LAB TESTING – RESILIENT MODULUS

General Description

Resilient modulus (Mr) is a fundamental material property used to characterize unbound pavement materials. It is a measure of material stiffness and provides a mean to analyze stiffness of materials under different conditions, such as moisture, density and stress level. Also it is a required input parameter to mechanistic-empirical pavement design method. Mr is typically determined in laboratory by measuring stiffness of a cylinder specimen that is subjected to cyclic axle load. It is defined as a ratio of applied axle deviator stress and axle recoverable strain.

$$Mr = \frac{Jd}{Gr}$$

Where:
Jd = applied axle deviator stress
Gr = axle recoverable strain

MnDOT Testing Protocol

Currently, Mn/DOT, in general, follows the testing protocol (NCHRP Research Results Digest 285) recommended by the NCHRP 1-28a project. However, some improvements have been made on instrumentation and data quality control (see below).

Testing Setup and Data Quality Control

The following improvements have been made in MnDOT test configuration and data analysis procedures:

1. The NCHRP 1-28a protocol only uses two LVDTs, but Mn/DOT requires three on-specimen LVDTs to measure the specimen deformation (Figure 1). The three LVDTs are mounted between two aluminum rings and equally spaced around the specimen to directly measure axial displacement of the specimen. Also, two LVDTs located outside of the tri-axle chamber (external LVDTs) are

used on the MnDOT testing system to measure external displacements. Figure 2 shows the experiment setup. The 3 internal LVDTs are needed for test data quality control.

2. Mn/DOT recommends a minimum sampling rate of 400 points/second for data acquisition. The baseline values for Mr calculation is determined by taking the average load/deformation values of baseline from the last 60% of a time history cycle.

3. Data Quality Control: Due to non-homogeneity of material, the specimen deformation is not always uniform through the specimen height. Also, the testing system could contribute errors to the results, such as system noise. Therefore, it is important to control data quality during data analysis. Based on our testing data, Mn/DOT has developed a set of data quality control criteria to replace the NCHRP recommended criterion (1.1 ratio of two vertical LVDT measurements). The criteria are Angle of Rotation (AR); Signal-to-Noise ratio (SNR) and Coefficient of Variation of resilient modulus (COV).

ANGLE OF ROTATION (AR)

AR is used as a measure to control specimen deformation uniformity.

$$\cos\theta = \frac{\frac{3}{2}R}{\sqrt{\delta_1^2 + \delta_2^2 + \delta_3^2 - \delta_1\delta_2 - \delta_1\delta_3 - \delta_2\delta_3 + \frac{9}{4}R^2}}$$

R- radius of specimen
δ_i - recoverable displacement of LVDT "i" (i= 1,2 ,3)

Limit: AR< 0.04°

A detailed documentation of AR criterion development can be found in Paper

SIGNAL-TO-NOISE RATIO (SNR)

Noise from measurement devices, such as LVDT, affects data quality, especially when the measured displacement is small. SNR is used to control noise effects on Mr results. SNR is calculated from time history data of each load and displacement measurement.

$$SNR = \frac{Peak}{3 \times SDev(Baseline)}$$

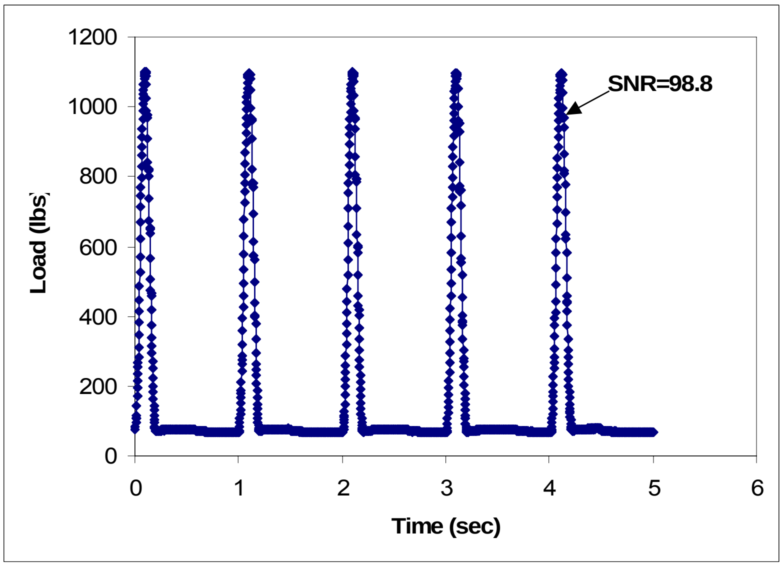
Peak – Peak values of load or LVDT from time history data.
Sdev(Baseline) -- standard deviation of baseline values

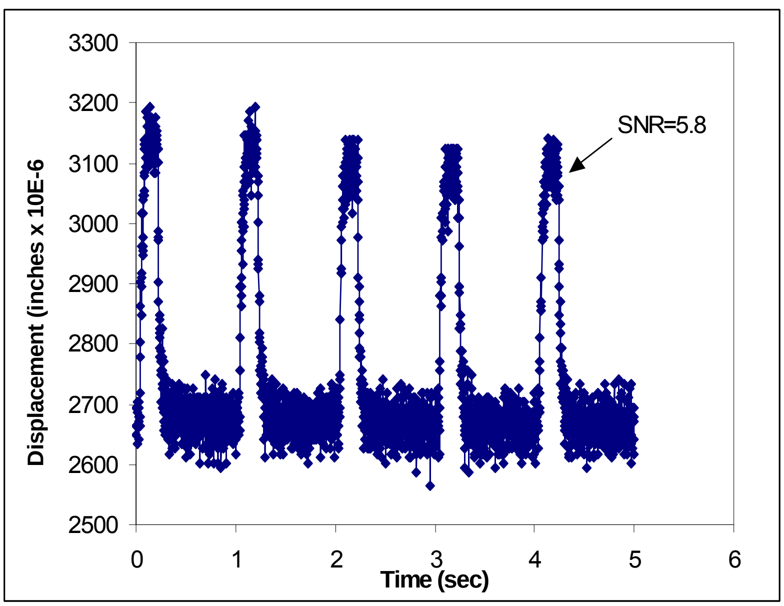
$$SDev = \sqrt{\frac{\sum_{0}^{N} (\mathrm{Y(n)} - \mu)^2}{N-1}}$$

μ – mean of baseline values
Y(n) = value at point n
N = total data points

Limit: SNR >= 3, for each LVDT at each cycle of the last 5 cycles used to calculate Mr.
SNR >=10, for load at each cycle of the last 5 cycles used to calculate Mr.

The following are the examples of SNR:





COEFFICIENT OF VARIATION (COV)

Mr is calculated using each cycle data of the last five cycles in each sequence. Mr values for the last five cycles should be similar. Therefore, it is important to control the variation for each sequence. COV of resilient modulus values is defined as:

$$COV(\%) = \frac{SDev}{Average}$$

Sdev – Standard deviation of Mr values during the last five cycles in each sequence.
Average – Average Mr value of the last five cycles.

<u>Limit</u>: COV < 10%

Figure 1 - LVDT configuration

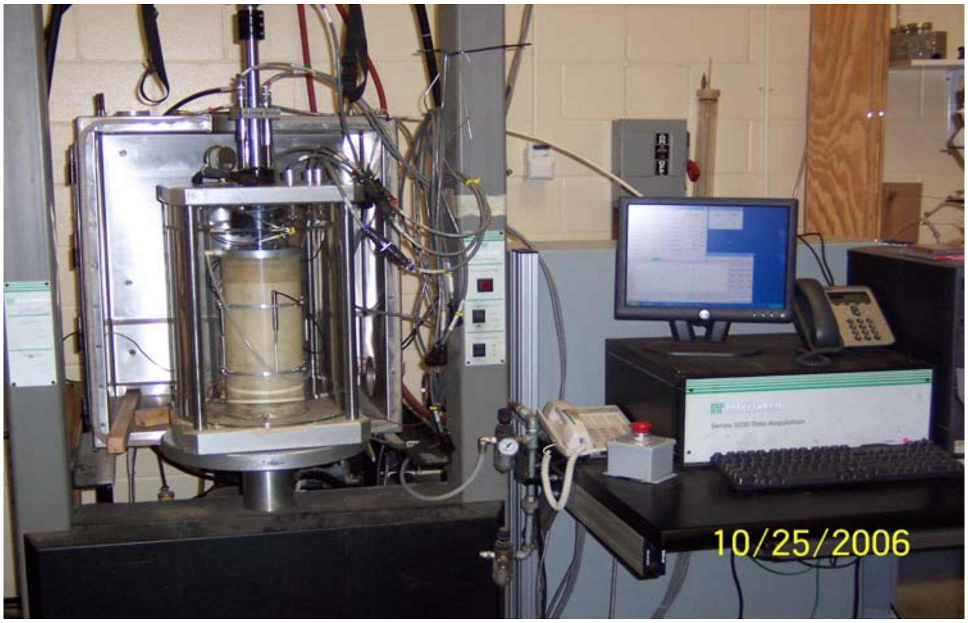


Figure 2 - Experiment Setup

MATERIAL INDEX TESTS

The following index tests are generally conducted associated with resilient modulus test:

Gradation
Proctor test for obtain optimal moisture content and maximum density
Mn/DOT material classification
For fine-grained soils, the following index are also obtained:

Liquid limit; Plastic limit; Plasticity index; % silt; % clay, and AASHTO group.

RELATED PUBLICATIONS

http://www.mrr.dot.state.mn.us/research/pdf/200705.pdf
Resilient Modulus and Strength Of Base Course With Recycled Bituminous Material

http://www.mrr.dot.state.mn.us/research/pdf/2003MRRDOC008.pdf
Resilient Modulus of Minnesota Road Research Project Subgrade Soil

http://www.mrr.dot.state.mn.us/research/pdf/199621.pdf
Resilient Modulus Testing of Materials from MnROAD, Phase I

Data Process and Storage

Raw load and deformation time history data collected from the testing machine are directly loaded to an Oracle database. The data are automatically processed in the database, first to perform data quality control to eliminate bad data, then to determine necessary parameters such as, deviator stress, recoverable strain to calculate resilient modulus. The raw time history data and calculated resilient modulus along with other parameters are stored in the database. The time history format and the database structure are presented below.

Time History Data Format

POINT	TIME_SEC	INT_LOAD_LBS	EXT_LVDT1_MIC-IN	EXT_LVDT2_MIC-IN	INT_LVDT1_MIC-IN	INT_LVDT2_MIC-IN	INT_LVDT3_MIC-IN	EXT_LOAD_LBS	STROKE_IN	CONF_PRES_PSI
1	0.002	17	38572	40460	20868	9585	28447	-468.6	-0.722	2.9
2	0.004	17	38595	40483	20883	9563	28493	-468.8	-0.722	2.9
3	0.006	17	38587	40483	20891	9501	28485	-468.8	-0.723	2.9
4	0.008	18	38564	40498	20868	9532	28447	-468.8	-0.723	2.9
5	0.01	18	38587	40506	20921	9501	28500	-468.7	-0.723	2.9
6	0.012	19	38618	40514	20914	9501	28485	-468.5	-0.723	2.9
7	0.014	23	38709	40659	20906	9570	28462	-468.4	-0.722	2.9
8	0.016	24	38978	40805	20921	9532	28477	-468.5	-0.722	2.9
9	0.018	25	39162	41004	20914	9532	28546	-468.4	-0.722	2.9
10	0.02	29	39277	41157	20906	9593	28630	-468.6	-0.722	2.9
11	0.022	32	39430	41242	20937	9570	28745	-468.7	-0.722	2.9
12	0.024	31	39598	41395	20929	9578	2760	-468.7	-0.721	2.9
13	0.026	33	39729	41602	20898	9685	28768	-468.6	-0.721	2.9
14	0.028	38	39890	41709	20914	9700	28845	-468.6	-0.721	2.9
15	0.03	38	40066	41854	20929	9708	28974	-468.4	-0.721	2.9
16	0.032	41	40212	42046	20898	9769	28936	-468.5	-0.72	2.9
17	0.034	45	40380	42238	20875	9815	28989	-468.6	-0.72	2.9
18	0.036	47	40595	42414	20921	9807	29081	-468.7	-0.72	2.9
19	0.038	51	40832	42713	20937	9838	29150	-468.8	-0.72	2.9
20	0.04	55	41085	43034	20993	9876	29234	-468.8	-0.719	2.9
21	0.042	57	41407	43272	21098	9868	29341	-468.8	-0.719	2.9
22	0.044	61	41599	43456	21166	9906	29440	-468.6	-0.72	2.9
23	0.046	64	41714	43686	21182	9968	29817	-468.5	-0.719	2.9
24	0.048	64	41928	43770	21243	9975	29616	-468.5	-0.719	2.9

25	0.05	65	41990	43800	21235	9983	29593	-468.4	-0.719	2.9
26	0.052	65	41959	43869	21220	10044	29601	-468.5	-0.719	2.9
27	0.054	65	42005	43816	21235	10044	29624	-468.7	-0.719	2.9
28	0.056	64	42036	43839	21243	10036	29616	-468.6	-0.719	2.9
29	0.058	65	42013	43869	21189	10090	29578	-468.6	-0.719	2.9
30	0.06	65	42005	43839	21228	10090	29631	-468.6	-0.719	2.9
31	0.062	64	42043	43831	21235	10036	29646	-468.4	-0.719	2.9
32	0.064	64	42013	43877	21189	10105	29608	-468.4	-0.718	2.9
33	0.066	64	42020	43908	21228	10075	29624	-468.5	-0.718	2.9
34	0.068	64	42005	43862	21120	10067	29669	-468.5	-0.719	2.9
35	0.07	64	41997	43869	21197	10059	29646	-468.7	-0.719	2.9
36	0.072	65	41990	43885	21205	10067	29646	-468.8	-0.718	2.9
37	0.074	64	41997	43869	21235	10014	29669	-468.8	-0.719	2.9
38	0.076	63	41990	43854	21228	10029	29646	-468.7	-0.719	2.9
39	0.078	63	41928	43831	21243	10044	29616	-468.6	-0.719	2.9
40	0.08	62	41944	43777	21258	10036	29616	-468.5	-0.719	2.9
41	0.082	59	41867	43701	21258	10059	29570	-468.4	-0.72	2.9
42	0.084	60	41767	43670	21189	10067	29501	-468.5	-0.719	2.9
43	0.086	58	41760	43586	21266	10052	29524	-468.6	-0.719	2.9
44	0.088	57	41706	43548	21235	10059	29509	-468.7	-0.719	2.9
45	0.09	59	41675	43609	21182	10090	29440	-468.7	-0.719	2.9
46	0.092	57	41706	43555	21220	10075	29486	-468.7	-0.719	2.9

Resilient Modulus Database Format

Several tables are created in the database to store various data from resilient modulus testing and associated material index test results. Fig. X shows the database tables. The raw time history data containing both load and displacement are stored in the table “Mr_Time_History_28A”. The material specification and conditions, such as density and moisture content of results of the tested specimen along with locations where the material was taken are stored in Mr_LOG table. The table Mr_AGG_LAB contains material index test results for aggregate bases associated with resilient modulus testing specimen, while Mr_SOILS_LAB contains index results for fine grained subgrade soils.

MR_LOG
FILE_NAME
TEST_DATE
MNDOT_SPECIFICATIONS
MATERIAL_TYPE
LOCATION
RESEARCH_OBJECTIVES
MOISTURE_PCT
DRY_DENSITY_PCF
SPNUM
ROUTE
RP_BEGIN
RP_END
STA_BEGIN
STA_END
OFFSET
SAMPLE_DEPTH_IN
SAMPLE_TYPE
DIAMETER_IN
LVDT_SPACING_IN
MR_SAMPLE_HEIGHT_IN
OPERATOR
PROTOCOL
TEST_SITE
COMMENTS

MR_TIME_HISTORY_28A
FILE_NAME
SEQUENCE
ELAPSEDTIME_SEC
LOAD_LBS
TRXLOAD_LBS
CPRESSURE_PSI
EXVDFRM1_MIC
EXVDFRM2_MIC
INVDFRM1_MIC
INVDFRM2_MIC
INVDFRM3_MIC
LOAD_DATE

MR_DATA
FILE_NAME
SEQUENCE
STATUS
BULKSTRESS_PSI
OCTASTRESS_PSI
CONFSTRESS_PSI
DEVISTRESS_PSI
MR_PSI
EXT_MR_PSI
SDEV_MR_PSI
SDEV_EXT_MR_PSI
ROTATION_DEG

MR_K123
FILE_NAME
K1
K2
K3
K123_R_SQ_PCT
MIN_BULKSTRESS_PSI
MAX_BULKSTRESS_PSI
MIN_OCTASTRESS_PSI
MAX_OCTASTRESS_PSI
K4
K5
K6
K456_R_SQ_PCT
MIN_CONFSTRESS_PSI
MAX_CONFSTRESS_PSI
MIN_DEVISTRESS_PSI
MAX_DEVISTRESS_PSI
N_TESTS

MR_AGG_LAB
FILE_NAME
SAM_ID
MNDOT_CLASS
OPT_MOIST
MAX_DENS_PCF
D10
D60
PP_75MM
PP_63MM
PP_50MM
PP_37_5MM
PP_31_5MM
PP_25MM
PP_19MM
PP_16MM
PP_12_5MM
PP_9_5MM
PP_4_75MM
PP_2_36MM
PP_2MM
PP_1_18MM
PP_600UM
PP_425UM
PP_300UM
PP_150UM
PP_075UM

MR_SOILS_LAB
FILE_NAME
LAB_ID
MNDOT_CLASS
AASHTO_CLASS
AASHTO_GI
OPT_MOIST
MAX_DENS_PCF
PP_50MM
PP_25MM
PP_19MM
PP_9_5MM
PP_4_75MM
PP_2MM
PP_850UM
PP_425UM
PP_250UM
PP_150UM
PP_075UM
SILT_PCT
CLAY_PCT
LIQUID_LIMIT
PLASTIC_LIMIT
PLASTIC_INDEX

For more information:

For more information about MnROAD and the Road Research program at Mn/DOT:

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