coefficient(s)       0.994626           84.05740  -894.505
Std Err of Coef.       0.000696

log(E)(MPa) vs A,B,A^2,B^2(A=logTheta,B=logSigma-1)(load)
             Regression Output:
Constant                        -27.0534
Std Err of Y Est                0.041735
R Squared                       0.919798
No. of Observations                   62
Degrees of Freedom                    57

X Coefficient(s)       8.261441 8.984606 0.692334 -3.21490
Std Err of Coef.       6.102550 5.110531 0.907559 1.833435

log(E)(MPa) vs A,B,A^2,B^2(A=logTheta,B=logSigma-1)(unload)
             Regression Output:
Constant                        -16.2464
Std Err of Y Est                0.134621
R Squared                       0.939965
No. of Observations                  270
Degrees of Freedom                   265

X Coefficient(s)       23.27765 -5.52578 -6.25119 2.531164
Std Err of Coef.       9.497701 1.683441 1.526920 0.652644

log(E)(MPa) vs A,B,A^2,B^2(A=logTheta,B=logSigma-1)(load + unload)
             Regression Output:
Constant                        47.29761
Std Err of Y Est                0.182130
R Squared                       0.889748
No. of Observations                  331
Degrees of Freedom                   326

X Coefficient(s)       -24.4032 -3.10556 1.832576 2.538415
Std Err of Coef.       10.24082 2.039104 1.670003 0.764897
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