calculation of TMI is based on a period of one year using monthly weather data. The calculation of TMI by Thornthwaite (1948) approach is computationally intensive. On the other hand, the methods given by Thornthwaite and Mather (1955) and Witczak et al. (2006) are relatively simple and only consider annual precipitation and potential evapotranspiration computed on a monthly basis.

TMI is a simple climatic parameter and is easy to determine with, in many cases, readily available data from local weather stations. The parameter has the appeal of relevance to moisture conditions of a site, and thus, has been correlated with the depth of moisture active zone (depth to constant suction) and the equilibrium suction (Fityus et al. 1998). However, the review of literature indicates that there are discrepencies between the established correlations in the literature. It is believed that those differences are coming from the TMI calculation methods, and to some extent from the local soil and weather conditions.

BACKGROUND

The Thornthwaite Moisture Index (TMI) has become an acceptable climatic parameter in geotechnical engineering because of its relative simplicity and practicality, and it has been used in engineering practice with success over the last several decades. Russam and Coleman (1961) developed a relationship between soil suction at depths below the moisture active zone and the TMI. Edris and Lytton (1976) studied the effects of climate on subgrade soils in Texas using the TMI for predicting the equilibrium soil suction beneath the pavements using the relationships developed by Russam and Coleman (1961). Wray (1978) adopted the TMI for predicting the horizontal moisture variation distance for slabs-on-ground foundations. McKeen and Johnson (1990) employed the TMI parameter in the estimation of the unsaturated soil moisture diffusion rates in subgrade soils. Fityus et al. (1998) employed the TMI as a predictor for determining the depth of seasonal moisture change in unsaturated soils in Australia. Recently, Perera et al. (2004) expanded on the work of Russam and Coleman (1961) and introduced a model to predict suctions beneath pavements using the TMI and basic soil index properties.

The original TMI given by Thornthwaite (1948) is based on an annual water balance calculation using records of long term climatic parameters such as precipitation, temperature, and estimated potential evapotranspiration. The moisture balance is determined in terms of precipitation, evaporation, water storage, deficit, and runoff. The water balance is computed by month. The process begins by calculating the difference between precipitation and corrected evaporation. If the difference is larger than zero, it is added into storage up to a maximum value. The amounts exceeding the maximum storage are considered as runoff. On the other hand, if the difference between the precipitation and corrected evaporation is less than zero, it is deducted from the storage up to zero. The amounts lower than zero are defined as deficit. A detailed analysis of the Thornthwaite (1948) method is given by McKeen and Johnson (1990). Later, Thornthwaite and Mather (1955) modified the original Thornthwaite (1948) equation by eliminating the water balance approach and reducing the amount of data required and computational effort in determining the climatic index. Recently, Witczak et al. (2006) offered a slightly different version of the Thornthwaite and Mather (1955) equation as part of a NCHRP research study for the Mechanistic

Empirical Pavement Design Guide (MEPDG). These models are described in the following section.

THORNTHWAITE MOISTURE INDEX

Thornthwaite (1948) defined a moisture index (known as the Thornthwaite Moisture Index or TMI) as a relative measure indicating the wetness or dryness of a particular region. The TMI has been a popular and attractive parameter in the geotechnical engineering community due to the fact that the data required for its determination are usually readily available from local weather stations and it is based on a simple climatic model as compared to some of the rigorous models in the literature (Edris and Lytton 1976; McKeen and Johnson 1990). Thornthwaite (1948) equation is given as:

$$TMI = (100R - 60D)/PE \quad (1)$$

where, D is the moisture deficit; R is the runoff; and PE is the net potential for evapotranspiration. TMI calculations are based on a period of one year with monthly values of precipitation, adjusted potential evapotranspiration, storage, runoff, and deficit by conducting a moisture balance approach. The calculation process requires the total monthly precipitation, average monthly temperature, initial and maximum water storage values, the day length correction factor, and the number of days for each month. The precipitation and temperature values can be obtained from the local weather stations. The maximum water storage is a function of the soil type and the initial water storage depends on the climate and site condition. The day length correction factor is a constant for a given month and location (latitude). Thornthwaite (1948) adopted a relatively simple model for the calculation of the adjusted potential evapotranspiration as compared to some of the sophisticated (yet complex in terms of the parameters involved) models available in the literature. The heat index for each month is determined using the mean monthly temperatures as follows:

$$h_i = (0.2t_i)^{1.514} \quad (2)$$

where, h_i is the monthly heat index and t_i is the mean monthly temperature. The annual heat index is simply calculated by summing the monthly heat index values as:

$$H_y = \sum_{i=1}^{12} h_i \quad (3)$$

where, H_y is the yearly heat index. The unadjusted potential evapotranspiration is then determined for each month as follows:

$$e_i = 1.6\left(10t_i/H_y\right)^a \quad (4)$$

where, e_i is the unadjusted potential evapotranspiration for a month with 30 days and a is a coefficient given by:

$$a = 6.75 \times 10^{-7} H_y^3 - 7.71 \times 10^{-5} H_y^2 + 0.017921 H_y + 0.49239 \quad (5)$$

The unadjusted potential evapotranspiration is then corrected for the location (latitude) and the number of days in the month as:

$$PE_i = e_i(d_i n_i/30) \tag{6}$$

where, PE_i is the adjusted potential evapotranspiration for the month i; d_i is the day length correction factor (provided in McKeen and Johnson 1990); and n_i is the number of days in the month. A detailed explanation of the original TMI calculation process is given by McKeen and Johnson (1990) and Fityus et al. (1998). Equation 1 was later modified by Thornthwaite and Mather (1955) and is given as:

$$TMI = 100(P/PE - 1) \tag{7}$$

where, P is the annual precipitation. The potential evapotranspiration (PE) is determined using the same Thornthwaite (1948) model described above. As part of the NCHRP 1-40D research project for the development of the MEPDG, Witzack et al. (2006) modified Eq. 7 as follows:

$$TMI = 75(P/PE - 1) + 10 \tag{8}$$

TMI CONTOUR MAPS

TMI contour maps are produced based on the three models, Eqs. 1, 7, and 8, mentioned above using the climatic data obtained from seventy seven Oklahoma Mesonet weather stations representing seventy seven counties in the state. Contour maps consist of lines connecting points of equal values of TMI for a certain region. To create the contour maps of TMI, the method of Inverse Distance Weighting (IDW) has been applied in ArcGIS software. IDW is a type of interpolation scheme with a known scattered set of points. Having the TMI values for the seventy seven points (representing climatic data for the seventy seven counties in Oklahoma), the values to unknown points are calculated with a weighted average based on the available TMI values.

The original TMI calculations based on Eq. 1 are related to maximum water storage as well as the initial water storage. The original TMI maps produced by Thornthwaite (1948) were based on the assumption that the maximum water storage of 10 cm regardless of the soil type. Studies (i.e., Russam and Coleman 1961; Aitchison and Richards 1965; Wray 1978; and others) that established correlations between the TMI and unsaturated soil parameters (i.e., depth to constant suction and equilibrium suction) were based on the original TMI map using a maximum water storage of 10 cm. In order to make a comparison and to use the same established correlations for the equilibrium soil suction and depth to constant suction, a TMI contour map was constructed using the original Thornthwaite (1948) equation with the maximum water storage of 10 cm. The map is depicted in Fig. 1.

Using the same climatic data obtained from the seventy seven Mesonet weather stations across Oklahoma, TMI contour maps using Eq. 7 and Eq. 8 were also obtained and are shown in Fig. 2 and Fig. 3, respectively. Although there are similar TMI contour patterns in the three maps (e.g., Figs. 1, 2, and 3), there are some significant differences in the TMI values across Oklahoma. This clearly emphasizes the importance of the methodology employed in the calculation of the TMI and the use of those values in the prediction of the moisture active zone. Therefore, caution should be exercised when attempting to predict a climate-dependent unsaturated soil parameter (e.g., depth to constant suction and equilibrium soil suction) from a TMI contour map.

Table 1 gives a number of TMI values selected from Figs. 1, 2, and 3 representing different climatic regions in Oklahoma. As it was mentioned above, the three TMI prediction models resulted in different values even though they showed similar trends across Oklahoma. However, Table 1 indicates that the differences between the original Thornthwaite (1948) and Witczak et al. (2006) methods are relatively small as compared the results based on the Thornthwaite and Mather (1955) method.

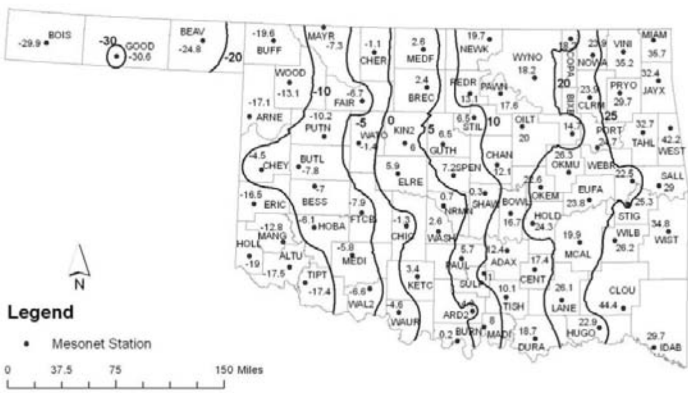

FIG. 1. TMI Contour Map Based on Thornthwaite (1948) Equation.

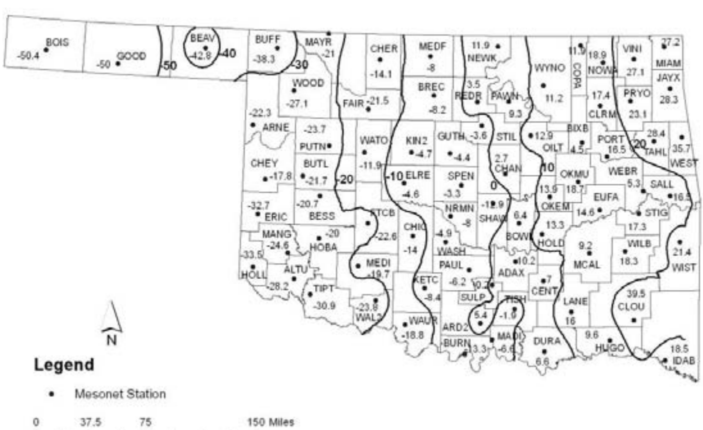

FIG. 2. TMI Contour Map Based on Thornthwaite and Mather (1955) Equation.

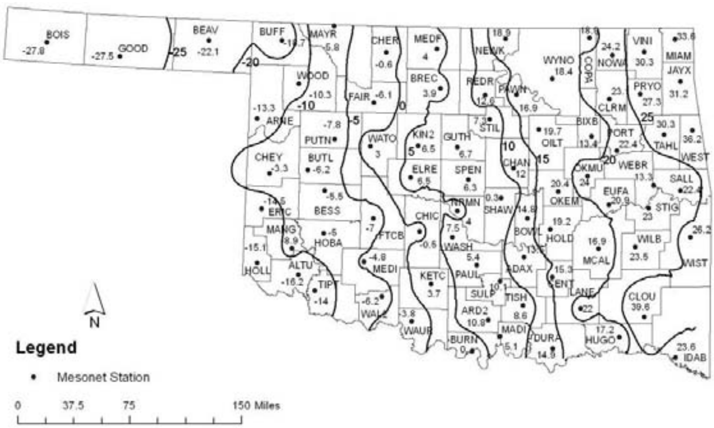

FIG. 3. TMI Contour Map Based on Witczak et al. (2006) Equation.

Table 1. Comparison of TMI Values Between Different Methods and Climatic Conditions.

Weather Station	Dry Climate		Equilibrium Climate		Wet Climate	
	BUFF	HOLL	MEDF	ARD2	MIAM	IDAB
Thornthwaite (1948)	-19.6	-19.0	2.6	4.3	35.7	29.7
Thornthwaite and Mather (1955)	-38.3	-33.5	-8.0	5.4	27.2	18.5
Witczak et al. (2006)	-18.7	-15.1	4.0	10.8	33.6	23.6

TMI IN ENGINEERING PRACTICE

TMI is widely used in Australia for the design of footings in expansive soils, and has been endorsed by the Australian standard AS 2870 (Fityus et al. 1998). The correlation between TMI and the depth to constant suction has been established over the years from field observations, site monitoring, and experience (Aitchison and Richards 1965; Fityus et al. 1998). They have proposed a correlation between the climatic classification, TMI and depth to constant water content as given in Table 2.

McKeen and Johnson (1990) conducted a comprehensive theoretical analysis of the moisture diffusion process in unsaturated soils for the prediction of the depth to constant suction, and attempted to correlate this depth with TMI. The analyses indicated that depth to constant suction varies from about 1.2 m to about 10 m depending on different climatic and soil conditions. McKeen and Johnson (1990) also reported correlations between TMI and moisture active zone from field observations and experience. These correlations are given in Table 3.

Table 2. TMI and Depth to Constant Suction Classification in Australia Based on Thornthwaite and Mather (1955) model (from Fityus et al. 1998).

Climate Classification	TMI	Depth to Constant Suction (m)
Wet Coastal/Alpine	>40	1.5
Wet Temperate	10 to 40	1.5 to 1.8
Temperate	-5 to 10	1.8 to 2.3
Dry Temperate	-25 to -5	2.3 to 3.0
Semi-arid	<-25	3.0

Table 3. TMI versus Depth to Constant Suction for Several Cities in US Based on Thornthwaite (1948) model (from McKeen and Johnson 1990).

Site	TMI	Depth to Constant Suction (m)
Amarillo	-55.6	3.7
Dallas	-30.5	2.1-4.6
Houston	45.7	1.5-3.0
San Antonio	-40.6	3.0-9.1
Jackson	76.2	3.7
Gallup	-81.3	1.2
Denver	-25.4	3.0

Comparison of the results from Table 2 and Table 3 indicates that the correlations between TMI and moisture active zone (depth to constant suction) could be misleading. For instance, for wet climates with TMI values larger than 40, the Australian method limits the constant suction depth to 1.5 m, while it can be between 1.5-3.0 m for a TMI value of 45.7 as suggested by McKeen and Johnson (1990). This simple analysis clearly indicates that it is very important to realize the limitations of such correlations. In the literature, these correlations are simply known as the TMI versus depth to constant suction regardless of the methods used in deriving them. However, as far as a consistent methodology is adopted, TMI can still confidently be used to predict ranges of those depths. Applications of TMI in predicting moisture active zone and constant suction have been widely used for pavement design and evaluation in Texas (Gay 1994; Lytton et al. 2004).

CONCLUSIONS

This research paper has evaluated historical climatic data from weather stations in Oklahoma and obtained Thornthwaite Moisture Index (TMI) contour maps using three different approaches. The analysis of the different approaches with the results of the correlations between TMI and moisture active depth clearly indicates that caution should be exercised in adopting a methodology (a TMI analysis model) for the prediction of the climatic-related unsaturated soil parameters. The TMI methods can be improved further with more rigorous models for the computation of the potential evapotranspiration.

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REFERENCES

Aitchison, G.D. and Richards, B.G. (1965). "A Broad Scale Study of Moisture Conditions in Pavement Subgrades throughout Australia." *Moisture Equilibria and Moisture Changes in Soils Beneath Covered Areas*, Butterworths, Sydney.

Edris, E.V. & Lytton, R.L. (1976). "Dynamic Properties of Subgrade Soils, Including Environmental Effects." *Research Report No. TTI-2-18-74-164-3*, Texas Transportation Institute, College Station, Texas.

Fityus, S.G., Walsh, P.F., and Kleeman, P.W. (1998). "The Influence of Climate as Expressed by the Thornthwaite Index on the Design Depth of Moisture Change of Clay Soils in the Hunter Valley." *Conference on Geotechnical Engineering and Engineering Geology in the Hunter Valley*, Conference Publications, Springwood, Australia: 251-265.

Gay, D.A. (1994). "Development of a Predictive Model for Pavement Roughness on Expansive Clay." *Doctoral Dissertation*, Texas AandM University, College Station, Texas.

Lytton, R.L., Aubeny, C.P., and Bulut, R. (2004). "Design Procedure for Expansive Soils." *Research Report No. FHWA/TX-05/0-4518-1*, Texas Transportation Institute, College Station, Texas.

McKeen, R.G., and Johnson, L.D. (1990). "Climate Controlled Soil Design Parameters for Mat Foundations." *ASCE Journal of Geotechnical Engineering*, Vol. 116 (7): 1073-1094.

Perera, Y.Y., Zapata, C.E., Houston, W.N., and Houston, S.L. (2004). "Long term moisture conditions under highway pavements." Geotechnical Engineering for Transportation Projects: *Proceedings of Geo-Trans 2004. ASCE Special Publication No. 126.*

Russam, K. and Coleman, J.D. (1961). "The Effect of Climatic Factors on Subgrade Moisture Conditions." *Geotechnique*, Vol. 3 (1): 22-28.

Thornthwaite, C.W. (1948). "An Approach Toward A Rational Classification of Climate." *Geographical Review*, Vol. 38 (1): 54-94.

Thornthwaite, C.W. and Mather, J.R. (1955). "The Water Balance." *Publ. Climatol*., Laboratory of Climatology, Vol. 8 (1): 104 p.

Witczak, M.W., Zapata, C.E., and Houston, W.N. (2006). "Models Incorporated into the Current Enhanced Integrated Climatic Model for Used in Version 1.0 of the ME-PDG." *NCHRP 9-23 Project Report*, Arizona State University, Tempe, Arizona.

Wray, W.K. (1978). "Development of a Design Procedure for Residential and Light Commercial Slabs-on-Ground Constructed on Expansive Soils." *Doctoral Dissertation*, Texas A&M University, College Station, Texas.

Performance Evaluation of Superflex Modified Thin Asphalt Overlay

Xudong Hu[1,2], Qisen Zhang[3], Sheng Zhao[4], Wei Chen[5], Yan Sun[2] and Liangyun Tao[2]

[1] PhD candidate, School of Civil Engineering, Central South University, Changsha, China, 410072; sailor24@126.com
[2] Lecturer, Dept. of Transportation Engineering, National University of Defense Technology, Changsha, China, 410072; sailor24@126.com
[3] Professor, School of Transportation Engineering, Changsha University of Science and Technology, Changsha, China, 410004; 13808418373@139.com
[4] Graduate Student, Civil & Environmental Engineering, University of Tennessee, Knoxville, Tennessee, USA, 37996; szhao2@utk.edu
[5] Engineer, Hunan Transportation Department, Changsha, China, 410072; 5514614@qq.com

ABSTRACT: The use of thin asphalt overlay is an effective way in preserving and maintaining the road surface. In this study, the virgin asphalt was mixed up with Superflex modifier at varied concentrations to get the modified asphalt overlay, and the optimum modifier content was 15% by weight of the total mix. Aggregate gradation of the overlay was acquired by means of volume method, and the optimal asphalt content was obtained through Marshall mix design. The performance of the modified overlay mixture evaluated in the laboratory included high-temperature stability, moisture susceptibility and skid resistance. In order to investigate the effects of different thickness levels and structure patterns, four thin overlay sections were paved on route G321 in Guangdong, China. Deflection, skid resistance, permeable performance and roughness were inspected four times in the following six years. The laboratory test results showed that all the testing indices satisfied the criteria specified in China. The field inspection data proved that the thin asphalt overlays evaluated in this study performed well in terms of skid resistance, permeable performance and roughness in every section, without sharp damage on the surface. It can be concluded that the Superflex modified asphalt mixture can be used as thin overlay and this technology is worth popularizing.

INTRODUCTION

Although the structures of most cement concrete pavements are in good condition in terms of the ultimate strength, there are some surface function damages occurring, such as exfoliation, slippage and poor roughness after several years' service. The pavement could recover from the surface function damage by reducing the influence of elevating the pavement and economizing the construction resources. According to previous construction experiences, however, thin asphalt overlay might be a better solution to this problem. It can improve the smoothness of the road surface, relieve the pressure of road investment and serve as an effective preventive measure for road maintenance, which is, in addition, adapted to the tendency towards low-carbon economy.

LABORATORY EXPERIMENTAL PROGRAM

Virgin Asphalt

Esso 70# (Penetration grading system) was chosen as the virgin asphalt. It is now widely used in highway construction in hot and rainy areas. This asphalt is frequently used to produce SBS modified asphalt. The SHRP classification indices of Esso 70# virgin asphalt are listed in Table 1. The testing indices of Esso 70# satisfied AASHTO specifications according to Table 1. In the meanwhile, this asphalt can be graded as PG 64-22 or even higher grade following SHRP grading system.

Table 1. Esso 70# Virgin Asphalt SHRP Indices

Item		Unit	Criteria	Result	Method
64℃ Dynamic Shearing, G*/sin δ		kPa	⩾1.0	1.465	AASHTO T315-04
Residue after RTFOT[1] 64℃ Dynamic Shearing, G*/sin δ		kPa	⩾2.2	2.571	AASHTO T240-03 AASHTO T315-04
Residue after PAV[2]（100℃）25℃ Dynamic Shearing, G*/sin δ		kPa	⩽5000	2544	AASHTO R28-02 AASHTO T315-04
Residue after PAV （-12℃）	Creep	MPa	⩽300	256	AASHTO R28-02 AASHTO T313-04
	m Value	/	⩾0.3	0.313	

Notes: [1]Rolling thin film oven tests. [2] Pressurized aging vessel.

Modified Additive

Superflex modifier is a mixture of modified asphalt with natural dust particles. The Superflex modifier used in this study was produced in TMA Company in Indonesia (Figure 1). The main advantage of this modifier is better cohesiveness and high-temperature stability. Superflex modified asphalt was made by mechanical blending Superflex modifier with virgin asphalt. Some of the test indices of Superflex are listed in Table 2.

Superflex modifier is similar to Trinidad Lake Asphalt (TLA) in ambient temperature which has high viscosity. Three concentrations (10%, 15% and 20% by total weight) of the modifier were chosen in this study in order to verify the optimum modifier content claimed as 15% by TMA. Table 3 presents the results of some basic tests conducted on the modified binder. It can be seen that 15% is the optimum modifier content since penetration, ductility, softening point and elasticity recovery rate of the modified binder containing 15% Superflex meet the criterion of SBS I-D of China with viscosity satisfying the standard of modified asphalt in Japan.

FIG. 1. Superflex Modifier.

Table 2. Superflex Modifier Test Indices

Item	unit	Result	Method
Penetration（25℃,100g,5s）	0.1mm	42	T 0604-2000
PI	/	5.9	
Softening Point (R&B)	℃	>100	T 0606-2000
Ductility（5℃）	cm	21	T 0605-1993
Recovery of elasticity	%	85	T 0662-2000

Table 3. The Conventional Test Results of Superflex Modified Asphalt

Virgin Asphalt		Esso 70#			
Superflex modifier content		0%	10%	15%	20%
Penetration（100g,5s）（0.1mm）	25℃	70	66	64	62
Ductility（5cm/min）（cm）	15℃	0.6	6.4	7.6	8.1
Softening point	℃	48.0	51.0	68.5	74.5
Mass loss after RFOT	（%）	0.07	0.02	0.05	0.02
Ratio of penetration after RFOT（25℃）	（%）	70.5	78.2	78.8	86
Rotary viscosity（135℃, 27,100RPM）	（Pa·s）	0.33	1.03	1.439	2.109
Elasticity recovery rate （25℃）	（%）	4.0	19.0	29.0	34.0

Mix Design

The coarse and fine aggregates were sieved according to AASHTO T30, which were all from Luohong stone ground in Zhaoqing, China. The gradation of filler and three types of aggregates are presented in Table 4. The specified gradation range was also provided by TMA. The synthetic gradation satisfied the demand of the specified range as shown in Figure 2.

Table 4. Gradation of the Aggregates

Sieve Size (mm)	The mass percentage of passing through the sieve size(%)										
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	<0.075