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Systems Approach for Estimating Field Moisture Content

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ABSTRACT

This paper describes a software tool developed for estimation of the field moisture content of subgrade materials. Subgrade behavior is directly related to its moisture content. Unfortunately, some approaches of estimating field moisture content are too complex to be used in routine design. In this paper, the authors attempt to provide an approach that is easy to use. The software presented here was developed using expert system approaches. It is capable of analyzing data entered by the users, and providing estimations to meet different scenarios. The information entered by the user is first examined for its reasonableness and accuracy. Then, proper estimation models, of which there are many integrated into the system, and data searching processes are initiated. All results are evaluated based on how well the data is meeting the limitations existing during the model's original development. In the end, engineers can estimate the field moisture content based on the most appropriate descriptions of the site.

INTRODUCTION

Because a pavement structure is directly exposed to the natural environment, changes of materials' properties are related to the factors surrounding the pavement. For fine-grained soil subgrades, changes in moisture contents will result in changes in material properties, such as resilient modulus. In the new mechanistic-empirical pavement design guide (*1*), a computer program, Enhanced Integrated Climatic Model (EICM), was incorporated with the design guide software for determining the moisture content data based on field and weather information (*2*, *3*). Instead of using a complex computer program to estimate field moisture contents based on all the effects from different factors, an alternative approach is presented. An expert system approach (*4*) was used combining different estimation models and experiences of researchers. It is intended to assist pavement engineer in finding a reasonable value and avoiding unreasonable errors.

To have a better understanding of subgrade moisture changing behavior, researchers have categorized the salient factors into three groups, external, pavement-related, and materials and construction.

External Factors

External factors include precipitation, temperature and seasonal variation, groundwater table, time and equilibrium.

1. Precipitation. Past research has not established a clear and practical relationship between precipitation and the change in ground water content. This is because of the "pause" or "postponement" between rainfall and the change of moisture content that happens and the complexity of the analysis. It might take four to six weeks for water to infiltrate the subgrade from the surface and cause any variations in moisture content (*5, 6*), although increases may not be measurable (*7*). Distribution of rainfall is another important factor. Rainfall events can be classified as either convective or frontal systems (*8*). Convective rainfall generally occurs as a thunderstorm that is quite sporadic during the warm season, while rainfall from frontal systems may often be steady for a number of days.
2. Temperature. Field observations revealed that subgrade moisture contents are usually at their highest level during late winter or early spring (*5, 7, 9*). During freezing of the subgrade, both vapor and liquid state water is drawn from the groundwater table to the freezing front. This movement of moisture is mainly caused by the difference of energy level (*10*, *11*). Moisture variations beneath pavements were temperature dependent. Due to temperature change, moisture variations have been found to be within the range of 1 to 5 percent (*12*).
3. Groundwater table. Another important source of subgrade moisture is groundwater. It has been indicated that the water table had a significant effect on the moisture condition of the subgrade other than from climatic effects (*13*). It has been indicated that the fluctuations in groundwater levels are related to seasonal variations of temperature and precipitation. Groundwater levels commonly rise in the spring and drop in the winter.
4. Time and equilibrium. According to thermodynamics, water inside a porous body will eventually reach a state of equilibrium distribution. Based on the study of several U.S. airfields in non-frost regions, it has been shown that moisture contents might fluctuate following construction but reach some stable level after about 2 years (*14*, *15*). Other

researchers observed that these variations were cyclic, but the general trend of subgrade moisture seemed to be a gradual increase (*16*).

Pavement-Related Factors

Pavement-related factors are related to the condition of the pavement, drainage design, shoulders and edges, and pavement cross-sections.

1. Pavement surface condition. One of the main purposes of the pavement surface is to protect the entire pavement structure and subgrade from the weakening effects of moisture. Therefore, the infiltration of runoff could significantly affect the magnitude and frequency of change of subgrade moisture contents. Under poor pavement conditions, the seasonal variations of subgrade moisture were more notable and strongly influenced by precipitation. For newly constructed highways, it was found that the subgrades were well protected and the moisture variations were much smaller (*5*, *13*).
2. Drainability. With proper drainage design and base material selections, the amount of moisture penetrating a subgrade caused by infiltration can be reduced. In order to remove runoff more quickly, a good surface drainage design (including shoulder features) is necessary. Additionally, internal drainage design features can be extremely beneficial (*17*).
3. Shoulders and edges. The edge of any pavement structure is where water can enter the subgrade most quickly. Moisture variations are directly related to the type of shoulder used. Wide, paved shoulders reduce the amount of infiltration (*18*).
4. Pavement cross-section. Fill and transition sections were subjected to the worst moisture conditions (*19*). Some fill sections might block or change the natural outflow of water. A cut section might intersect the water table. Pavements constructed on a grade or in shallow cut sections showed lower potentials of changing moisture in the subgrade (*19*).

Materials and Construction Factors

Material and construction related factors include compaction and soil dry unit weight, depth of the subgrade materials, and soil type.

1. Compaction and soil dry unit weight. Possible changes of moisture content are lower when the constructed moisture content is close to the moisture content of in-situ soils at their natural state. Soils will already be close to their long term moisture content if they are compacted at the wet side of the optimum moisture content.
2. Depth. Field data has implied that levels of moisture content variation decreased at greater depths under rigid pavements. It has been demonstrated that the moisture contents near the surface of subgrades were about 1 to 1.5 percent higher than those that were 30 inches deep (*19*).
3. Soil type. The texture of soils affects their ability to attain and retain water. Sandy soils showed a larger moisture increase (3 to 4 percent) than silty (2 to 3 percent) or clayey soils (only 1 percent) in March and April (*7*). During September and October, moisture contents reverting to the base level is faster for sands than for silts and clays (*5*).

In the estimation system developed in this paper, the system obtains the field conditions through some simple questions and performs an analysis based on various combinations of answers. Users will enter the information based on their understanding, and the system will make recommendations about how difficult it will be for the moisture to reach the subgrade.

These recommendations could be used as a reasonable basis to select the proper moisture content for further applications.

LITERATURE RESEARCH

Because the main purpose of this system is to estimate field moisture contents under pavements, initial efforts were concentrated on finding tools and models that are capable of either identifying environmental effects on pavements or estimating field moisture content. These tools and models are summarized in the following sections.

Tools Identifying Environmental Effects on Pavements

Several approaches have been developed to provide a better way to describe the pavement performance related to field moisture conditions in different locations.

Regional Classification

Regional classification is a way to classify areas with similar performance patterns into different categories in order to understand the effects from different environmental factors. The two regional classifications utilized by the proposed system are the Federal Highway Administration (FHWA) climatic regions (Long Term Pavement Performance (LTPP) regions) (*20*, *21*) and Thornthwaite climatic regions (*22*).

Drainability of the Base and Subbase Materials

A relative scale (acceptable, marginal, and unacceptable) of the drainability of base and subbase materials is useful for determining the subgrade moisture condition relationship to pavement performance. The basic idea of this approach is that permanent deformation of coarse grained materials increases dramatically when the level of saturation is exceeding 85 percent. The more quickly saturation is lowered to the 85 percent level, the better the performance will be. Drainability of a granular layer is a function of saturated permeability, layer thickness, lane width, longitudinal grade, and cross-slope.

Natural Drainage Index of the Soil

The moisture condition of the subgrade is affected by many factors including climate, soil type, water table depth, and topography. Under the agricultural soil identification system, each soil has a drainage classification that represents the interactions of the above factors. The drainage condition can be found in county soil maps or reports along with complete descriptions of the soil and its expected behavior. A series of numerical values for these descriptive drainage terms was first suggested in 1953 (*23*). These numerical values were called the Natural Drainage Index of the soil. In this system, a value of +10 is given to a soil classified as very poorly drained. A value of -10 is given to a soil classified as very excessively drained.

Moisture Accelerated Distress Index

This is an integrated approach of all three previously discussed tools (Thornthwaite climatic regions, drainability of base and subbase materials, and Natural Drainage Index). In a report (*17*) published by the FHWA, the concept of the Moisture Accelerated Distress (MAD) Index was proposed. It provides tools for engineers to examine the components of any pavement structure. It then combines the tools in an orderly and logical process and the final result can be ranked for different performance levels related to moisture accelerated distress. The MAD index ranges from 0 to 100. This number represents different degrees of moisture accelerated distress. It can be divided into six categories: Negligible (85~100), Low (70~84), Normal (55~69), Moderate (35~54), High (15~34) and Excessive (0~14).

Soil Suction

Soil suction (or total suction) is related to the field moisture content of the subgrade. Field data shows that climatic patterns have a direct effect on soil suction. Soil will exhibit greater suction if the environment is dry, while a wet environment will result in a low soil suction number. At the same time, different soil types also have an impact of the suction values. For example, the suction of clayey soil is higher than silty or sandy soils. There are three factors related to this phenomenon: the capillary rise (which is directly linked to the pore size distribution), the physico-chemical need of clay minerals, and the physico-chemical need of cations within the soil pores.

The soil-water characteristic curve (SWCC) is also a powerful tool for estimating field moisture content (*24*, *25*). The SWCC represents the relationship between matric suction and water content for a particular soil. Even though several attempts have been made to estimate the SWCC based on grain-size-distribution and other soil properties, the authors feel it may over-simplify the actual complex phenomena of the soil's physical-chemical behavior. Therefore, it is recommended to develop the actual SWCC by using the test methods available. This can provide a better understanding of the real soil behavior in the field. Users could develop their own SWCC for the soils encountered and use it to compare the estimated moisture contents provided by the system. In the past, measuring and developing the SWCC is very time consuming and expensive. But new technologies are available to help engineers to develop the SWCC faster with a reasonable cost.

Moisture Content Estimation Models

Various models have been suggested for determining the field moisture content based on soil properties and field observations. In the software developed for this research, the following estimation models are included:

1. Swanberg and Hansen (*26*) – requires plastic limit (PL).
2. U.S. Navy (*27*) – requires plastic limit.
3. Kersten (*28*) – requires plastic limit; typically clay equilibrium moisture contents exceed the PL, silts are equal to or just under the PL, and sandy soils are less than PL. Thus, for many soils, the lower limit of expected subgrade moisture contents will be between the Optimum Moisture Content (OMC) and the PL while the upper limit will be between the PL and 100% saturation.
4. Arkansas Highway and Transportation Department (*19*) – requires % minus #200 material, liquid limit, plasticity index and permeability.
5. Volumetric Moisture Content Estimation Equations from the SMP Program (*29*) – requires plastic limit, liquid limit, gradation, dry unit weight, and dielectric constant.

SYSTEM DEVELOPMENT

Because the objective was to develop a user-friendly, Microsoft® Windows® based system with interfaces similar to Word® and Excel®, many software developing environments were considered. Ultimately, the Microsoft® Visual Basic® 6.0 Professional Edition was selected. Many current software packages have been developed using this environment. The structure and user interfaces provided by it are the most common format and are widely accepted by developers as a standard. Software developed by using Visual Basic® can be used on any machine using a Windows® based operating system such as Windows 98®, Windows XP® and others. It also allows programmers to expand the scope of the final product into different resources such as database and the internet.

The system works by asking the user about the project site and material characteristics. Then it outputs a range of estimated moisture contents and advice on narrowing the choice. If possible, degree of saturation is also output because some resilient modulus estimation equations require saturation rather than moisture content. Figure 1 is the basic structure diagram of this program.

The following is a brief outline of the capabilities and use of the expert system. For more detailed instructions on use, reference is made to the original documentation (*4*).

"Field Moisture Content Estimation System" Screen

Once the program initiates with a new set of data, the first screen users will see is as in Figure 2. It is the main screen (or interface) where users can interact with the software. The user can find "New", "Open", "Help" and "Exit" on the top left part. "New" means the user will start with a new set of data. "Open" means the system will start with a set of data that has been saved previously. "Help" will show a simple screen with a brief description of what this software is designed to do. "Exit" implies that the user would like to leave the system. As described next, there are three types of input information: 1) data required for calculation of moisture content, 2) data required for location of moisture content in existing databases so a selection can be made, and 3) information that will assist the user in deducing a reasonable moisture content or range from one of the first two methods. It is not necessary for all fields to have information entered. However, the more fields entered, the more output choices will be created.

"Field and Environmental Information" Form

The "Field and Environmental Information" form, shown in Figure 2, is where the user will enter general project information (such as Project Name, Location, State), and information needed for estimation of field moisture content. Types of input that reflect the general factors previously mentioned (environmental, pavement, and material/construction factors) are divided into the following: 1) location or climate (LTPP Climatic Region, Thornthwaite Environmental Region (including moisture region, temperature region, category, Moisture index, Aridity index and Humidity index)), 2) proneness to saturation (shoulder design, drainage design, pavement condition, and cut/fill situation), 3) granular base layer drainability, 4) soil subgrade drainability (Natural Drainage Index range, soil classification (both USCS and AASHTO systems), Atterberg Limits, gradation, permeability, compaction information, soil suction, the dielectric constant from Time Domain Reflectometry (TDR) sensor readings), 5) initial moisture content, 6) interval after construction, and 7) season of interest.

Most of the frames represent information that is the basis the system uses to establish how easily the moisture can reach the subgrade through the pavement structure. Once the ease of moisture reaching the subgrade can be established, the system will provide some comments. By combining all the comments from different approaches, users can narrow the possible choices for the field moisture content. Users can remove all the options previously selected by clicking the "Reset" button at the bottom of the "Field and Environmental Information" Form.

For the LTPP climatic region classification, the information can be obtained from the weather information collected under the LTPP program (*21*).

Two features help the user find suitable information: buttons for "Show Definitions" and "Thornthwaite Maps".

"Definitions of Terms" Form

By clicking "Show Definitions", a new form will be added into the screen (Figure 3) which will provide the definitions of the terms used in climatic classifications. These include LTPP climatic regions, Thornthwaite environmental regions, and granular layer drainability and the Natural Drainage Index from the Moisture Accelerated Distress (MAD) system. Because they are more complicated and users may not be very familiar with them, it is helpful to provide these definitions to the user for reference.

Thornthwaite Maps

The next feature is the "Thornthwaite Maps" button. By clicking it, two maps will be displayed on the screen (Figure 3). On the top is the continental U.S. map classified into nine climatic zones (I-A, I-B, I-C, II-A, II-B, II-C, III-A, III-B, and III-C) based on Thornthwaite's definitions. On the bottom are the seasonal moisture variation categories of the continental U.S. Users can use them as a reference material to decide which environmental region combination is the most appropriate for their project. These regions are useful in delineating the LTPP regions, which in turn are necessary for estimation of moisture contents based on LTPP database information. Thornthwaite analyses are also useful for establishment of intervals of frozen, saturated, and moisture deficit seasons for use in estimation of the subgrade moisture content during different seasons, leading to estimations of the effect on resilient modulus.

"Moisture Index Calculation" Form

If the weather observation records (such as monthly average temperature (°C), monthly average rainfall (cm), and North latitude (degrees)) are available, the information such as Moisture Index (I_m), Aridity Index (I_a) and Humidity Index (I_h) can be calculated by using the "Moisture Index" button at the lower left part of the "Field and Environmental Information" Form, or by using equations listed in the reference materials and software tools such as DAMP (*30*) or MODAMP (*31, 32*). Figure 4 is an example of using the "Moisture Index" calculation feature of this software. Input includes precipitation, temperature data, and latitude.

Once the Thornthwaite indices are available, the next step is to enter them into the system and find the most suitable climatic region. Users can choose the range of values in which their Thornthwaite indices fall and the system will determine which regions are to be used. Alternatively, they can select the regions, and the system will enter the proper range for these indexes automatically. If there are contradictory data, the system will display warning messages to alert users to the problem. Unless the conflict of information is resolved, the system will not move to the next stage. By entering the correct Thornthwaite climate classifications, the system can combine them with other information and have a more reasonable basis to describe the pavement behavior in the field. Therefore, it is important to choose the appropriate classification based on the project's location.

Estimate of Moisture Content/Degree of Saturation

The next step is to determine the field moisture content based on all the information provided by the user. This process will be initiated by clicking the "Estimate" button at the bottom of the "Field Moisture Content Estimation System" Form. First, the system will examine all the data to make sure it is reasonable and accurate. The data examination processes involved include whether the data is numerical or alphabetical, whether it is in a reasonable range for different properties (including positive or negative), and whether possible conflicts exist between different variables. In addition, the system will estimate missing data based on other available information.

In order to consider the effect of swelling, the system will interact with users to determine whether to initiate the process or not. The basic idea is to collect information (such as percent swell and moisture content after swelling) from users and calculate the field dry unit weight after swelling. Once the field dry unit weight after swelling is known, it is possible to estimate the degree of saturation based on different moisture conditions.

If the data passed the examination process without any error, two new forms will be added to the screen as seen in Figure 5. They are “Field Moisture Estimation and Recommendations” and “Field Moisture Contents from LTPP Database”. If there is no climatic and environmental information available, the “Field Moisture Contents from LTPP Database” will not be displayed.

“Field Moisture Contents from LTPP Database” Form

The next form is the “Field Moisture Contents from LTPP Database” (Figure 5). Three separate windows are included in this form. They represent field moisture content records from the LTPP database under different criteria. The first window shows the LTPP Seasonal Monitoring Program (SMP) sites located in the same state as the project. The second window shows the LTPP SMP sites classified in the same Thornthwaite environmental region as the project location, but not in the same state. The third window is LTPP SMP sites located in the same LTPP climatic region, but not in the same state or Thornthwaite environmental region. For each site, the information presented includes the following: 1) state, 2) Strategic Highway Research Program (SHRP) identification (ID) (the unique ID assigned to each test site), 3) subgrade material (fine or coarse), 4) subgrade soil classification (based on the AASHTO system), and 5) yearly moisture content data (minimum and maximum numbers). These field moisture content data are available for 57 LTPP SMP sites located in the U.S. All data was retrieved from the LTPP database and re-analyzed by the authors. Users can use these actual field observations presented in these three windows as a reference material when determining the field moisture content.

“Field Moisture Estimation and Recommendations” Form

The “Field Moisture Estimation and Recommendations” Form (Figure 5) includes the following: 1) a recommendation window (including soil suction related information), 2) information related to Moisture Accelerated Distress Index, 3) additional information for before and after swelling, and 4) field moisture contents based on different approaches (including TDR measurement based approach).

The top box with green texts on a black background contains the recommendations made by the system. These recommendations were based on the input entered by the user and it is related to how easy the moisture can reach the subgrade. At the same time, soil suction (if available) can also provide a possible range of moisture content the subgrade will be at. The next item displayed is the “Moisture Accelerated Distress (MAD) Index” frame. The next item is field moisture content estimation based on TDR measurements using the approaches developed by the LTPP program. This was based on the information entered in the Field and Environmental Information Form.

The next frame is labeled “No Swelling Condition”. First, it is based on the dry unit weight and specific gravity of soil solids that the user provided for “Field Condition” in the “Field and Environmental Information” Form. Second, the system calculates the degree of saturation for the optimum moisture content based on the dry unit weight if no swelling occurs. This saturation level is sometimes recommended as the lower boundary for possible field moisture content estimation (*28*). Next, the system calculates the moisture contents for degree of saturation at 80%, 85%, 90%, 95%, and 100%, again, if no swelling occurs. These are designed to help users to get a feel for the possible moisture content values that are reasonable.

The "After Swelling Condition" frame is similar to the frame, "No Swelling Condition". The main difference is that the dry unit weight and moisture content are different from the Initial Point (No Swelling Condition). The After Swelling Condition dry unit weight is actually the value calculated based on the percent swell. The assumption is the volume of soil solids remains constant, but the total volume will increase due to swelling. Therefore, the "after swelling" dry unit weight can be calculated. The moisture content after swelling (which can be obtained from swell tests or soaked CBR testing) is entered by the user in the "Field and Environmental Information" Form. The degree of saturation after swelling will be calculated. In essence, the program draws a straight line between the Initial Point and After Swelling point, as illustrated in Figure 6. Moisture contents, degree of saturation and dry unit weight are calculated for two points (labeled as Middle Point and Middle Point 2) on this straight line. This information is displayed to assist the user in determining reasonable estimations.

The next part is labeled as "Rules of Thumb", which is based on different agencies' experiences. When there is no other data available, the OMC is the basis for estimating a field moisture content. In the Taiwan area (tropical and marine climate), for example, optimum moisture content plus 2% normally represents the worst field condition based on field engineers' experiences. One review of the literature indicates that the highest degree of saturation of fine-grained subgrade can attain up to 8% above the degree of saturation associated with the maximum dry unit weight – OMC point under standard proctor compaction (*31, 32*). The China Engineering Consultants, Inc. (CECI) recommendations displayed as degrees of saturation for summer (dry) and fall (wet) seasons are 87% and 92%, respectively. These can be compared to the saturations calculated in the above discussions to temper choices of final moisture content.

The four frames at the bottom are "Swanberg and Hansen", "U.S. NAVY", "Kerstern", and "Arkansas (Rao and Hall)". These represent the values obtained from these different estimating models. If there is no number showing in any of these four frames, it means that there is not enough data for that model to be initiated or the estimation is not reasonable. The Arkansas model does not function properly at the present time, possibly due to errors in the original code, but it has been retained in the system pending future developments.

Summary

Nine possible methods for field moisture estimation are included in the software presented: 1) calculation via TDR measurements, 2) calculation via Swanberg and Hansen, 3) calculation via U.S. Navy, 4) calculation via Kersten, 5) calculation via Arkansas model, 6) calculation via swell test data, 7) estimation from the Rules of Thumb, 8) estimation by comparison to LTPP SMP data, and 9) estimation from CECI.

EXAMPLE

An example will be used to clarify the use of this system (Figure 5). A project is located in Region I-A (wet-freeze), category "r", with subgrade soil characteristics as follows: A-7-6(25), LL = 49, PL = 27, % minus #200 = 96%, standard proctor compaction maximum dry unit weight = 93.6 lbs/ft^3, OMC = 23.7, NDI = poor, in a cut, with no base drainage provided, narrow and open shoulders, and poor maintenance. The results indicate that with a MAD index of 11 there will be an excessive damage potential with moisture likely accumulating in the structure. Model moisture content predictions are as follows: Swanberg and Hansen = 23.9%, Navy = 29%, Kersten = between the 21.6% and 32.3% (recommends 32.3%), Rules of Thumb range from 82% to 88% saturation, and CECI experience = 87% and 92% saturation during dry and wet seasons, respectively. Two sites (390901 and 204054) from the LTPP database have similar soils (A-7-6) and the annual moisture contents range from 17.2% to 26.5%. For Thornthwaite region I-A, the analysis shows saturated conditions in March-May and part of November, frozen in January, and dry the rest of the year. Because the system advice emphasizes the wet side of predictions, and most of the predictions are above the OMC and could be at or above the PL, the first level estimate for the wet season would be between 25% and 32% (saturation above 85%). Subsequent swell data shows that swell = 1% (from soaked CBR testing) with a moisture content = 25.7% (saturation 85%). Altogether, a value of 26% could be used for wet season predictions. For the dry season, the lower end of the predicted values, say, 24% (saturation around 80%), could be used as a conservative value.

SYSTEM VERIFICATION

The largest readily available data source of field moisture content observations currently available is the LTPP SMP database. Two approaches coming from this database have been incorporated into this system (the TDR estimation and yearly field moisture content information for 57 LTPP SMP sites). If more field moisture content information is available in the future, it can be used to further check accuracy and improve the performance of this system.

Weather data for 24 locations within the U.S. were used to check whether the system can determine the proper Thornthwaite Climatic Regions and the length of frozen, saturation, and deficit periods. The analysis showed that for most locations, the predicted regions were the same as in the original Thornthwaite Map (*20*). However, several locations are different. For example, Orlando, Tampa and Miami, Florida, were classified as “II-C” instead of “I-C”. The reason may be due to weather patterns having changed somewhat from when the original data was collected to develop the Thornthwaite system (1948) to when the weather data was used by the authors (late 1990’s).

CONCLUSIONS

This system can help engineers estimate the possible range of field moisture contents based on the data available. Instead of using complicated relationships and rigorous models that require thermodynamic and other property information that is difficult to obtain or verify for applicability, the use of engineering experience, empirical models, and data mining are the three main features of this system. Material properties (such as drainability of materials above the subgrade, the Natural Drainage Index of subgrade, and soil suction) and factors that relate to pavement moisture conditions are incorporated into the moisture content estimation process. At the same time, weather and geographical information were used to retrieve annual field moisture content data from the 57 LTPP SMP sites within the U.S. Engineers can use all the information and recommendations available to remove unreasonable estimations and determine a realistic field moisture content. It is still difficult to pinpoint the field moisture content, but a reasonable range can be established based on the information provided by users and their own engineering judgment.

When more field data is available, this software can be further improved and be used as a decision-assistance tool in the pavement design process. It can also be modified to utilize any field moisture content observation database (such as the SMP 2 project under the LTPP program) which could further expand the flexibility and accuracy of the field moisture content estimation.

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List of Figures

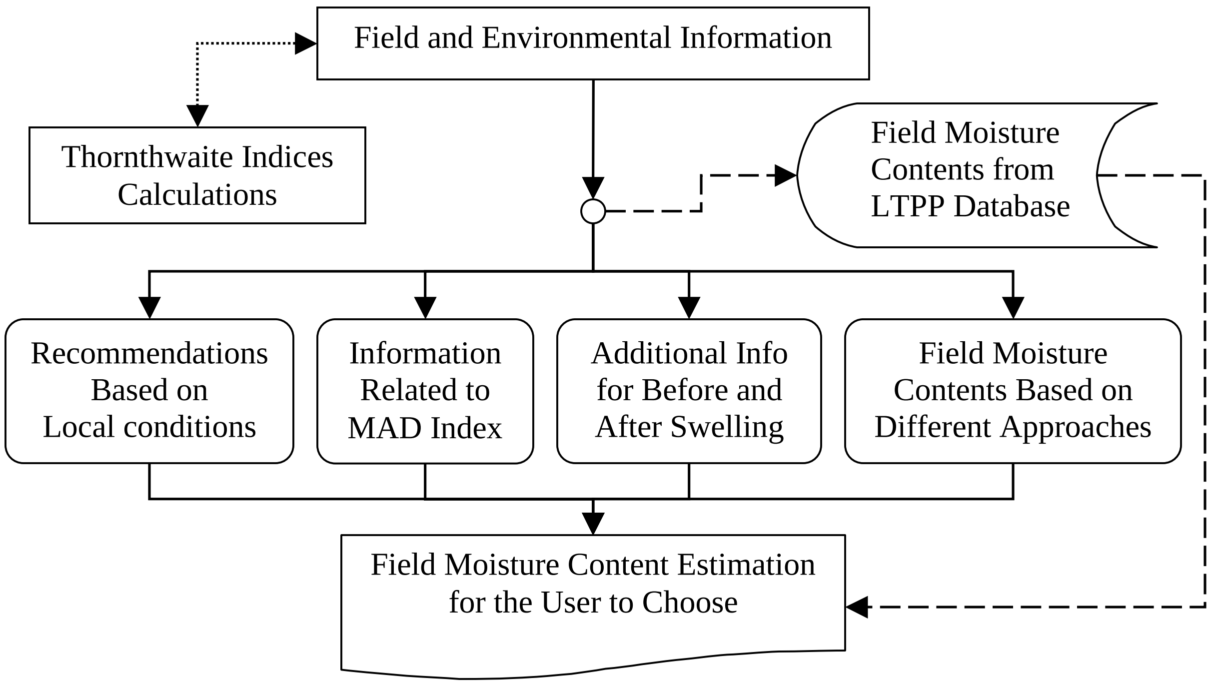


FIGURE 1 System structure diagram.

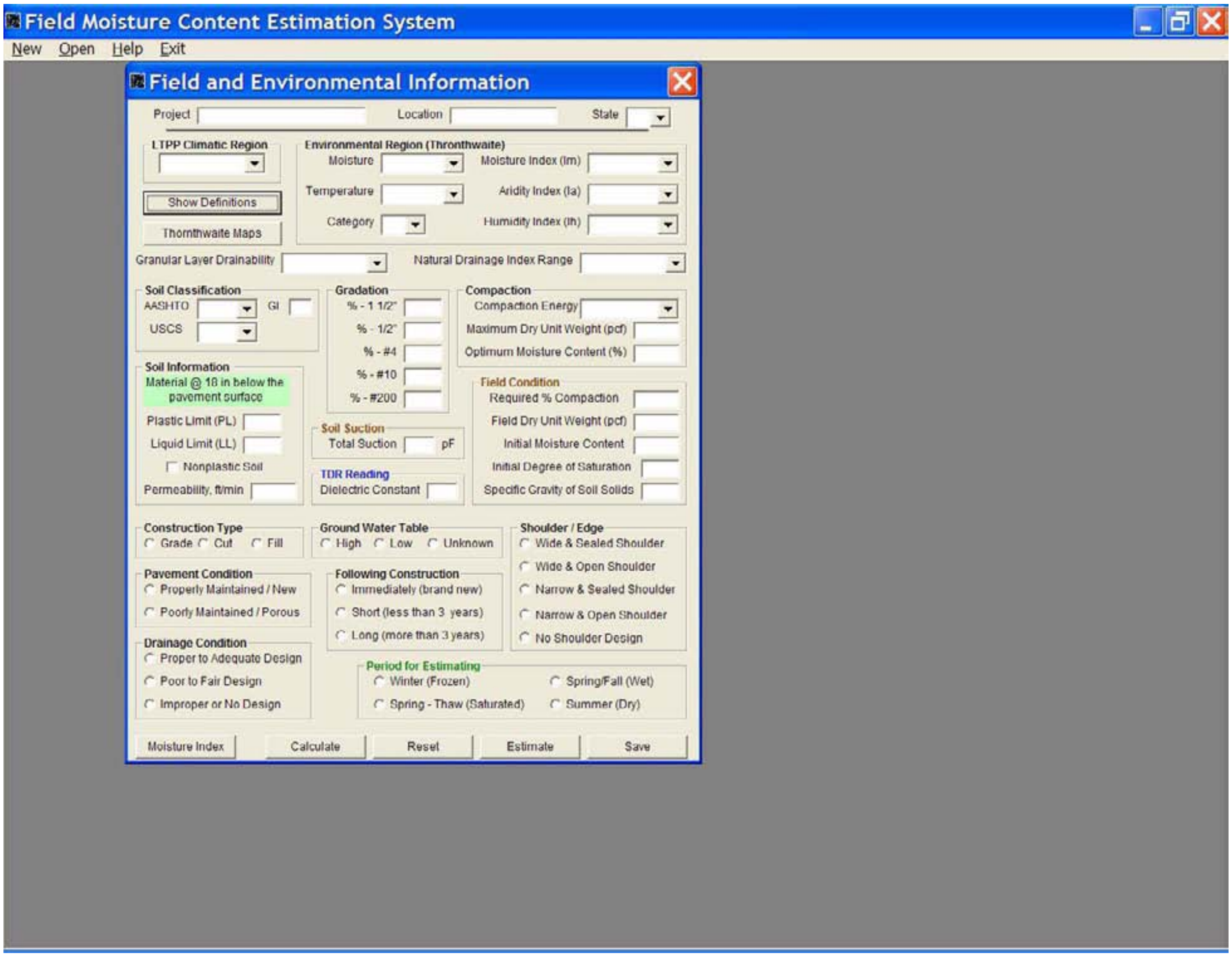


FIGURE 2 Screen shot when the program was initiated with a new set of data.

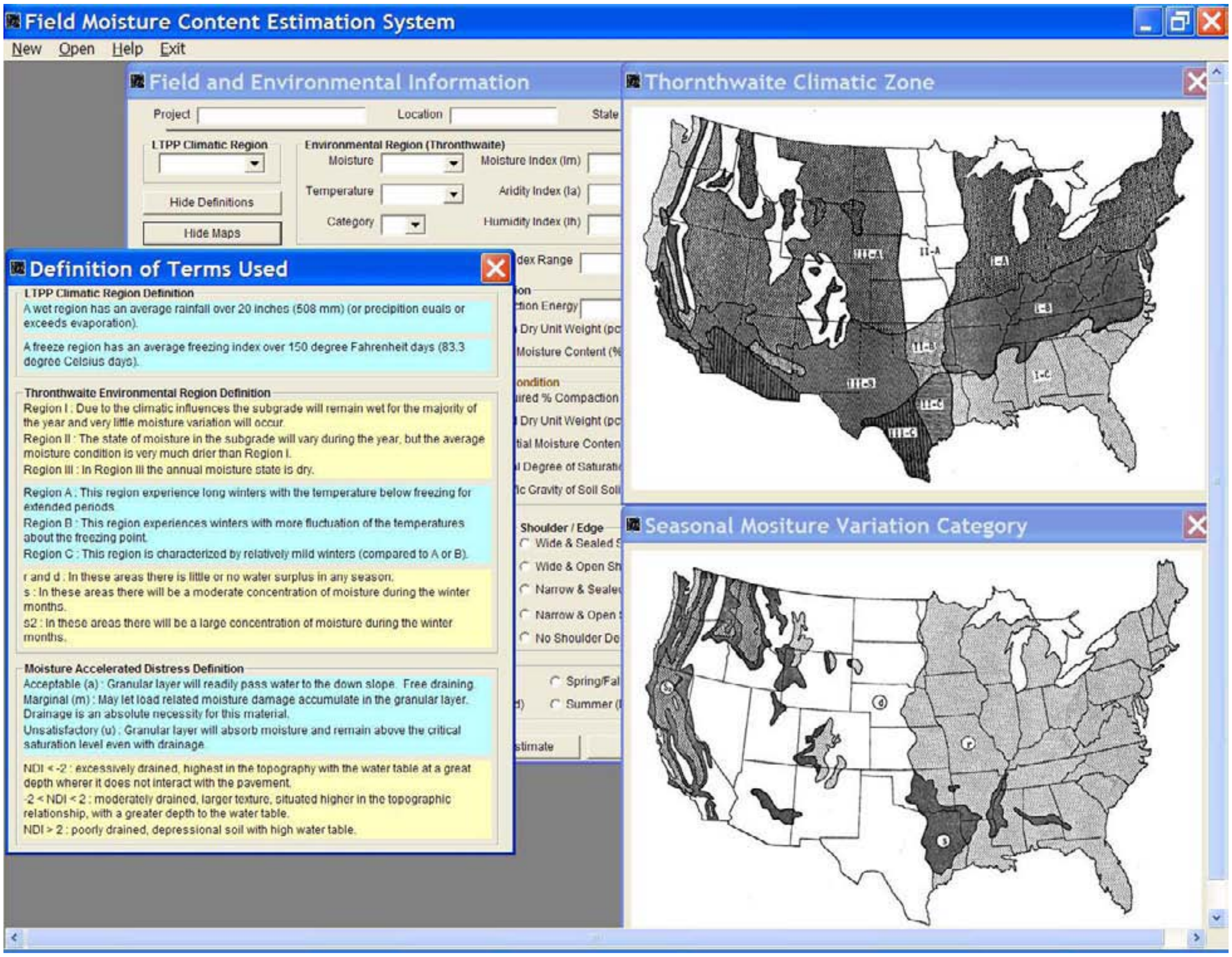
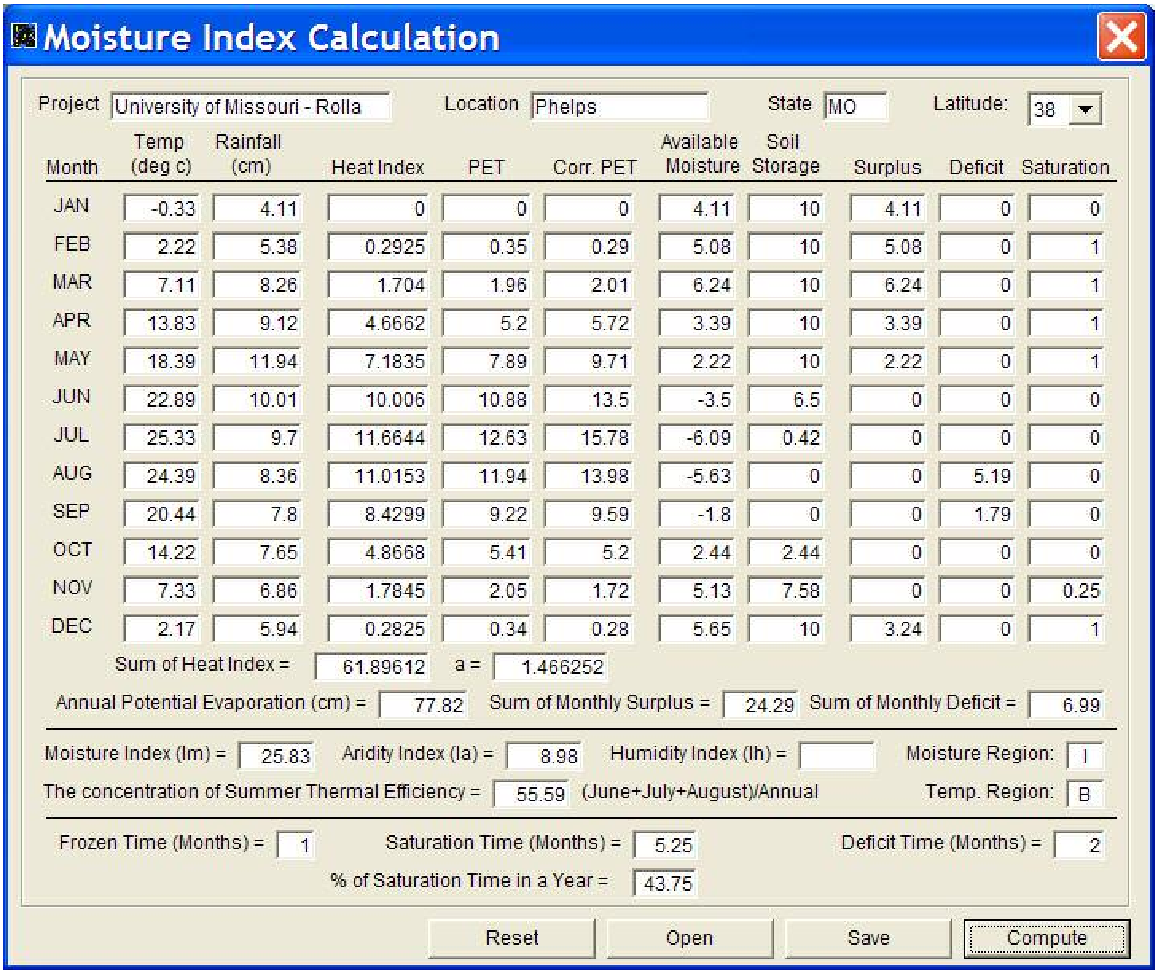


FIGURE 3 Screen shot when "Show Definitions" and "Thornthwaite Maps" buttons were clicked.



Moisture Index Calculation

Project: University of Missouri - Rolla Location: Phelps State: MO Latitude: 38

Month	Temp (deg c)	Rainfall (cm)	Heat Index	PET	Corr. PET	Available Moisture	Soil Storage	Surplus	Deficit	Saturation
JAN	-0.33	4.11	0	0	0	4.11	10	4.11	0	0
FEB	2.22	5.38	0.2925	0.35	0.29	5.08	10	5.08	0	1
MAR	7.11	8.26	1.704	1.96	2.01	6.24	10	6.24	0	1
APR	13.83	9.12	4.6662	5.2	5.72	3.39	10	3.39	0	1
MAY	18.39	11.94	7.1835	7.89	9.71	2.22	10	2.22	0	1
JUN	22.89	10.01	10.006	10.88	13.5	-3.5	6.5	0	0	0
JUL	25.33	9.7	11.6644	12.63	15.78	-6.09	0.42	0	0	0
AUG	24.39	8.36	11.0153	11.94	13.98	-5.63	0	0	5.19	0
SEP	20.44	7.8	8.4299	9.22	9.59	-1.8	0	0	1.79	0
OCT	14.22	7.65	4.8668	5.41	5.2	2.44	2.44	0	0	0
NOV	7.33	6.86	1.7845	2.05	1.72	5.13	7.58	0	0	0.25
DEC	2.17	5.94	0.2825	0.34	0.28	5.65	10	3.24	0	1

Sum of Heat Index = 61.89612 a = 1.466252

Annual Potential Evaporation (cm) = 77.82 Sum of Monthly Surplus = 24.29 Sum of Monthly Deficit = 6.99

Moisture Index (Im) = 25.83 Aridity Index (Ia) = 8.98 Humidity Index (Ih) =   Moisture Region: I

The concentration of Summer Thermal Efficiency = 55.59 (June+July+August)/Annual Temp. Region: B

Frozen Time (Months) = 1 Saturation Time (Months) = 5.25 Deficit Time (Months) = 2

% of Saturation Time in a Year = 43.75

Reset Open Save Compute

FIGURE 4 Result of Moisture Index calculation for Rolla, Missouri.

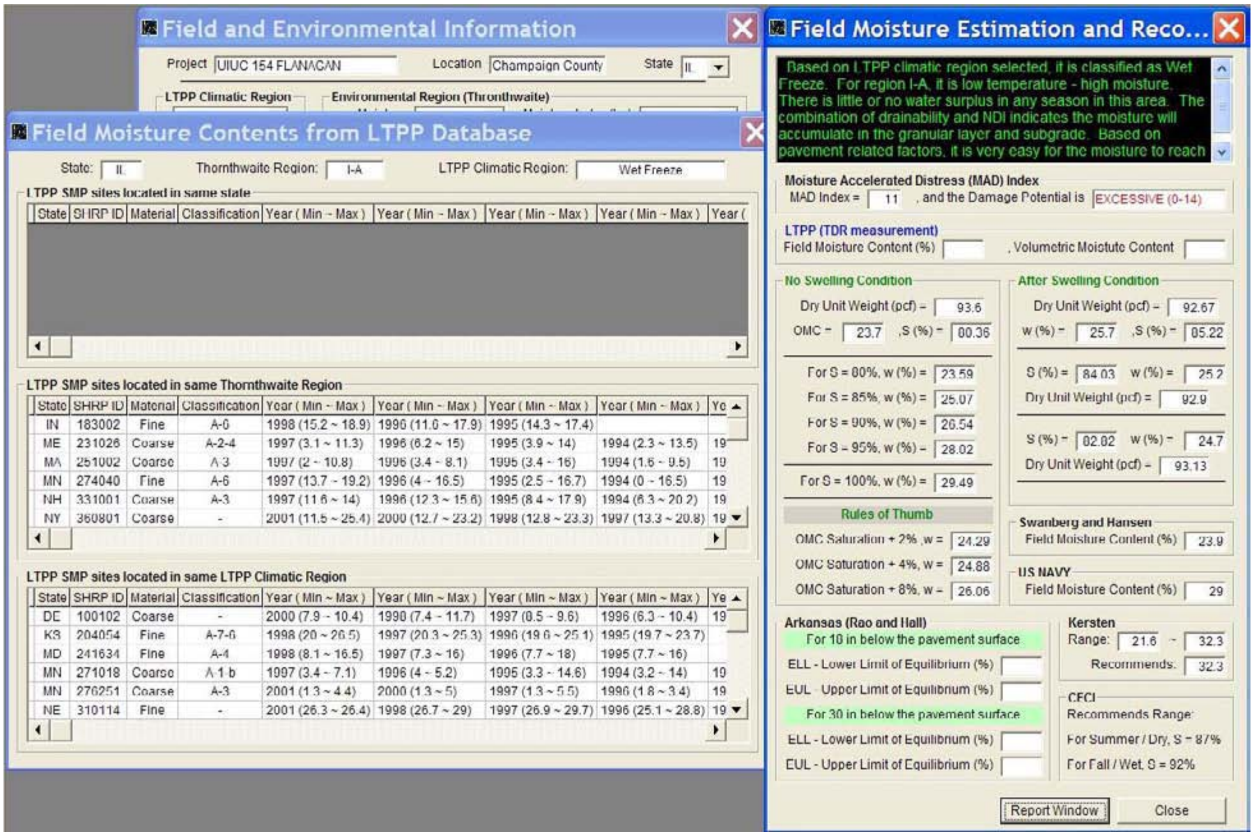


FIGURE 5 Partial screen shot when field moisture content estimation was completed.

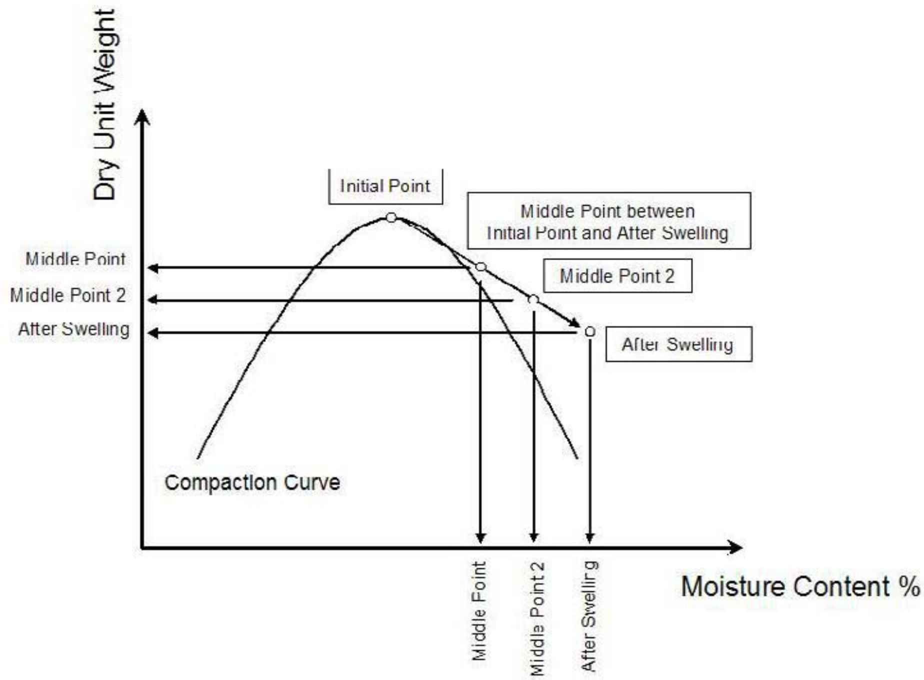


FIGURE 6 Calculation process for after-swelling condition.