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Selection of suitable treatment for cracking in flexible pavements using optimization models

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Abstract

Cracking types of flexible pavements is one of the sophisticated problems in the domain of highway engineering that can decrease the serviceability of the highway, reduce its service life, and increase its operating cost. Identifying the cracking, discovering its causes, and deciding on the suitable treatment is an essential objective that can reduce the operating cost of the highway and prevent future deterioration of the pavements, especially if the treatment is applied in the early stage. However, selection of the optimum treatment is not that easy as it is affected by numerous inherent and external parameters. Therefore, providing an effective tool to manipulate those parameters and suggest the optimum treatment is a vital objective. Therefore, this study aims to develop a computerized package that contains mathematical models to attain this objective. The models used two main components. First, the weights of each factor affect the identification and treatment of the cracking types. These weights were determined based on data collected from professionals in the domain. Second, field data is fed to the models by the end users. The models can process the input data with knowledge embedded within their inference engine to suggest the optimum treatment for 11 different cracking types. The program was validated by professionals and evaluated by the users. Its overall acceptability was 85% for the users due to its ease of use, flexible interface, and speed of running. The program can be updated anytime and can be upgraded to include other types of pavement deterioration.

Keywords: Flexible pavements, Cracking, Treatment, Optimization models, Optimum solution, Causes

1. Introduction

Fast urbanization and population growth generate a great demand for transportation facilities [1], [2]. Among miscellaneous transport modes, roads are the basic one as their use represents about 70% in overall [3], [4], [5], [6], [7]. Pavements are the major element of roads [8], [9]. Flexible pavement represents the widespread type as a result of its serviceability and low cost in comparison with other types [10], [11]. Nonetheless, traffic loading and environmental conditions lead to severe damage in flexible pavements, causing a decrease in the serviceability of the road due to a reduction in safe and comfortable riding [12], [13]. Among the different damages in flexible pavements, cracking types are the most popular [14]. When they appear, cracking types cause uncomfortable riding and damage to the vehicles, which leads to economic losses [15]. If not treated, simple cracks such as hair cracks can develop into severe ones, such as alligator cracks, and subsequently those can develop into potholes; dramatically, the road serviceability can decrease [16].

Therefore, effective treatment must be adopted to solve the problem and to eliminate its aggravating effects. However, the choice of the optimum treatment is not always easy and depends on numerous factors [17], [18]. Handling and considering such factors result in effective problem identification, accurate cause prediction, and selecting optimal solutions [19], [20]. This procedure needs high skills and knowledge, which can be absent or costly when needed [21]. Therefore, providing mathematical models that have the capability to handle and analyze the available factors is beneficial to select the optimal treatment for different cracking types in flexible pavements. This study aims to develop such models to deal with domain problems. The models consider all available data, including technical, economic, environmental, and other factors, to overcome the domain problem. Early overcoming of domain problems can prevent serious effects. The present models were packaged in a computer-based environment that provides an interactive interface. The user interface of the computerized model was designed to be flexible and user-friendly to ensure simple communication between the users and the model, to simplify the diagnosing and solving process. The proposed package can be used by pavement engineers to overcome different cracking types easily and efficiently. To expose the gap in knowledge in this domain of study, a literature review was implemented. Based on this review, the research can be classified.

First, researchers focus on a specific type of cracking, such as top-down cracks and fatigue cracks; for example, references [22], [23]. Second, researchers deal with the initiation and progression of cracks in flexible pavements. These studies focus on the mechanism of cracking itself but not on treatments [24], [25]. Third, research deals with the optimization of crack treatment time [26]. Regardless of the treatment procedure and materials used, these researchers considered specific methodologies to determine the optimum time for crack treatment based on prioritization factors. Fourth, researchers focus on image detection using image processing [27], [28]. The concern of this research was related to the identification and classification of cracking types, but not on the treatments. Fifth, researchers focus on the effects of materials properties and/or environmental conditions on flexible pavement cracking [29], [30]. However, these studies did not cover the treatment of the cracks. Sixth, researches covered other miscellaneous approaches deals with modelling of cracking in flexible pavements such as effects of recycling, using specific additives, or adopting specific testing methods on the pavements susceptibility [31], [32], [33], [34], [35], [36], [37]. However, to the best of the authors, no such study was found within the research covered by this review that proposed a model specialized in the selection of optimum treatment for flexible pavement cracking types. This finding supports the significance of this study.

2. Data collection

To identify the cracking types and the available treatments to rectify each type, two surveys were implemented. First, a literature survey was implemented through the specialized written sources to initiate a comprehensive understanding of the domain problems. Second, a field survey was implemented to collect the knowledge from professional engineers specialized in the flexible pavements domain. The second survey consisted of two phases. The first phase involved in-depth interviews with four professionals to collect the knowledge related to the domain of the study. The second phase represents validation of the collected knowledge by two professionals who did not participate in the first phase. They reviewed the collected knowledge and provided some comments. Their comments were considered to improve the quality of the collected knowledge. Table 1 abstracts the history of the professionals.

The data collected in the two surveys were refined and abstracted. The analyzed data included the identification and classification of cracking types in flexible pavements, their possible causes, and the applicable treatments. Figure 1 illustrates the identification of the cracking types based on shape, location, pattern, field conditions, and some causes of propagation.

Table 1. History of professionals who participated in knowledge collection and verification

Professional	Degree	Years in the field	Phase	Role
1	PhD	23	1	Knowledge transfer
2	PhD	20	1	Knowledge transfer
3	PhD	15	1	Knowledge transfer
4	MSc	21	1	Knowledge transfer
5	PhD	22	2	Knowledge validation
6	PhD	18	2	Knowledge validation

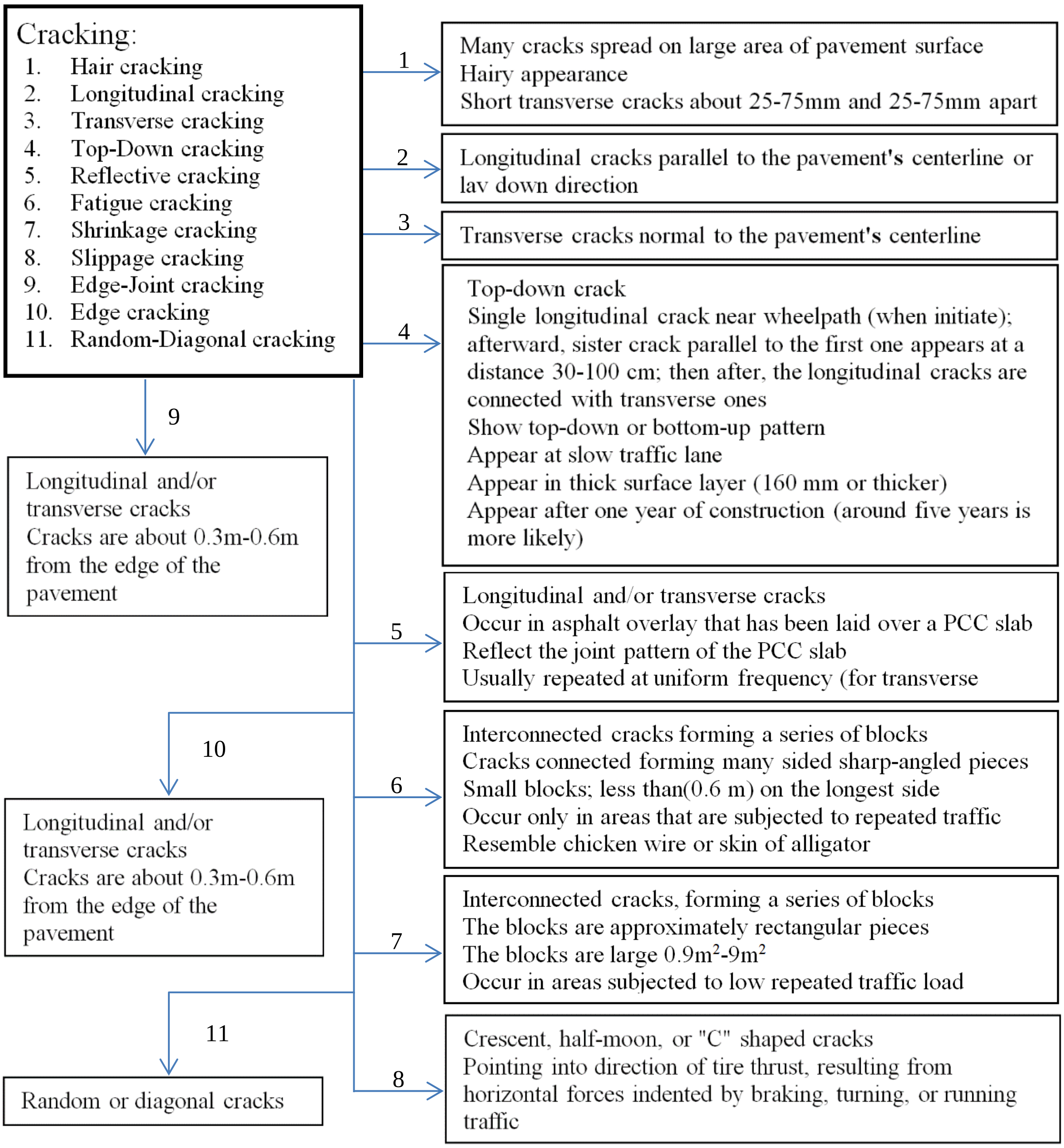

Figure 1. Identification of cracking types

Table 2 presents the probable causes of the cracking types. In general, the causes can be classified into three classes. First, those related to pavements themselves, including materials such as asphalt content and consistency, structural properties such as thickness and strength of the layers, drainage conditions, and construction conditions such as compaction quality of asphaltic layers or subgrade soil. Second, the environmental conditions, such as air temperature and rain conditions, vary during the year. Third, the traffic characteristics. Heavy traffic causes cracking types that differ from those caused by light traffic. For example, heavy traffic [38], [39] causes fatigue cracking, whereas lack of traffic causes shrinkage cracking. Usually, different combinations of specific causes can result in one type of cracking or more. In addition, some causes can worsen the cracking level, which reduces the serviceability of the pavements and increases the need for costly treatments. Some of the cracking is unavoidable, such as environmental conditions; however, some causes are avoidable, such as inefficient properties of pavement materials and structure. Therefore, avoiding such causes can increase the efficiency of pavement, increase its service life, and reduce the cost of maintenance. The vital section in the refined data is represented by the applicable treatments for the cracking types. The suitable treatment ranges from neglect in minor cases to pavement replacement in severe cases. However, the selection of the optimum action is sophisticated. Therefore, this study adopts the proposed models to do so effectively. Table 3 abstracted the applicable treatments for each cracking type.

Table 2. Possible causes of cracking types

Cracking Type	**Possible Causes**
Hair Cracking	Improper preparation of underlying layers Tender mixture: tender mixture shovels under compaction Low temperature of the mixture during compaction Excessive compaction
Longitudinal cracking	Poorly constructed paving joints Lack of internal friction in the base and/or subgrade Poor drainage Frost action Heavy traffic loading
Transverse cracking	Poorly constructed paving joints Lack of internal friction in the base and/or subgrade Poor drainage Frost action
Top-down cracking	Age hardening of the asphalt cement Low stiffness upper layer caused High temperatures Excessive traffic loading Poor mixture properties of pavements Improper construction (segregation, moisture damage, insufficient compaction)
Reflective cracking	Thermal movements of the concrete slab beneath the asphaltic overlay Earth movements Traffic loading
Fatigue cracking	Excessive underlying layers Excessive traffic loading Insufficient pavement structure Inadequate base support Aging of the asphalt mixture Poor drainage
Shrinkage cracking	Volume change in asphalt mix, fine aggregate, base, or subgrade Stiff or hardened asphalt cement Lack of traffic Daily stress/strain cycling (Temperature cycling)
Slippage cracking	Lack of bond between the surface layer and the core beneath it Excessive sand content in the mixture Poor compaction
Edge-Joint cracking	Wetting and drying, or freezing and thawing, beneath the shoulder surface Poor drainage Shoulder settlement

Cracking Type	**Possible Causes**
	Mix shrinkage Tracks straddling the joints
Edge cracking	Lack of lateral or shoulder supports Settlement or yielding of the material underlying the crack area Difference in elevation between the traffic lane and the shoulder Excessive traffic loading
Random cracking	If the area is subjected to heavy traffic, probable causes are similar to fatigue cracking. If not, probable causes are similar to longitudinal cracking.

Table 3. Applicable treatments for the cracking types

Cracking Type \ Applicable Treatment	1	2	3	4	5	6	7	8	9	10	11	12
Hair Cracking	✓	✓										✓
Longitudinal cracking	✓		✓	✓			✓	✓				✓
Transverse cracking	✓		✓	✓			✓	✓				✓
Top-Down cracking	✓								✓	✓		✓
Reflective cracking	✓		✓	✓			✓	✓				✓
Fatigue cracking	✓			✓	✓	✓	✓	✓	✓	✓		
Shrinkage cracking	✓				✓	✓						
Slippage cracking	✓			✓		✓						✓
Edge-Joint Cracking	✓		✓						✓			
Edge cracking	✓		✓						✓		✓	
Random cracking	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓

Applicable treatments:

1. Do Nothing
2. Rectify by sealing with rolling
3. Crack Seal/Fill
4. Patching
5. Fog Seal
6. Slurry Seal
7. Scrub Seal
8. Chip Seal/Armor Coat
9. Thin Cold Mix Overlay
10. Thin Hot Mix Overlay
11. Shoulder Maintenance
12. Replacement

3. Building optimization models

To select the optimal treatment of each cracking type from the applicable treatments, mathematical models were built. The proposed models involve parameters related to each cracking type, represented by values based on field conditions multiplied by pre-calculated weights. Since the selection of the optimum solution depends on the correct diagnosis of the problem, sub-models were adopted. The sub-models use pre-constructed rules in diagnosing. The processing operation involves identification and analysis of the problem, features, and severity level, conditions (environmental, traffic characteristics), causes, usage and importance of the facility, and environmental considerations. The weight of each parameter is based on its contribution to the cracking occurrence and severity. Those weights were determined during the data collection and verification stage, as explained in Section 2. The same parameters may cause different effects in the same members based on the contribution of other factors. The model must be fed by the field data to start processing. Afterward, the model determines the value of each factor based on the field data. Consequently, the model reaches the optimum solution. The mathematical model can be illustrated by Equation 1.

$$\mathrm{DV} = \frac{\sum_{i=1}^{n} (X_i \times Y_i)}{\sum_{j=1}^{m} (W_j \times Z_j)} \times C \quad (1)$$

Where; DV represents a value used to determine the best decision (optimum treatment), X_i and Y_i represent the i^{th} coefficients (weights) and the i^{th} field values of the technical factors respectively, W_j and Z_j represent the j^{th} coefficients (weights) and the j^{th} field values of the non-technical factors respectively, C is a pre-calculated constant. To simplify the working of the models, one model, which is the model related to hair cracking in the wearing course of flexible pavements, can be explained as an example. To control such a problem, three solutions are applicable:

1. Neglect the problem (Do nothing).
2. Rectify the cracked area by spreading a tack coat, applying hot fine sand, and then compacting using rubber-tired rollers.
3. Replace the defective area.

To decide the optimum treatment, the model employs the formula stated in Equation 2, depending on conditions collected from the field. Table 4 presents the values related to parameters affecting the decision to solve the hair cracking problem in a flexible pavement lot, as well as their related average weights. The model must be fed with field conditions to substitute the related values in order to compute the DV_{hc}-value.

The rules that control the decision are as follows:

If DV_{hc} = 0.00 - 0.33 → apply the first treatment: Neglecting

If DV_{hc} = 0.34 - 0.66 → apply the second treatment: Rectifying

If DV_{hc} = 0.67 - 1.00 → apply the third treatment: Replacing

$$DV_{hc} = \frac{\mathrm{V_{tc}}}{\mathrm{V_{nt}}} \times \mathrm{C}_{hc} \quad (2)$$

$$V_{tc} = W_{t1} \times F_{D1} + W_{t2} \times F_{D2} + W_{t3} \times F_{D3} + W_{t4} \times F_{D4} + W_{t5} \times F_{D5} + W_{t6} \times F_{D6} + W_{t7} \times F_{D7} + W_{t8} \times F_{D8} + W_{t9} \times F_{D9} + W_{t10} \times F_{D10} + W_{t11} \times F_{D11} + W_{t12} \times F_{D12} + W_{t13} \times F_{D13} + W_{t14} \times F_{D14} \quad (3)$$

$$V_{nt} = W_{n1} \times F_{Dn1} + W_{n2} \times F_{Dn2} + W_{n3} \times F_{Dn3} + W_{n4} \times F_{Dn4} + W_{n5} \times F_{Dn5} + W_{n6} \times F_{Dn6} \quad (4)$$

C_{hc} constant; (C_{hc} =0.096 in this example)

Where DV_{hc} specifies the optimum solution, V_{tc} represents the value of technical factors, V_{nt} represents the value of non-technical factors, and the further symbols are identified in Table 4.

Table 4. Parameters affect the decision-making for hair cracking

[1]WS	[2]F_D	Field Data description	Field Data values			[3]AW value
			F_D = 1	F_D = 2	F_D = 3	
Technical Factors						
Wt_1	F_{D1}	Asphalt Content in Mixture (%)	high about 7%	average about 6%	low about 5%	0.88
Wt_2	F_{D2}	Asphalt Grade Penetration	soft more than 100	average 100-40	hard less than 40	0.88

[1]WS	[2]F_D	Field Data description	Field Data values			[3]AW value
			$F_D = 1$	$F_D = 2$	$F_D = 3$	
Technical Factors						
Wt_3	F_{D3}	Filler (%)	low less than 4%	average 4-6%	high more than 6%	0.07
Wt_4	F_{D4}	Air Voids (%)	low 3-3.66%	Medium 3.67-4.33%	high 4.34-5%	0.81
Wt_5	F_{D5}	Flow (mm)	high 4-3.34	medium 3.33-2.67	low 2.66-2	0.91
Wt_6	F_{D6}	Stability (KN)	high more than 9kN	average 8-9kN	low less than 9kN	0.73
Wt_7	F_{D7}	Course Thickness (mm)	thick more than 60 mm	medium 45-60mm	thin less than 45 mm	0.78
Wt_8	F_{D8}	Structural Number	high more than 3.5	average 3.5-1.5	low less than1.5	0.87
Wt_9	F_{D9}	Compaction Degree (%)	high more than 96%	average 92-96%	low less than 92%	0.68
Wt_{10}	F_{D10}	Average Crack Width	low less than 1mm	medium 1-2mm	high more than 2mm	0.96
Wt_{11}	F_{D11}	Cracking Extent (% of Lot)	low less than 10%	medium 10-25%	high more than 25%	0.82
Wt_{12}	F_{D12}	Lane Position	near median	middle	near edge	0.62
Wt_{13}	F_{D13}	Traffic Load (ESAL)	low less than 10^4	medium 10^4-10^6	high more than10^6	0.91
Wt_{14}	F_{D14}	Region Climate	hot	medium	cold	0.77
Non-Technical Factors						
W_{n1}	F_{Dn1}	Class of Area	urban	suburban	rural	0.60
W_{n2}	F_{Dn2}	Highway Class	high arterial, freeway	medium collector	low local	0.61
W_{n3}	F_{Dn3}	Facility Importance	high	medium	low	0.61
W_{n4}	F_{Dn4}	Budget Availability	high	medium	low	0.62
W_{n5}	F_{Dn5}	Proficiency Availability	high	medium	low	0.31
W_{n6}	F_{Dn6}	Environment Protection	low importance	medium importance	high importance	0.32

[1]WS: Weight Symbol for each factor in Equations 3 and 4;
[2]F_D: Field data symbol in Equations 3 and 4 (their values must be collected from the field)
[3]AW: Average weight for each factor in Equations 3 and 4

4. Computer-based environment

As previously mentioned, the models require some inputs collected from the field to determine the optimum treatment and to specify the probable causes of the problem. To simplify the process of data feeding by the users, a computer-based program was developed. The program helps users to input data through its flexible interface. The user interface supports the user with helpful facilities such as validation (scroll) lists that enable the users to select the suitable inputs without using the keyboard. It also guides the user to select the correct option via the description texts and images. After completion of data input, the program processes the inputs by its inference engine using knowledge embedded within to provide the model with the required values. Afterward, the model determines the optimum treatment and informs the user via the graphical interface. Figure 2 shows an example of the graphical user interface. The code of the computerized program was debugged to correct any errors. Afterward, the program was subjected to several testing processes to ensure that it is free of errors and defects.

To evaluate the performance of the computerized program, it was tested by 30 users with different knowledge and expertise in the domain of transportation engineering. After the usage of the program, the users were requested to fill out a brief questionnaire that included four questions and evaluate on a scale of 1 – 5, where the value 5 is more acceptable. The answers of the users were abstracted as shown in Table 5. The results of the evaluation showed that the program is highly acceptable due to its flexibility and ease of use.

Table 5. Abstract of user-program evaluation

Seq.	Question	Average value of the user's answers
1	The program can be used easily	4
2	The program can run rapidly	4.75
3	The program has a user-friendly interface	4.25
4	The overall evaluation of the program	4.25

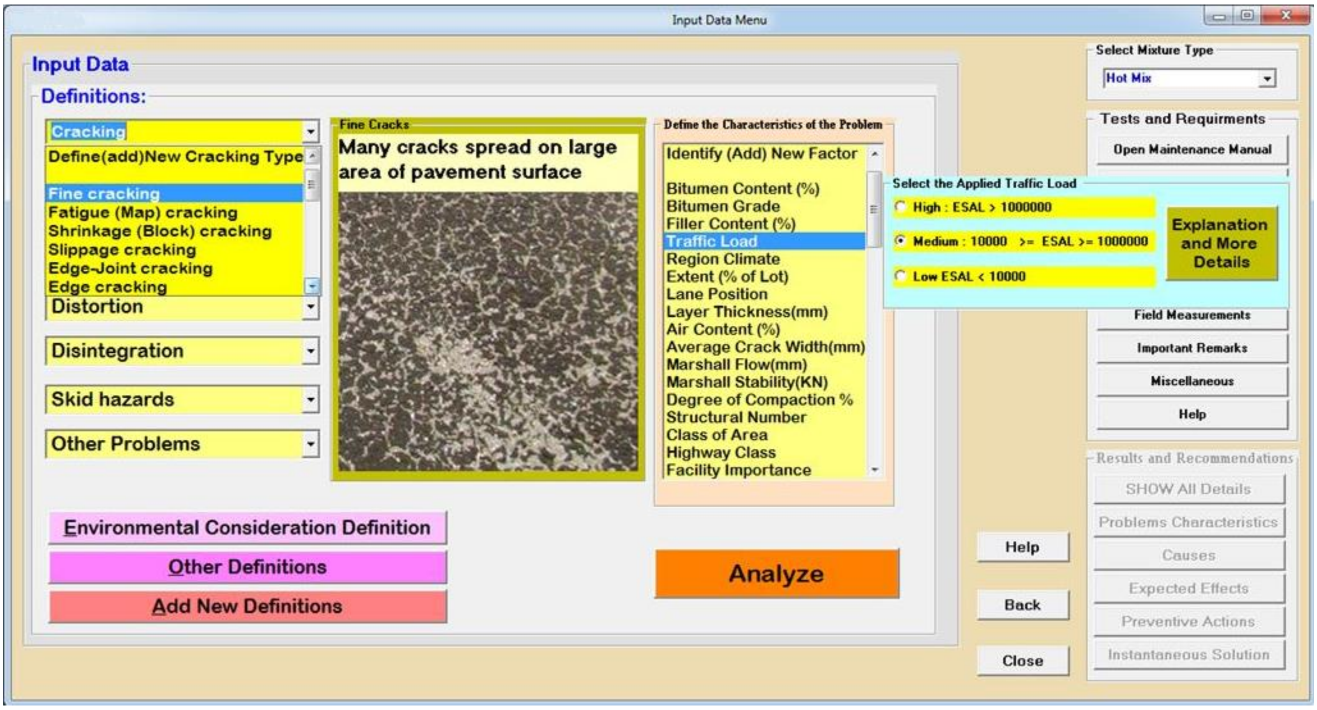

Figure 2. An example of a graphical user interface

5. Conclusions

This study covered the development, validation, and evaluation of an unprecedented computerized program that contains effective mathematical models capable of suggesting the optimum treatment for different cracking types in flexible pavements. The following conclusions can be drawn from the findings of the study:

1. The models can help the workers in the domain of flexible pavements to select the optimum treatments for cracking easily, rapidly, and with low cost.

2. The treatments selected by the proposed models are more assured as the models consider all factors during the processing stage. In addition, the models were validated by domain professionals.
3. The models are capable of identifying the problems and specifying the probable causes.
4. Packaging the proposed models within a computerized program increases their effectiveness as it assists the users in data input and eliminates the probability of incorrect data feeding.
5. The user-friendly interface of the computerized program encourages users with different knowledge levels to use it to attain its advantages.
6. The program can be updated easily when new treatments and/or techniques appear in the domain.
7. The program can be considered as a core for future studies, as it can be upgraded to cover other pavement distresses in a similar concept.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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