PAVEMENT MATERIAL DATABASE - A TOOL TO FACILITATE IMPLEMENTATION OF THE NEW M-E PAVEMENT DESIGN GUIDE

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ABSTRACT

The new mechanistic-empirical model (M-E) developed under the NCHRP 1-37A initiative is a significant advancement in pavement design mainly because it addresses industry needs to switch to a performance-based practice. However, achieving this performance-based design goal with the new M-E guide depends substantially on employing mechanistic material characteristics in the analysis to produce accurate predictions of a number of distress types and smoothness.

Material properties needed as input by the new M-E model for conducting an advanced design exercise (level 1) are beyond what is available from conventional characterization techniques adopted in the current practice. Laboratory facilities are not yet ready to meet testing requirements related to the mechanistic characterization scheme. Review of alternatives introduced to circumvent the need to perform elaborate mechanical tests revealed that the simplified approach adopted in the lower input levels 2 and 3 undermines the impact of material properties on performance. Results of the review suggest that the potential for accumulation of permanent deformation may be underestimated by 45% as a result of overestimating the dynamic modulus of asphalt concrete (AC) layer.

This paper describes a proposal for using generic mechanistic material properties to perform design based on level 1 for AC and level 3 for unbound materials. These properties include the dynamic modulus of typical HMA mixes prepared according to a local standard and the resilient modulus of commonly used unbound materials (granular aggregates). Preliminary results indicate that the proposed approach is more reliable and results in lower design errors compared with the process incorporated in the current version of the M-E guide. The generic properties may be used to expedite implementation of the M-E guide in Canada until adequate mechanical testing capabilities are established. The generic pavement material properties produced at NRC are now stored in a database "Material Library", which could be further populated using results from new tests that cover a wider range of material and construction variables; mainly to reduce the margin of error. The proposed database will not only provide the input properties needed for applying the M-E design model but will also support tasks associated with the calibration of the M-E component used to predict performance to make the model more sensitive to unique local conditions and construction practices.

EVALUATION OF THE APPROXIMATE APPROACH IN THE M-E GUIDE

The National Research Council's (NRC) road research group completed a preliminary review of the mechanistic-empirical (M-E) pavement guide produced under an NCHRP project (1-37A). Material characteristics related to asphalt concrete and unbound materials were the focus of an in-depth review because of their impact on the response of the pavement structure. The approximate approach for obtaining material properties for levels 2 and 3 input revealed two critical components; the equation used in the model to predict the dynamic modulus of hot mix asphalt (HMA) [1, 2] and the relationship established between the material class, based on AASHTO soil classification system, and the resilient modulus of unbound materials [1, 2].

On the asphalt concrete side, the laboratory investigation covered a wide range of HMA mixes prepared with different binders (PG 58-22, PG 64-34 and PG 52-34). The mixes considered included both Marshall and SuperPave mix design methods. The specifications of the Ministry of

Transportation of Ontario (MTO) [3] were followed in designing the Marshall mixes (HL3, HL4 and HL8). AASHTO specifications [4] were followed in designing two SuperPave mixes. The results of the NRC testing program were used to assess the merit of the dynamic modulus concept in characterizing asphalt concrete materials and the adequacy of the predictive equation provided in the guide in estimating the dynamic modulus in level 2 and 3 in the absence of direct laboratory measurements. Results shown in Figure 1 for two mixes prepared using an engineered binder (PG 64-34) and a neat binder (PG 58-22) suggest that one of the design objectives of the binder producer related to reducing its brittleness at low temperatures, intended to minimize the potential for cracking, is fulfilled [2]. The study also showed that the predictive equation used in the M-E model managed to correctly rate the mix response at low temperatures as influenced by the properties of the two binders. However, the predictive equation was less successful in quantifying the difference between the two binders as measured in the laboratory. The predicted responses suggest a difference of less than 10% between the two binders whereas the measured response reflected a difference of 100% [2]. An overall assessment showed that estimates of the AC modulus made using the predictive equation deviate from laboratory measurements by an average of 77% [2] as shown in Figure 2.

Since there was no access to unbound materials level 1 input, which involves finite element analysis, NRC study concentrated on input level 3. Level 3 is critical for implementing the M-E model in the near future due to the lack of adequate resources, nationwide, for conducting the resilient modulus test. The practicality of this design level makes it popular. However, its reliance on the correlation established in the M-E model between AASHTO soil classification and the resilient modulus is problematic. The study examined two granular materials (granular I and II) based on results from laboratory tests performed using standard AASHTO protocols for evaluating physical and mechanical properties (see Table 1). The determined physical properties classified both materials as A-1-a according to traditional AASHTO specifications. Level 3 of the M-E model offers a narrow range of resilient modulus of 265 to 290 MPa. However, mechanical test results revealed resilient moduli of 180 and 356 MPa for granular I and II, respectively.

In summary, evaluation of the approximate approach included in the M-E pavement design guide revealed the inability of built-in empirical equations and correlation relationships to correctly estimate the mechanistic properties of HMA and unbound materials needed as input for running the analytical model. This limitation raises questions about the effectiveness of the model in yielding accurate performance predictions. The potential for inaccurate performance predictions associated with the less than satisfactory estimates of the AC dynamic modulus using the predictive equation of the M-E model was examined in this study. First, a level 1 M-E model run was executed using as input the dynamic modulus measured in the laboratory. Then, a second run was executed using dynamic modulus values estimated by the predictive equation as in input to level 3. Results from the two runs are shown in Figure 3. The dynamic modulus values estimated by the predictive equation for the two HMA mixes have no effect on base or subgrade rutting. However, as a result of overestimating the AC modulus using the predictive equation, rutting predictions in the asphalt concrete layer was underestimated by 45%.

The impact on the accuracy of performance predictions associated with the use of estimated unbound materials mechanical properties based on correlations established with AASHTO soil classes, incorporated in the M-E model, was also investigated. The moduli measured in the laboratory for the two granular materials I and II mentioned earlier were found to be outside the proposed range included in the M-E model. The modulus of granular II fell above the upper limit by 23% and that of granular I was below the lower limit 32%. Application of the two resilient moduli that represent the range proposed in the guide for the A-1-a class resulted in the prediction of relatively similar rutting levels between the two materials. The base rutting predicted using as input actual laboratory data for granular I was 25% higher as shown in Figure 4. Similarly, the application of modulus estimates from the M-E guide for granular II resulted in overestimating base rutting by 20% compared with that predicted by the model using laboratory data (see Figure 5).

Shortfalls in the tools incorporated in the M-E pavement design guide to estimate mechanistic material properties affected the ability of the model to accurately predict performance. These tools came short of reasonably estimating the mechanical properties of HMA and unbound materials. Although the use of results from actual laboratory test remains the best approach, there is a need for a practical means for estimating the needed mechanistic properties until adequate laboratory testing capabilities are established in the country. This need motivated researchers at NRC to pursue such an approach, which is discussed in the following sections.

PROPOSED ALTERNATIVE

The alternative proposed for estimating the mechanistic properties needed to run the M-E model calls for adopting generic values established from results of tests performed on typical roadway construction materials. The materials used for producing the generic properties represent those manufactured according to widely used standards. The tested samples also simulated typical construction quality commonly achieved in the field for HMA and unbound materials. The effectiveness of the proposed approach was evaluated at NRC and preliminary results are discussed in this paper.

Dynamic modulus values produced from the laboratory tests performed earlier on specific HMA mixes, compiled in a database “material library”, were examined in this study in order to overcome deficiencies associated with application of the predictive equation currently incorporated in the M-E model. This paper discusses a particular set of data from tests performed on HMA mixes prepared according to the Ministry of Transportation of Ontario (MTO) specifications. Dynamic modulus values from the database are referred to in this paper as “generic properties”. The pilot study performed at NRC compared between modulus values estimated with the predictive equation and generic data.

To demonstrate the effectiveness of generic modulus values in representing variations allowed within one mix design, two AC mix batches were prepared using different aggregate gradations, both satisfying one specific MTO mix requirements (HL4). The first batch was prepared using an aggregate combination that produced a gradation curve on the fine side and the other on the coarse side of the specified limits. Samples of these two batches were compacted to 5% air voids and tested using the complex modulus protocol. Dynamic modulus values of the two batches obtained at different temperatures and loading frequencies were compared with those listed in the Material Library representing the generic value for the HL 4 mix. The results, plotted in Figure 6, suggest that the generic dynamic moduli reasonably represent actual values for the fine and coarse alternatives of the same mix (HL 4). The generic values accurately represented the coarse mix with an average percent error of less than 3%. Less accuracy was achieved with the fine mix where the error reached 14%. However, this error is substantially lower than that associated with application of the M-E predictive equation where the error in estimating the dynamic modulus for HL 4 mixes reached an average of 151%. These errors reflected in the performance (AC rutting) predicted by the model as shown in Figure 7. Application of generic dynamic modulus values lowered the error from that discussed in the previous section obtained using the predictive equation (45%) down to 12%.

The current M-E approach of estimating the resilient modulus of unbound materials using a correlation established with the AASHTO soil classification system was further investigated. The study focussed on the impact of applying the estimated value of the resilient modulus on the accuracy of the M-E model predictions of accumulated permanent deformations. Results of repetitive compression tests used in this study to evaluate permanent deformation trends in the two materials, discussed earlier, are shown in Figure 8. Based on the shape of the mechanistic response plots, granular I and II are two uniquely different materials. Permanent deformation potential of granular I is four times that of granular II. The results suggest that correlations based on AASHTO soil classification system are not reliable for estimating the mechanical properties of the tested materials. Inaccuracies of the correlation relationships incorporated in the M-E model motivated researchers at NRC to pursue a mechanistic soil classification system to function as an effective and practical alternative for estimating the resilient modulus to support implementation of the proposed design guide. To achieve this goal, a vast array of unbound materials was tested at NRC. Materials exhibiting similar mechanistic behaviour under similar loading condition (stress level) were clustered in a single group, thus creating a mechanistic classification system based on material mechanical properties. The achieved classification systems differ from those relying on physical properties, as is the case in the current AASHTO classification system. A Material Library (database) was established to house unbound groups according to their new classes based on the material mechanistic response evaluated under various stress levels, densities and moisture conditions.

To facilitate application of the new unbound material classification system in the new M-E pavement design guide, a physical-mechanical link was established. The physical properties considered for establishing the link are mainly gradation parameters and Atterberg limits. These parameters were found to correlate well with the mechanistic response. The new classification system includes five granular material classes, namely NRCG1 to NRCG5. This mechanistic classification proved to be consistent with experience accumulated within the road construction industry and conform with performance records related to relevant granular material classes. In simple terms, the sequence of the material classes reflects physical characteristics that are governed by aggregate particle distribution (gradation) with special emphasis on the cleanliness of the material in terms of the fine dust fraction present in the material:

- NRCG1: fine clean base material
- NRCG2: coarser clean base material
- NRCG5: gap-graded, somewhat dirty (excessive fine content) base material
- NRCG3: poorly-graded, somewhat dirty base material
- NRCG4: dirt rich base material

The two materials, granular I and II, that are classified under the AASHTO system as A-1-a were reclassified using the mechanistic approach. Granular I classified as NRCG4 and granular II as NRCG1. The generic resilient modulus corresponding to granular I, for example, was 175 MPa differing by less than 3% from actual laboratory results (180 MPa). The ability of generic values to satisfactorily represent actual laboratory results also reflected on the M-E model predictions as shown in Figure 9. Base rutting obtained using generic modulus differed by less than 1% from that obtained using actual laboratory data.

MATERIAL DATABASE

The success achieved by using the generic mechanistic properties motivated researchers at NRC to develop the database that houses mechanistic properties for some commonly used pavement materials to be used as input to run the M-E model. Although limited in size and does not cover all material types in use today, application of Material Library generic values will overcome the impact of deficiencies identified in the current version of the M-E design guide until testing capabilities are established nationwide. The proposed database is in electronic format and consists of four components namely, the material database file, data access, database utility and a user interface as shown in Figure 10.

Material database file: In addition to user information, the material database file houses properties of both asphalt concrete and unbound materials. The information related to AC mixes housed in the database file include mix design characteristics based on Marshall or SuperPave methods, aggregate properties, binder properties (PG grade), air voids content and the dynamic modulus of the mix at different temperatures and loading frequencies; the property needed as input level 1 for the M-E design model. Typical screens showing this information for an HMA mix prepared with a PG 52-34 binder is shown in Figure 11. Currently, the database is being populated with data for thermal analysis, such as creep compliance, and other mechanistic properties that will be critical for the calibration task of the model as discussed below.

Unbound materials listed in the library includes a material classification table involving the physical properties (P1, P2, P3 and P4) that function as a link to mechanical properties. These properties are listed in Table 2. It also includes a master table housing the mechanical properties of different material classes for different densities and the recommended location of applying the material within the pavement structure as shown in Table 3. This last specification is intended to account for the dependency of unbound material response on the prevailing level of stress within the material.

Data access: This is a dynamic link library containing procedures that a program can call upon to retrieve data from the database using specialized procedures. It provides users with the ability to retrieve as well as update the data and at the same time preserve the data integrity. It contains all queries needed to retrieve information from the database.

Database utility: Using this utility, a Database Manager can directly work with the data stored in the Material Database File. It allows the manager to find, update, add and delete records as well as display database information (see Figure 12). This component also includes facilities to allow authorized users to connect to the database. It also encompasses data management capabilities such as data cleaning, quality checks and formatting.

Database user interface: It allows a user to retrieve information from the database that he can use in the M-E guide application. It allows the user to see, print or transfer information retrieved from the database (see Figure 10). The user will identify the information needed from the database. The input focuses the search on locating specific materials corresponding to the information entered by the user. For asphalt concrete, the input entered may be the HMA class that corresponds to a specific mix prepared according to a specific design method. It should also include physical properties, such as aggregate gradation and binder type. The user interface will interrogate the database file through the data access which will deliver back the required dynamic modulus table needed as input for the M-E design model. For unbound materials, the user needs first to identify the material class, which is the link to the generic mechanistic properties needed as in put to the model. For that purpose, the user enters physical properties of the candidate construction material listed under the parameters P1, P2, P3 and P4. These properties will be used by the interface to identify the appropriate material class and proceed to the master table (Table 3). There, it will pick the resilient modulus value of the material taking into consideration its density (construction quality) and the depth within the road where it will be placed, which establishes the stress level the material will be exposed to within the road structure (base, subbase, subgrade). The data picked will correspond to the optimum moisture content (needed by the M-E guide to use in its integrated climatic module) and density specified by the local jurisdiction, e.g. 100% for crushed stone and 95% for sand.

As it stands now, the M-E model user has to enter the data retrieved from the database, through the database interface, manually into the input screens of the M-E model. In the future, the database may be linked to the M-E model to facilitate direct delivery of this information when the M-E model is ready to accommodate such a link.

CALIBRATION OF THE M-E MODEL

Preliminary evaluation of the M-E guide by a number of US states, universities and other research organisations pointed to some of its shortcomings, which resulted in launching numerous NCHRP projects such as 1-40A and 9-33. These projects are dedicated to the review and various aspects of the guide and to improve its capabilities. The projects deal with some basic structure functions of the model, including performance models. One task of primary interest relates to model calibration to local conditions. It is expected to produce guidelines for local calibration. The local calibration process is expected to include input data from instrumented road sections (state of stresses and strain and performance data) and the development of database populated with material properties, traffic, environment, etc).

Support offered by the NRC proposed Material Library is not limited to providing input data needed for running the M-E model. Results of physical and mechanical laboratory tests housed in the database are very critical to the next major implementation task related to calibrating the M-E model in order to make it sensitive to local practices and conditions. This need is dictated by the empirical nature of some components included in the theoretical construct of the analytical model. The performance models are very critical elements in the model calibration task and are expected to benefit from results of mechanical tests housed in the database together with performance data and exposure conditions related to traffic and the environment. Performance models were developed benefiting from the results of mechanical tests performed in the laboratory to generate prediction formulae such as that shown in Equation 1 for estimating HMA permanent deformation:

$$\frac{\varepsilon_p}{\varepsilon_r} = 10^{-3.15552} N^{0.39937} T^{1.734} \quad \text{……………………}(1)$$

The laboratory-generated formula (Equation 1) was then fine-tuned using field data to yield field calibration parameters incorporated in the M-E Model equation that predict permanent deformation as shown in Equation 2.

$$\frac{\varepsilon_p}{\varepsilon_r} = \beta_{r1} 10^{-3.15552} T^{1.734\,\beta_{r2}} N^{0.3993\,\beta_{r3}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

CONCLUSIONS AND RECOMMENDATIONS

The newly proposed M-E design guide provides an excellent opportunity to advance pavement analysis by establishing the link missing in the current practice between pavement structural issues, material design and construction variables. However, the implementation of the new design guide will be a real challenge because of the current lack of adequate mechanical testing facilities and expertise needed for laboratory determination of the AC dynamic modulus and unbound material resilient modulus. As a result of the shortcomings of the schemes incorporated in the guide for estimating the mechanistic properties and identified in this paper, performance predictions made by the model are not expected to meet users expectations and may discourage its implementation. The shortcomings include the AC stiffness predictive equation and the correlations established between AASHTO soil classification and the resilient modulus of unbound materials.

The NRC alternative proposed for overcoming M-E model shortcomings involves the use of generic properties generated from limited local testing of typical HMA mixes and unbound materials. Results presented in this paper suggest that these values represent a better estimate of the mechanistic properties needed for running the M-E model. Housing the generic values in a database (Material Library) will facilitate the implementation of the model in this early stage until testing capabilities are improved nationwide. Such a database has been established by NRC and furnished with the necessary features for providing material input data needed for running the design model and its calibration to make it more sensitive to local practices and operating conditions. The database is also expected to encourage involvement of more practitioners in the evaluation of the model and enrich the debate that will facilitate implementation of the M-E pavement design guide.

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[2] Zeghal, M., Adam, Y. E., Ali, O. and ElHussein, H. Mohamed. 2005. Review of the New Mechanistic-Empirical Pavement Design Guide - A Material Characterization Perspective. *Transportation Association of Canada Annual Conference,* Calgary, Alberta.

[3] Ontario Ministry of Transportation (MTO). 1990. *Ontario Provincial Standard Specification*, OPSS 1149 -1152, Ottawa, Ontario, Canada.

[4] AASHTO 1993. Standard Specifications for SuperPave Volumetric Mix Design. Designation MP2-02.

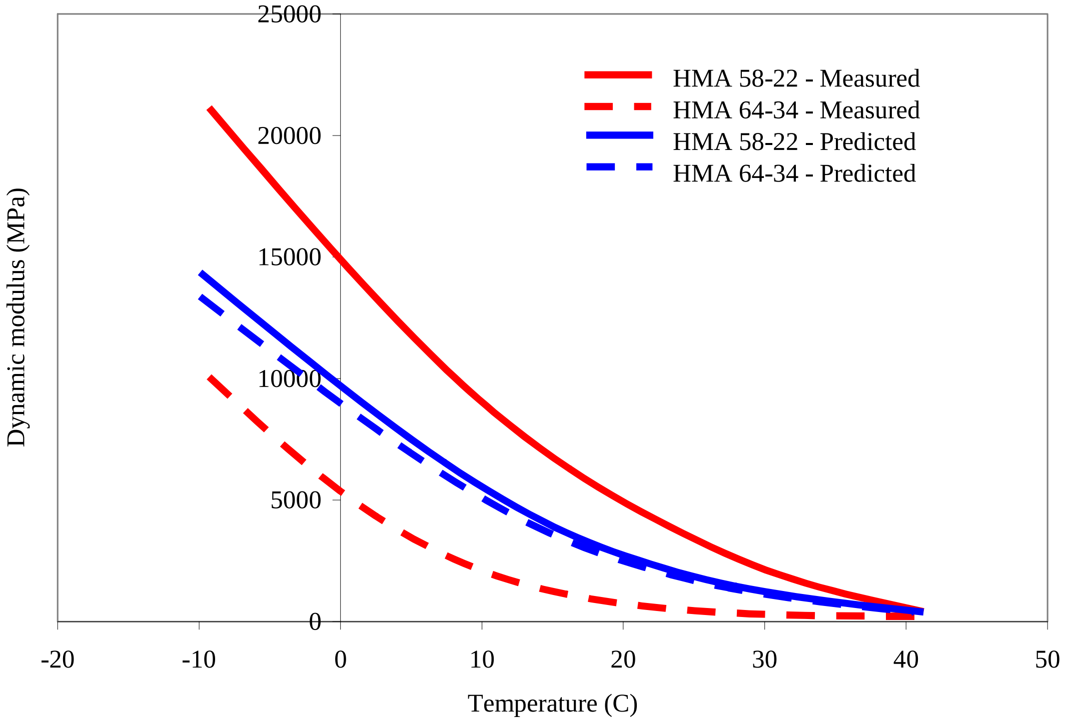


Figure 1. Measured and predicted modulus for two coarse mixes with different binders (Zeghal et al. 2005)

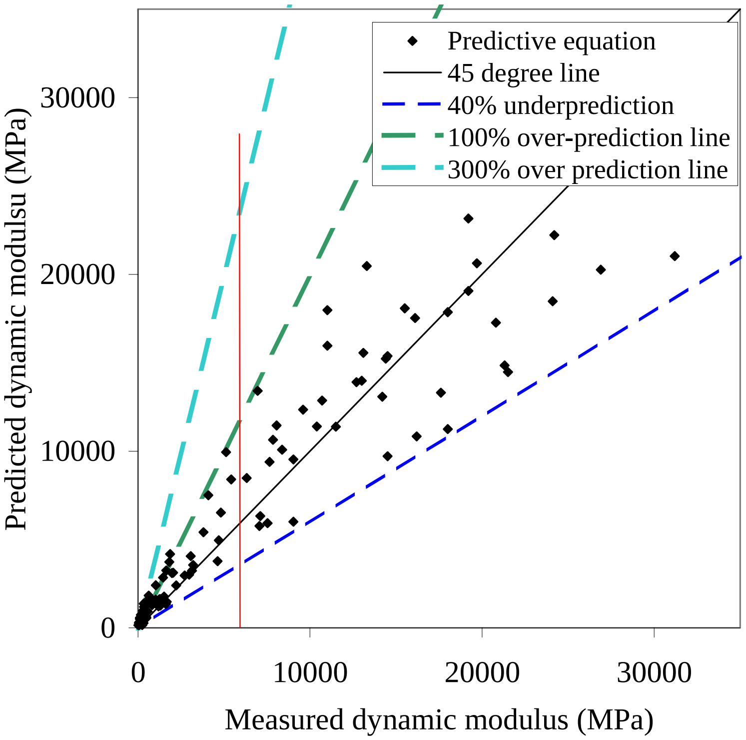


Figure 2. Predicted vs. measured dynamic moduli (Zeghal et al. 2005)

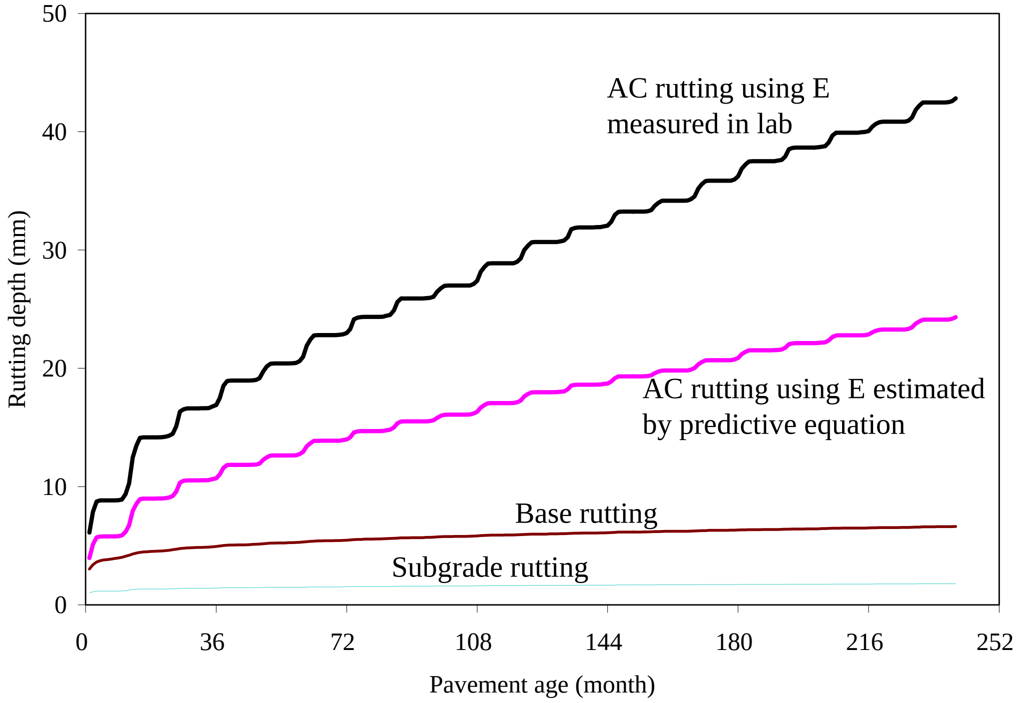


Figure 3. Effect of predictive equation estimation on performance

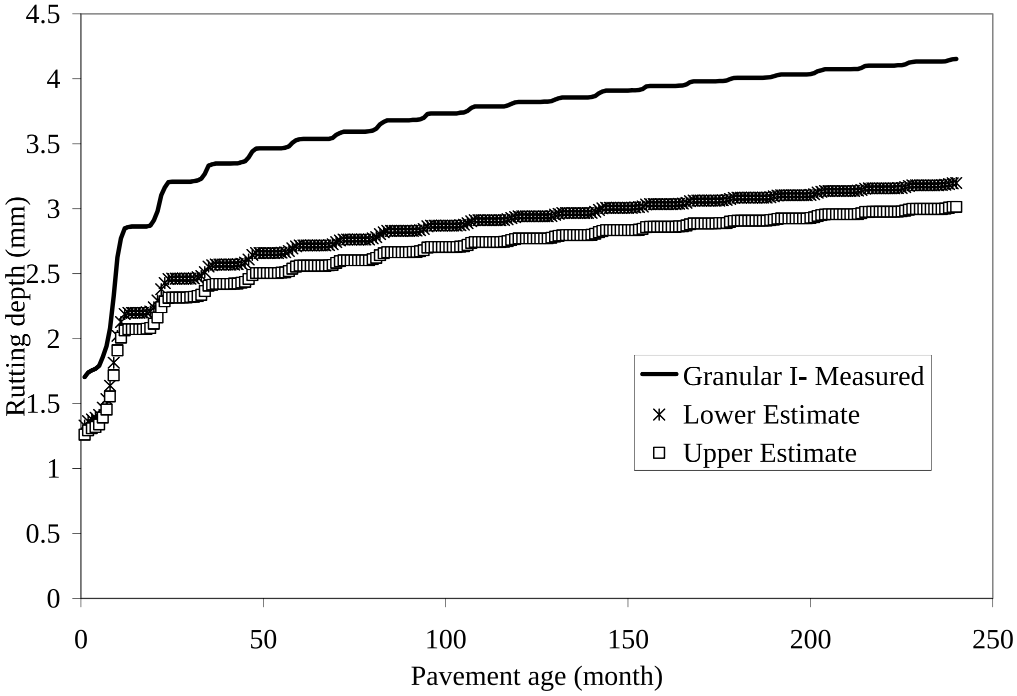


Figure 4. Base rutting for granular I

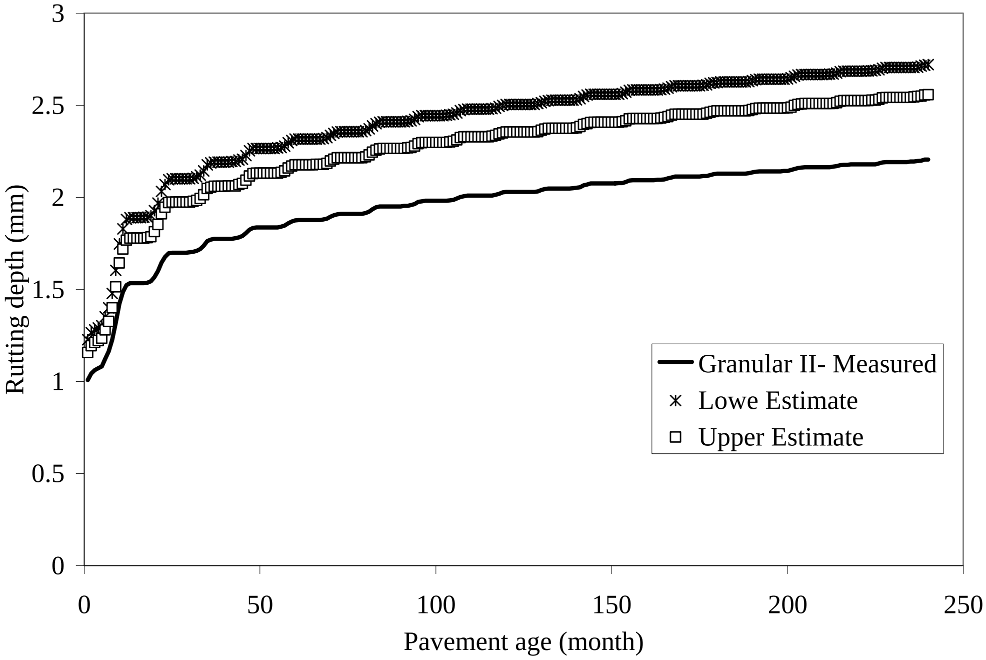


Figure 5. Base rutting for granular II

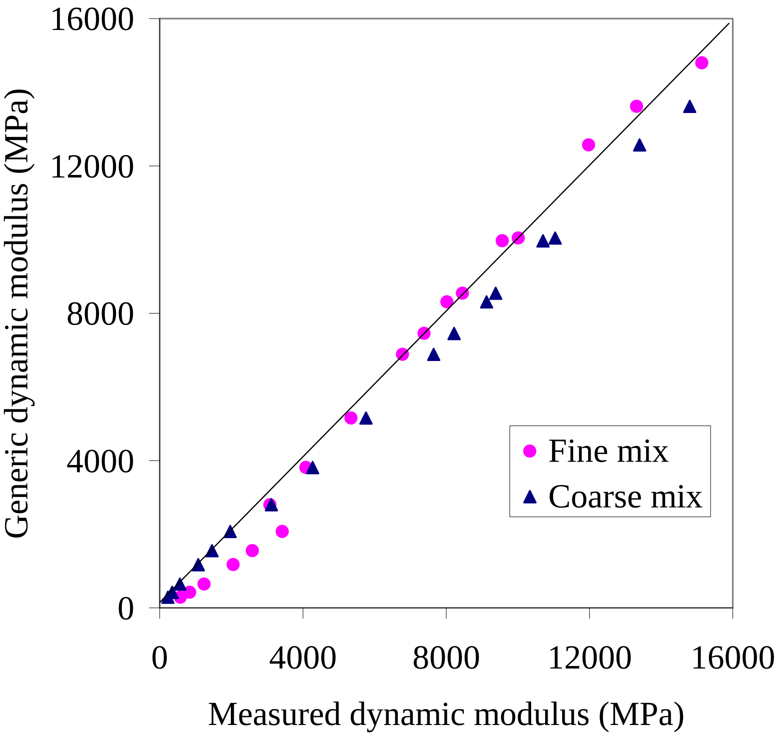


Figure 6. Effectiveness of generic values in representing the variation in the HL 4 mix

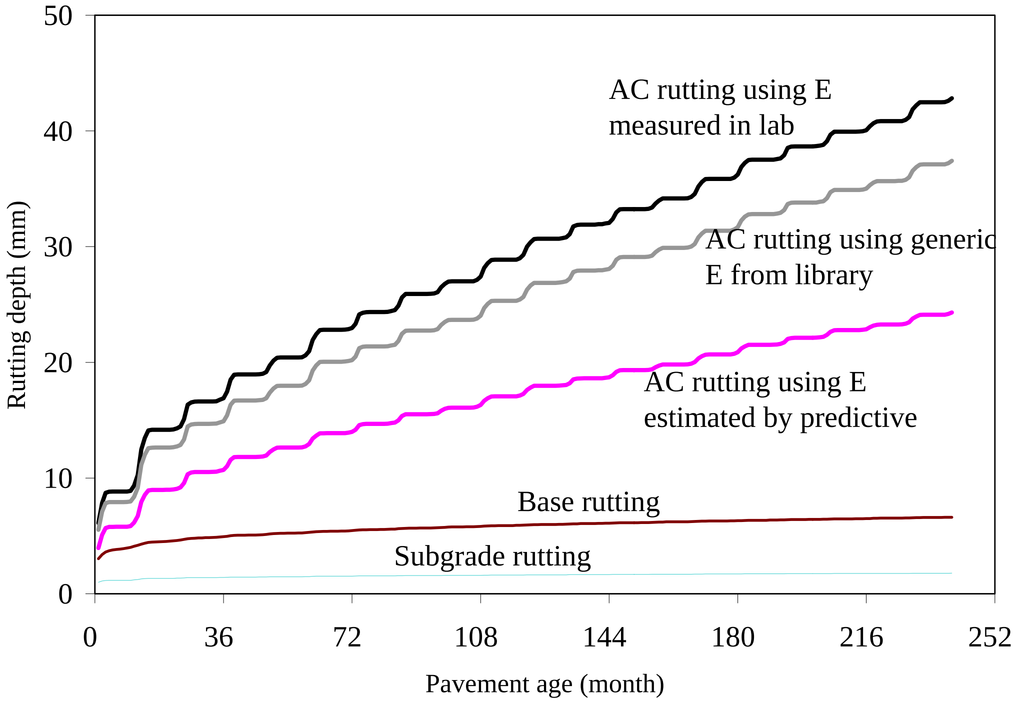


Figure 7. Comparison of performance using library and predictive equation to estimate the dynamic modulus of a fine mix

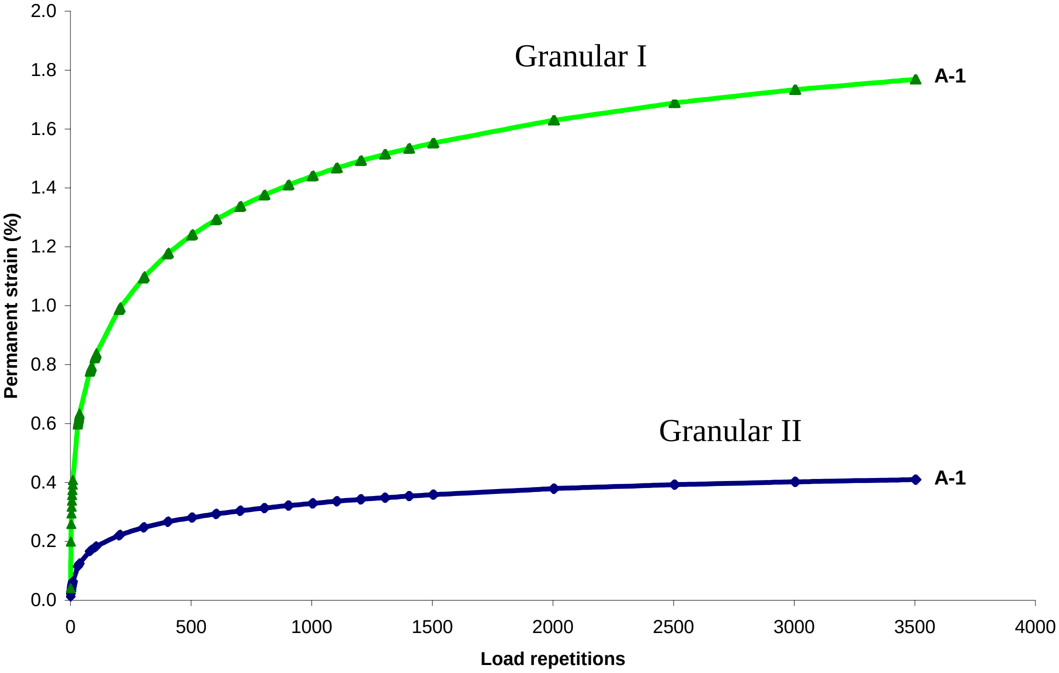


Figure 8. Comparison of permanent deformation potential of granular I and II

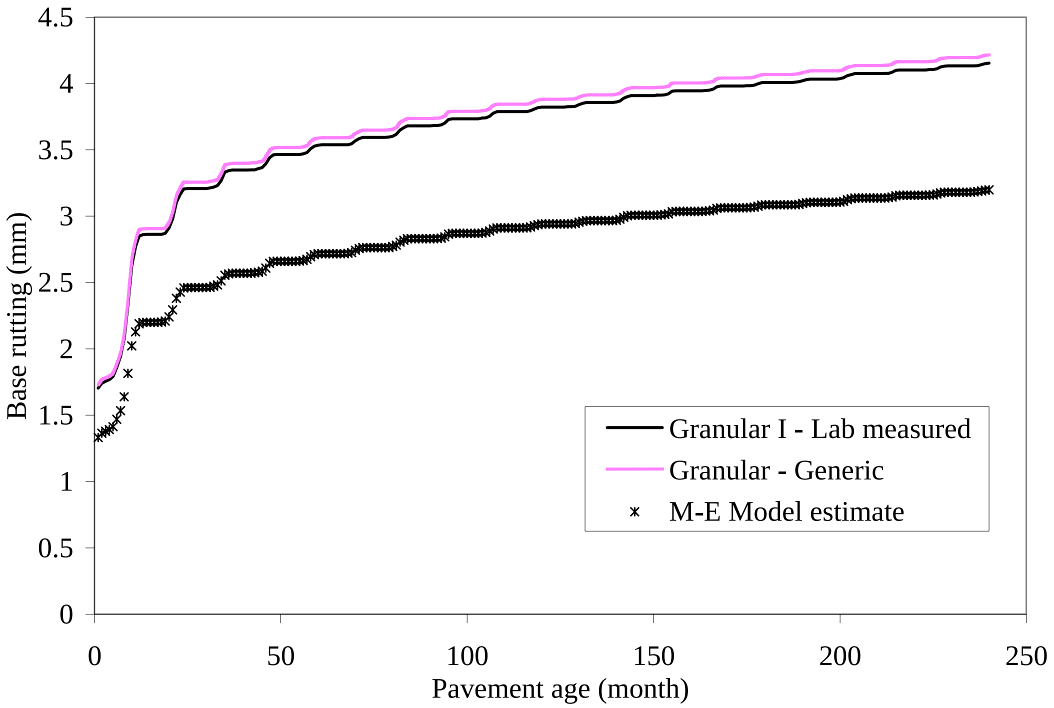


Figure 9. Comparison of base rutting predictions using generic and laboratory measured resilient moduli

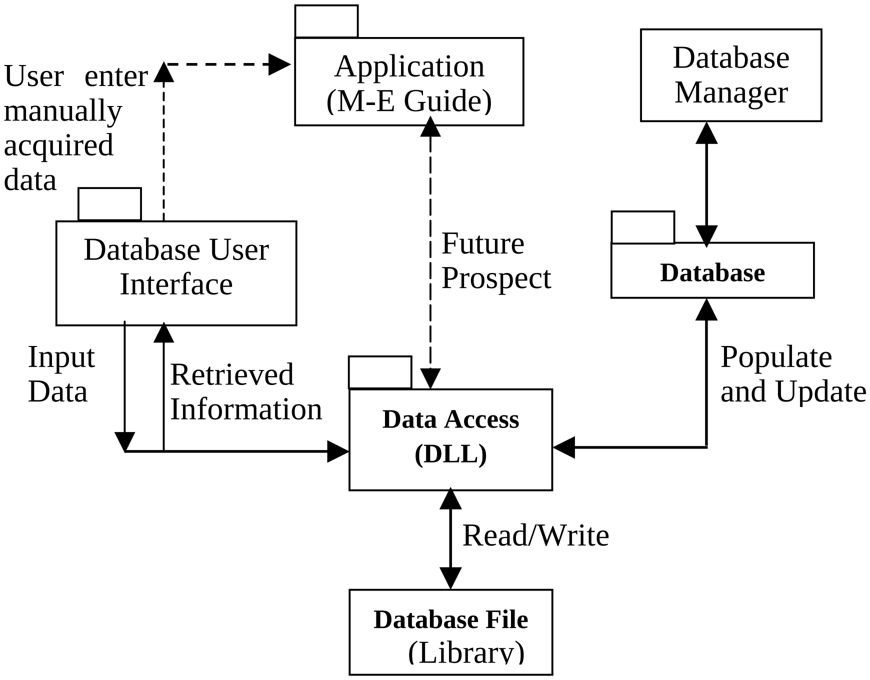
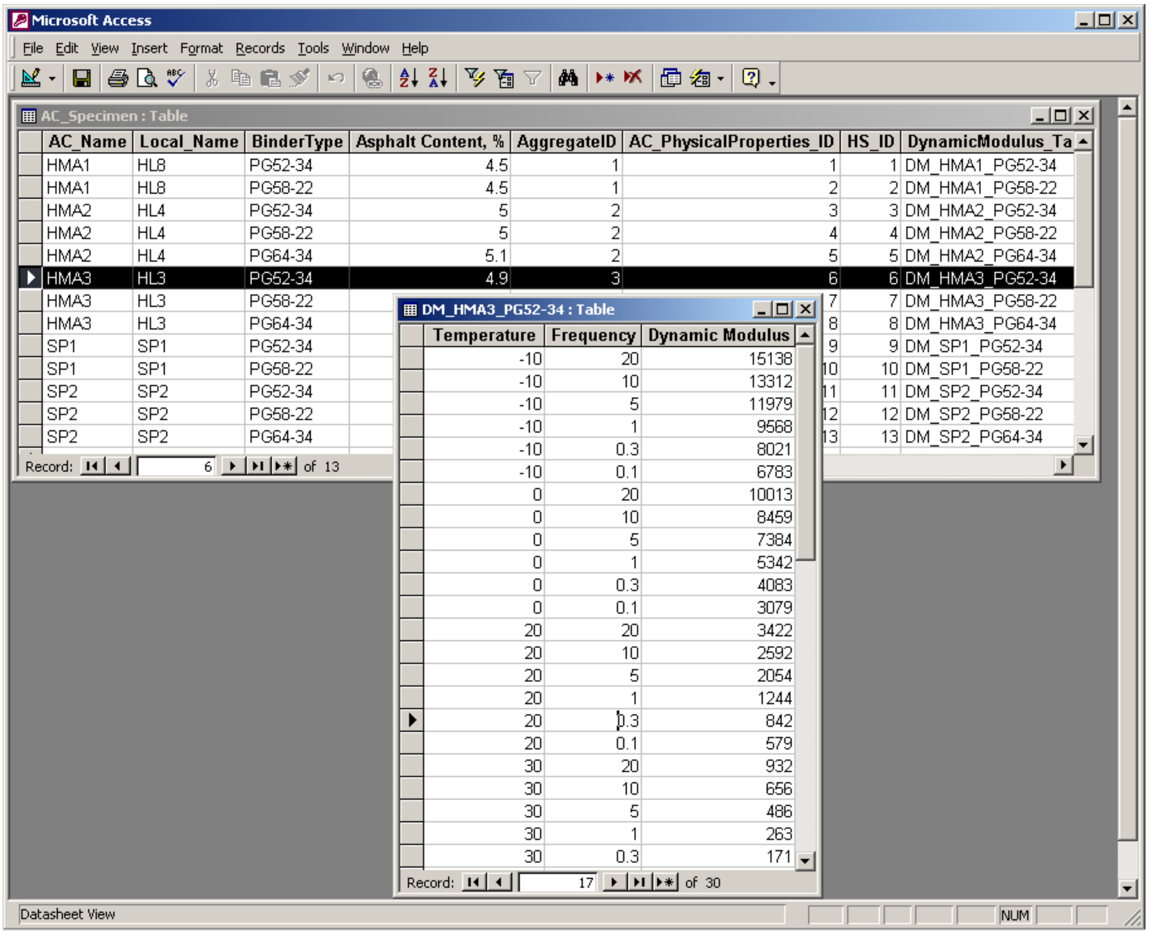


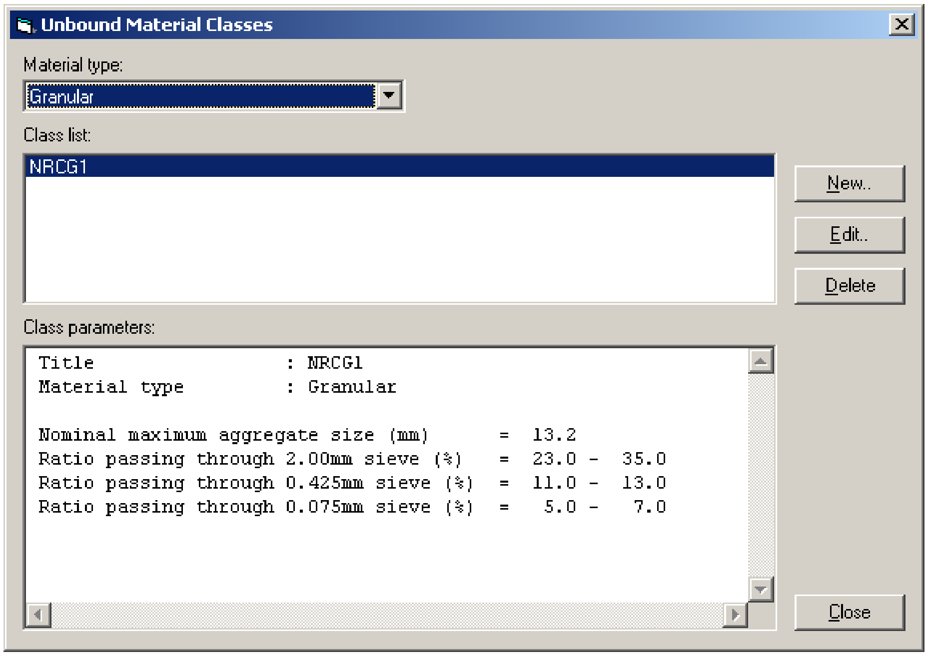
Figure 10. Database structure and application



AC_Name	Local_Name	BinderType	Asphalt Content, %	AggregateID	AC_PhysicalProperties_ID	HS_ID	DynamicModulus_Ta
HMA1	HL8	PG52-34	4.5	1	1	1	DM_HMA1_PG52-34
HMA1	HL8	PG58-22	4.5	1	2	2	DM_HMA1_PG58-22
HMA2	HL4	PG52-34	5	2	3	3	DM_HMA2_PG52-34
HMA2	HL4	PG58-22	5	2	4	4	DM_HMA2_PG58-22
HMA2	HL4	PG64-34	5.1	2	5	5	DM_HMA2_PG64-34
HMA3	HL3	PG52-34	4.9	3	6	6	DM_HMA3_PG52-34
HMA3	HL3	PG58-22			7	7	DM_HMA3_PG58-22
HMA3	HL3	PG64-34			8	8	DM_HMA3_PG64-34
SP1	SP1	PG52-34			9	9	DM_SP1_PG52-34
SP1	SP1	PG58-22			10	10	DM_SP1_PG58-22
SP2	SP2	PG52-34			11	11	DM_SP2_PG52-34
SP2	SP2	PG58-22			12	12	DM_SP2_PG58-22
SP2	SP2	PG64-34			13	13	DM_SP2_PG64-34

Temperature	Frequency	Dynamic Modulus
-10	20	15138
-10	10	13312
-10	5	11979
-10	1	9568
-10	0.3	8021
-10	0.1	6783
0	20	10013
0	10	8459
0	5	7384
0	1	5342
0	0.3	4083
0	0.1	3079
20	20	3422
20	10	2592
20	5	2054
20	1	1244
20	0.3	842
20	0.1	579
30	20	932
30	10	656
30	5	486
30	1	263
30	0.3	171

Figure 11. Typical database file screens for a hot mix asphalt



Material type: Granular

Class list: NRCG1

Class parameters:

```
Title                  : NRCG1
Material type          : Granular

Nominal maximum aggregate size (mm)       =  13.2
Ratio passing through 2.00mm sieve (%)    =  23.0 -  35.0
Ratio passing through 0.425mm sieve (%)   =  11.0 -  13.0
Ratio passing through 0.075mm sieve (%)   =   5.0 -   7.0
```

Figure 12. Typical screen for the database utility that allows display, entry and modification of data in the database file

Table 1. Properties of granular I an II materials (A-1-a)

Property	Laboratory Measured Property		M-E Guide Proposed Limits for A-1-A Materials	
	Granular I	Granular II	Lower	Upper
Plasticity Index	0	0	0	6
Passing # 200 (%)	6	7	0	15
Passing # 4 (%)	19	21	15	30
D60 (mm)	11	7	2	25
MDD (kg/m^3)	2366	2400	1972	2403
Specific Gravity	2.72	2.73	2	4
OMC (%)	5.0	5.4	2	40
Resilient Modulus (MPa)	180	356	265	290

Table 2. Material classification table based on physical properties

ID	Material type	P1	P2	P3	P4
1	Granular				
2	Clay				
3	Sand				

Table 3. Master table housing the mechanistic properties of different unbound material classes

ID	Class	Density (% SPD)	Location	Resilient modulus
1	NRCG-1	100	Base	…
2	…	…	Subbase	…
3	NRCC-1	95	…	…
4	…	…	Subgrade	…
…	…	…	…	…