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An Expert System to Remedy Concrete Imperfections and Their Effects on Rigid Pavements

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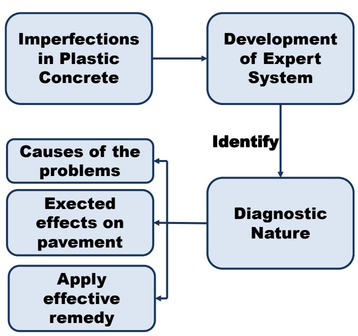
Graphical abstract



Abstract

Imperfections of plastic concrete can cause severe deteriorations in rigid pavements surface and structure and reduce its life and serviceability. Diagnosing these imperfections, identifying their causes, and applying effective remedies early can prevent costly repairs in rigid pavements. However, if these imperfections are not remedied in correct time, the deteriorations in rigid pavements shall be reminded as soon as possible to avoid worsening the pavement condition. This domain involves diagnostic nature which suitable to be modelled as an expert system to help practicing engineers to identify the causes of the problems and their expected effects on pavement as well as applying suitable remedies. This paper presents the stages of development of an expert system in this domain. The development process includes knowledge elicitation, knowledge representation, knowledge coding, system validation, verification and evaluation.

Keywords: Expert system, plastic concrete, imperfections, rigid pavements

1.0 INTRODUCTION

An expert system is a computer program that uses knowledge instead of data to solve problems. An expert system development team is led by a knowledge engineer and includes a domain expert and end user. The role of the knowledge engineer is to build the system by acquiring knowledge from written sources and from the domain expert. During the knowledge acquisition stage, the knowledge engineer works with the domain expert to acquire, classify and analyse the knowledge. The knowledge engineer codes the acquired knowledge in a classified form to construct a computer system using a programming tool. The constructed system is tested and evaluated by the end user, who is the third member of the team [1-2].

In the domain of concrete mix design, Clifton [3] developed an expert system prototype called DURCON for the selection of constituents for durable concrete. It covers four major deterioration problems, namely freezing and thawing, corrosion of reinforcing steel, sulphate attack and alkali–aggregate reactions. Data on DURCON was acquired from the American Concrete Institute's "Guide to Durable Concrete" via members of the ACI Committee 201. Smith [4] developed a rule- and frame-based expert system called COMIX that offers recommendations on the design of normal weight concrete mixes. It was developed to provide expert knowledge to concrete technologists, design engineers and consultants. In COMIX, the mix design is based on the New Zealand Guide to Specifications for Concrete [5].

Malasri and Maldonado [6] developed Concrete Mix Designer, a prototype rule-based expert system. The system provides the proportions for a trial concrete mix and is useful particularly for practising engineers. However, the main limitation of the system is that it was developed only for normal weight concrete with a strength ranging from 17 to 35 MPa without using any admixture.

Akhras and Foo [7] developed EXMIX, a rule-based, goal-driven knowledge-based system for proportioning normal concrete mixtures. It selects proportions of mixing water, cement and aggregates while taking the effects of air-entraining admixtures and moisture conditions of aggregates into consideration. EXMIX was developed in accordance with CSA A23.1-M90 (Canadian Standards Association 1990) and ACI 211 1-89. A rule-based expert system called CONCEX was developed by Bai and Amirkhanian [8] to assist the user in concrete mix design, including making necessary adjustments to the design. The system can handle mix designs for normal, heavyweight and lightweight concrete. Aside from workability, consistency, strength, durability and density, the expert system considers other criteria such as admixtures, transportation and air temperature that affect the concrete mix design. The selection of concrete proportions by the system compared favourably with that of the experts.

Zain *et al.* [9] developed the High-Performance Concrete Mix (HPCMIX) design system for the mix design of high-performance concrete. HPCMIX can select the proportions for mixing water, cement, supplementary cementitious materials, superplasticizer and aggregates, considering the effects of air content and water contributed by the superplasticizer and the moisture conditions of aggregates. Aside from proportioning concrete mixes, HPCMIX offers recommendations on the adjustment of mix performance. Zain *et al*. [10] developed an expert system for concrete mix design called SRCA. It is similar to HPCMIX because it was developed by the same team, uses the same concepts and depends on the same sources of knowledge, i.e. relevant published research and human expertise acquired from Malaysian experts in the domain of concrete technology. However, SRCA is helpful to improve concrete quality under a sulphate environment by reducing mistakes in selecting concrete components.

In the domain of rigid pavements, Shahin [11] developed a knowledge-based decision support system called PAVER for pavement management. PAVER was developed to optimise the use of funds allocated for rigid and flexible pavement maintenance and rehabilitation. The Pennsylvania Department of Transportation developed and implemented a pavement management system called 'Systematic Technique to Analyze and Manage Pennsylvania's Pavements' (STAMPP). STAMPP provides visual condition survey information on the highway pavement (rigid and flexible) [12]. A knowledge-based expert system called Expert System for Pavement Evaluation and Rehabilitation (EXPEAR) was developed by Hall *et al*. [13] for the Federal Highway Administration, which was further developed for the Illinois Department of Transportation. The system uses information provided by experienced paving engineers to identify the type and general causes of deterioration in jointed plain concrete pavement (JPCP), continuously reinforced concrete pavement (CRCP) and jointed reinforced concrete pavement (JRCP), select rehabilitation techniques and strategies to effectively correct existing deterioration and prevent its recurrence and predict the performance of rehabilitation alternatives.

Several expert systems have been developed in transportation engineering. Alshawi and Cabrera [14] developed an expert system called PAVEMNET EXPERT in the United Kingdom to assist inspectors and engineers in condition assessment and field observation of rigid pavements. The system was established for rigid pavements but can be extended to include flexible pavements. Seiler [15] developed the Airfield Pavement Consultant System (AIRPACS) for rehabilitating airfield rigid pavements. It focuses on the functional, structural, operational and safety aspects of the airfield system. Seongdong [16] developed a prototype called ESPRESSO, which stands for Expert System for Pavement Maintenance and Rehabilitation Strategies in State of Ohio. ESPRESSO was developed using an expert system shell named Level5 Object, tested by knowledge engineers and evaluated by independent experts in the Ohio Department of Transportation. A knowledge-based system called Pavement Management Advisory System (PMAS) was developed by Hanna *et al*. [17] in Newfoundland, Canada, where the system is used in selecting appropriate maintenance strategies for both flexible and rigid pavements in cold regions. Three types of surface distresses are considered in the PMAS system: alligator cracking, transverse cracking and rutting. The system uses several factors such as surface condition, riding comfort index, traffic volume and climate in selecting and recommending rehabilitation strategies.

Meanwhile, Tsao *et al*. [18] developed a rule-based vision system that allows the evaluation of concrete distress in pavements without the need for human interaction. The knowledge base of this system contains facts and rules that pertain to prominent features of different types of distress. The reasoning procedure is performed by gathering information on the input image and then deciding on the most effective sequence of image processing operations. Kaetzel *et al*. [19] developed HWYCON to assist highway department personnel involved in diagnostics, material selection and repair and rehabilitation activities to make better decisions on concrete structures including pavements. The concrete materials component of the knowledge base in HWYCON gives recommendations on selecting materials for the design of durable concrete in corrosive, sulphate, freeze-thaw and alkali–aggregate reactive environments. Dhitivara [20] developed a hybrid KBES called Expert System for Designing Asphalt Concrete Mixture Containing Waste Materials and By-products (EXDAW). It is useful in designing asphalt concrete mixtures which contain reclaimed asphalt pavement, reclaimed aggregate material, crumb rubber modifier, mineral filler and conventional asphalt concrete mixture. EXDAW was developed based on the Marshall Hot Mix Asphalt (HMA) mixture design concept. Wanyan *et al*. [21] developed the Expert System for Pavement Remediation Strategies (ExSPRS) to assist road engineers in the domain of pavements on expansive clays with a high plasticity index (PI). ExSPRS allows engineers to evaluate and improve road design to allow more rehabilitation miles with the same amount of funding and fewer future distress problems. Mansyur [22] developed the Expert Advisory System for Selection of Implementation Strategies for Transportation Management Demand (E-ASSIST). The process of organizing available knowledge on transportation management demand strategies as well as the process which leads to the selection of one or more recommended strategies is encoded in the KBES shell developed by using Kappa-PC version 2.4, which adopts an object-oriented and high-resolution graphical user interface. The strategies recommended by E-ASSIST were evaluated and validated by comparing the system output against the recommendations made by transportation professionals. The evaluations indicate favourable results for the system.

Construction of a highway system as a part of public infrastructure is a significant way for any country to improve its economy [23-24]. Transportation in developing countries typically depends on a road network rather than on other modalities. Therefore, there is high demand for construction of high-quality, durable, smooth new roads to connect city centres with the new expanding districts and other locations [25]. Pavement can be considered the most critical part of highway construction [26-27]. However, very little research on pavements, especially rigid pavements, has been conducted compared to flexible pavements [28], but research on this topic is still in great demand [29].

Rigid pavement is a concrete slab supported by a roadbed [30-32]. Imperfections in plastic concrete can reduce pavement strength and durability, which leads to severe deterioration in the pavement surface and structure and subsequently reduces its serviceability. Maintenance of such deterioration requires cost, time and efforts as well as obstructing the highway under maintenance and interrupting the traffic. Avoidance of imperfections in plastic concrete prevents several types of failure in rigid pavement. Therefore, preventive measurements should be adopted during concreting. However, if such imperfections occur, corrective actions should be applied to prevent pavement deterioration. In addition, if concrete imperfections are diagnosed after concreting, the surface and structure of the pavement must be tested and evaluated and corrections made to defective parts. The nature of these problems is suitable for representation in a rule-based expert system environment, as they require diagnosing and solving. Nowadays, employing expert systems is a common problem-solving technique in many fields of civil engineering [30]. Through the literature review previously described, a number of expert systems have been developed in the domain of concrete mix design, rigid pavement maintenance and rehabilitation, and other transportation engineering fields. However, no such expert system has been developed in the proposed domain to cover the deterioration of rigid pavements due to plastic concrete imperfections. Ismail *et al*. [33-34] performed a literature review in the domain of pavement management; however, the review includes no expert system in the proposed domain. Therefore, the development of an expert system that covers concrete imperfections and their effect on rigid pavement quality will help engineers to avoid domain problems and manage them if they occur.

2.0 DEVELOPMENT OF THE SYSTEM

2.1 Knowledge Elicitation and Analysis

Knowledge elicitation involves obtaining and classifying expertise from miscellaneous sources [35]. Knowledge elicitation is complicated and time consuming [36-37], especially for a knowledge-based expert system which requires specific analysis techniques [38].Knowledge elicitation begins with reviewing written sources in the study domain. Additional knowledge can be elicited from human experts. The elicited knowledge can be combined, studied and analysed repeatedly [30].

To construct the initial knowledge base in the study domain, a vast literature review was performed. Subsequently, six domain experts were consulted about their knowledge. There are two key criteria for a domain expert: the length of experience and the conditions in which the expertise is gained (theoretical and/or practical) [39]. Based on such criteria, the experts were chosen. The knowledge was elicited from three experts by interview and questionnaire, from two experts by interview and from one expert by questionnaire. The knowledge engineer concentrated on concrete imperfection identification, diagnostic procedures, their effects on pavement quality and the remedies for these imperfections as well as corrective actions for the defective parts of rigid pavements. This stage also includes the identification of reasons for imperfections and preventive measures to avoid them. The main concrete imperfections in rigid pavement are shown in Table 1. Meanwhile, Tables 2 and 3 summarise the remedies for concrete imperfections and pavement deterioration respectively.

Table 1 Effects of concrete imperfections on rigid pavement quality

<table>
<tr><th>Problems in pavements' quality</th><th colspan="12">Indicators</th></tr>
<tr><th></th><th>A</th><th>B</th><th>C</th><th>D</th><th>E</th><th>F</th><th>G</th><th>H</th><th>I</th><th>J</th><th>K</th><th>L</th></tr>
<tr><td>Fibre balls appear in mixture</td><td>x</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>x</td><td></td><td></td></tr>
<tr><td>Open (unsealed) concrete surface behind paver</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td></td><td></td><td>x</td><td></td><td></td></tr>
<tr><td>Tearing of concrete through paver</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td>x</td><td></td><td>x</td><td>x</td><td></td></tr>
<tr><td>Appearance of vibrator trails in pavement</td><td></td><td></td><td></td><td></td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td>x</td><td></td></tr>
<tr><td>Slab edge slump</td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td></td><td></td></tr>
<tr><td>Pavement honeycombing</td><td>x</td><td></td><td>x</td><td></td><td></td><td>x</td><td>x</td><td>x</td><td></td><td>x</td><td>x</td><td></td></tr>
<tr><td>Plastic shrinkage cracking at pavement surface</td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td>x</td><td></td><td>x</td><td></td><td></td><td>x</td></tr>
<tr><td>Map cracking (craze cracks)</td><td></td><td></td><td></td><td></td><td></td><td></td><td>x</td><td></td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Transverse and oblique cracks within the panel</td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Random longitudinal cracks within the panel</td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Corner crack (break at panel corner)</td><td></td><td>x</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Random transverse cracks at or near transverse joint</td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td>x</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Random longitudinal crack at or near longitudinal joint</td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Crack in front of saw during joint cutting</td><td></td><td>x</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Appearance of clay fractions at pavement surface</td><td>x</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Pop-outs at pavement surface</td><td>x</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Surface scaling</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td></td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Surface dusting</td><td></td><td>x</td><td>x</td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td></td><td>x</td><td>x</td></tr>
<tr><td>Concrete surface blistering</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>x</td><td></td><td></td><td>x</td></tr>
<tr><td>Efflorescence at pavement surface</td><td>x</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>x</td><td></td><td></td><td></td></tr>
<tr><td>Colour variation at pavement surface</td><td>x</td><td></td><td></td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td></td><td></td><td></td></tr>
<tr><td>Improper surface texture</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Surface irregularity (rough surface)</td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td>x</td><td>x</td><td></td><td></td><td>x</td><td></td></tr>
<tr><td>Transverse slope misalignment</td><td></td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Concrete disruption around the wet formed groove</td><td></td><td></td><td></td><td></td><td></td><td>x</td><td>x</td><td>x</td><td></td><td>x</td><td>x</td><td>x</td></tr>
<tr><td>Joint ravelling</td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td></td><td></td><td></td><td></td><td></td><td>x</td></tr>
<tr><td>Joint spalling</td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td></td><td></td><td></td><td>x</td><td></td><td>x</td></tr>
<tr><td>Slow concrete strength gaining</td><td>x</td><td>x</td><td></td><td></td><td></td><td>x</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Final concrete strength is less than the requirement</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td></td><td>x</td><td>x</td><td>x</td><td></td></tr>
</table>

A. Poor quality of raw materials, B. Concrete temperature does not comply with the requirements, C. Concrete density does not comply with the requirements, D.Air content does not comply with the requirements, E.Variable air content, F.Slump is out of specifications, G.Rapid slump loss, H.Concrete mixture is sticky, I.Concrete bleeding problems, J.Concrete mixture segregation, K.Concrete sets rapidly, L.Delayed setting of concrete

Table 2 The remedies for concrete imperfections

<table>
<tr><th>Imperfections</th><th colspan="3">Conditions</th><th>Remedies</th></tr>
<tr><td rowspan="3">(A) Poor quality of raw materials</td><td colspan="3">The problem is within the acceptable limits</td><td>Neglect the problem</td></tr>
<tr><td colspan="3">The problem is out of the acceptable limits and it can be remedied</td><td>Remedy as suitable</td></tr>
<tr><td colspan="3">The problem is out of the acceptable limits and it cannot be remedied</td><td>Reject the materials</td></tr>
<tr><td rowspan="6">(B1) Concrete temperature is less than the minimum</td><td colspan="3">After Placing</td><td>Record/perform additional samples for testing</td></tr>
<tr><td rowspan="5">Before Placing</td><td rowspan="3">Hauling by agitating truck</td><td>Sufficient time Sufficient number of revolutions</td><td>Revolve the concrete to increase its temperature</td></tr>
<tr><td>Sufficient time Insufficient number of revolutions</td><td>Delay concrete placing to increase its temperature</td></tr>
<tr><td>Insufficient time Insufficient number of revolutions</td><td>Reject the load</td></tr>
<tr><td rowspan="2">Hauling by non-agitating truck</td><td>Sufficient time</td><td>Delay concrete placing to increase its temperature</td></tr>
<tr><td>Insufficient time</td><td>Reject the load</td></tr>
</table>

(B2) Concrete temperature is more than the maximum	Before Placing			Reject the load
	After Placing			Record/perform additional samples for testing
(C) Concrete density does not comply with the requirements	Before placing	Project's requirement considers concrete density		Reject the load
	Before placing	Project's requirement does not consider concrete density		Check air content
	After Placing			Record/perform additional samples for testing
(D1) Air content is more than the required				Follow the procedure for (B2)
(D2) Air content is less than the required				Increase the air content by procedure in Figure 1
(E) Variable air content	Within the requirements			Apply preventive measures
	Out of the requirements			Apply procedures for (D)
(F1) Slump is less than the required	After Placing			Record/perform additional samples for testing
	Before placing	Hauling by agitating truck	Sufficient time Sufficient number of revolutions Superplasticizer admixture available before placing	Increase the slump by procedure in Figure 1
			Sufficient time Sufficient number of revolutions Superplasticizer admixture unavailable before placing	Increase the slump by adding 4.95 litres of water for each cubic metre of concrete and agitate for 30 revolutions at 18 rpm. Test the concrete again to make decision. Prepare additional samples for strength testing.
			Insufficient time OR Insufficient number of revolutions	Reject the load
		Hauling by non-agitating truck		Reject the load
(F1) Slump is more than the required Concrete temperature is less than the minimum	After Placing			Control edge slump Record/perform additional

				samples for testing
	Before Placing	Hauling by agitating truck	Sufficient time Sufficient number of revolutions	Revolve the concrete to decrease its slump
			Sufficient time Insufficient number of revolutions	Delay concrete placing to decrease its slump
			Insufficient time Insufficient number of revolutions	Use the load
			Specifications do not state concrete rejection due to slump problems Concrete is placed by fixed-form paver	Record/perform additional samples for testing
			Insufficient time Insufficient number of revolutions Specifications state concrete rejection due to slump problems	Reject the load
		Hauling by non-agitating truck	Sufficient time	Delay concrete placing to decrease its slump
			Insufficient time	Use the load
			Specifications do not state concrete rejection due to slump problems	Record/perform additional samples for testing
			Concrete is placed by fixed-form paver Insufficient time Specifications state concrete rejection due to slump problems	Reject the load
Rapid slump loss				Apply preventive measures Increase labour and machinery efforts to complete concreting as soon as possible
Concrete mixture is sticky				Apply preventive measures
Concrete bleeding problems	Excessive bleeding			Delay surface finishing until bleeding has stopped and when bleed water has evaporated

	Little or no bleeding	Apply precautions to avoid plastic shrinkage cracking
Concrete mixture segregation		Make investigations for honeycombing and concrete strength and take suitable actions accordingly
Concrete sets rapidly		Apply preventive measures Increase labour and machinery efforts to complete concreting as soon as possible Apply precautions to avoid cracking Saw-cut the joint as soon as possible
Delayed setting of concrete		Apply preventive measures Apply precautions to avoid cracking Saw-cut the joint as soon as possible

Table 3 The remedies of pavement deteriorations

Problems	Remedies
Fibre balls appear in concrete surface	Apply the preventive action to avoid the problem If there is a reduction in concrete strength, apply the solutions If plastic shrinkage cracking occurs, apply the solutions described
Pavement surface does not close behind paver	Form defective part Fill the low spots with plastic concrete Vibrate the concrete properly and carefully Float the surface by mechanical longitudinal float or long-handled float Check the surface with a 3 to 6m hand-operated straightedge
Tearing of concrete through paver	Float the surface by mechanical longitudinal float or long-handled float Check the surface with a 3 to 6m hand-operated straightedge Apply the preventive actions to stop the problem
Appearance of vibrator trails on pavement surface	Apply petrographic examination procedures to decide
Edge slump	Before concrete setting: rectify manually behind paver After concrete setting: rectify by diamond grinding after concrete hardening If the problem can be rectified, remove the defective part
Pavement surface honeycombing	Slight honeycombing in plastic concrete: rectify by floating and straight-edging Severe honeycombing in plastic concrete: form the area and rectify by floating and straight-edging If the problem was diagnosed after concrete hardening, apply the following: • If edge was honeycombed after removal of the forms, repair all the honeycombed areas • If the surface is slightly honeycombed (small holes less than 20 mm in diameter), rectify by diamond grinding. • If the surface is severely honeycombed (holes with diameter 20 mm or more), remove and reconstruct the defective slabs. • If deep honeycombing, cut cores and perform strength investigations

Plastic shrinkage cracks	Before concrete setting: form the defective part, re-vibrate the concrete to close the cracks and finish the concrete surface After concrete setting: take cut must be cut across cracking and consider the following conditions: 1. If hairline cracks, neglect the problem. 2. If the crack is intermediate (not more than 75 mm in depth, not more than 3 mm in width, not continuous and does not reach the slab edge), seal the cracks with waterproof expansive cement slurry or repair by injecting low viscosity epoxy or high molecular weight methacrylate into each crack 3. If the cracks are severe, deep or extensive (more than 75 mm in depth, more than 3 mm in width, continuous, or reach the slab edge), remove and reconstruct the defective panels
Craze cracks within the bay (map cracking)	Remove craze cracking by diamond grinding
Transverse and oblique cracks within the bay	Only one non-working crack in panel: reface the crack's sidewalls with diamond saw and seal it More than one crack in panel or working crack (displacement along crack): remove panel
Longitudinal crack within the bay	Only one non-working crack in panel: reface the crack's sidewalls with diamond saw and seal it More than one crack in panel or working crack (displacement along crack): remove panel
Corner crack (crack at the corner of the bay)	Remove the panel
Transverse crack near transverse joint	Remove the panel
Longitudinal crack near longitudinal joint	Remove the panel
Crack in front of saw during joint cutting	Stop joint sawing and resume it after concrete gains sufficient strength (within sawing window) using light saws (early-entry saws or Handel saws). Where cracks have formed below initial saw cuts, increase the width of sawn groove by an amount equal to the width of the crack.
Appearance of clay fractions at pavement surface	*If the voids are few (2 or less balls per square meter) and small (less than 50 mm in size), neglect the problem.* If the voids are few but large (50 -100 mm in size), repair them using the clay balls repair procedures. In both cases above, perform visual test on cores cut from defective area to ensure that the problem has not extended deeply and the strength is not affected, or apply non-destructive test. *If the balls are large and very deep (within the lower third of the pavement as detected by visual testing for the core specimens) or covering a significant portion of the affected panels (5% of panel area or more), remove and reconstruct the defective panels.*
Pop-outs at pavement surface	*If voids are few (two or fewer balls per square metre) and small (less than 50 mm in size), neglect the problem* If voids are few but large (50-100 mm in size), repair them using the clay balls repair procedures
Concrete surface scaling	*If voids cover a significant portion of the affected panels (5% of panel area or more), remove and reconstruct the panels* If the scaling is less than 20 mm in depth, rectify by diamond grinding; otherwise remove and reconstruct the scaled panels
Concrete surface dusting	Slight dusting: neglect the problem Moderate dusting: sandblast, shot blast or use a high-pressure washer to remove the surface layer then apply a chemical surface hardener Severe dusting: rectify by diamond grinding, followed by applying surface hardeners Very severe dusting: remove and reconstruct the defective area
Concrete surface blisters	If blisters form during finishing, flatten the trowel blades or tear the surface with a wood float and delay finishing as long as possible. If the blisters have been diagnosed after concrete hardening and they are covering a significant portion of the affected panels (more than 10%), rectify the surface by diamond grinding; otherwise neglect the problem.
Pavement surface bumps	If there are odd low areas (depressions) that cannot be corrected by diamond grinding as they are relatively deep (about 30 mm or more), remove and reconstruct the panel containing such depressions If the smoothness of any lot is less than required, rectify by diamond grinding
Transverse slope misalignment	If the misalignment is less than 3 mm in 3 m, neglect the problem If the misalignment is 3 mm or more in 3 m, correct the misalignment by diamond grinding If the required correction is more than 20 mm, remove and reconstruct the defective panels
Concrete surface marring (mortar wearing away)	Rectify the surface by diamond grinding

Colour variation at pavement surface	Check the strength by testing cores from the suspected area. If the strength is within the required limits, neglect the problem
Efflorescence	Apply petrographic examination to ensure that the concrete is durable. If examination proves that the concrete is not durable, remove and reconstruct the defective area; otherwise, rectify by the following procedures: Light efflorescence: remove by dry brushing, water rinsing with brushing, light water blasting or light sandblasting, followed by flushing with clean water Severe efflorescence: remove by washing the surface with a dilute solution
Disruption of concrete around the wet formed groove	If the problem has been diagnosed before concrete setting, correct by distributing the concrete humps using a 3-metre straightedge If the problem has been diagnosed after concrete setting, correct the hardened surface by diamond grinding
Ravelling along joints	If the problem has been diagnosed during sawing, stop sawing and resume after the concrete obtains sufficient strength within the sawing window. Use early-entry saws to perform the first saw cut If the problem has been diagnosed late (after sawing), apply the following: • Slight ravelling (10 mm or less in dimension): neglect the problem. • Moderate ravelling (10-30 mm in dimension): correct the ravelled parts by the second saw cut by widening the joint groove as wide as necessary. If the problem has not been solved entirely, apply diamond grinding to make the surface smoother • Severe ravelling (30-300 mm in dimension): rectify by the partial-depth repair technique using the concrete mixture used for paving • Very severe ravelling (more than 300 mm in dimension): remove and reconstruct the slab. The type of ravelling is considered to be spalling
Spalling along joints	Remove and reconstruct the defective panels
Slow concrete strength gaining	Protect concrete, continue curing, do not open pavement to traffic
Final concrete strength is less than the required	If the 28-day compressive strength test result is out of the specifications (less than the minimum acceptable by the project documents and based on standard criteria), consider the following: • If it is not less that the design strength (specified by the designer during the structural design process), accept the lot and apply the suitable price deduction • If it is less than the design strength, cut representative cores from the pavement slab in the field in accordance with ASTM C42 or AASHTO T24 to evaluate the lot. Test the cores and specify the compressive strength (based on standard criteria), then consider the following: o If the strength of the cores is not less than the design strength, accept the lot and apply the suitable price deduction o If the strength of the cores is less than the design strength, apply redesign procedure

2.2 Knowledge Representation

To use acquired knowledge, the knowledge is represented symbolically to be manipulated in an automated manner by expert system reasoning. Therefore, the implementation environment of the system must be selected prior to the selection of the knowledge representation method [40]. In this study, Visual Basic (VB) was selected to develop the proposed system because it offers ease of use, which is a requirement of the user interface. In addition, VB enables the visualisation of the logic structure of rules in a knowledge base and writes rules in a simple syntax in a natural mathematic language [41]. Expert system tools range from high-level programming languages to low-level expert system shell. The proposed system in this study is an expert system to detect problems and guide users through the diagnostic process. Knowledge of these problems can be represented in the form of rules. In addition, Visual Basic is suitable for rule representation. Therefore, a rule-based system can be considered as the most suitable option. When problems arise, experts need to collect information regarding the issue and then make a decision. Therefore, a forward-chaining inference engine (which is data driven) is suitable for knowledge representation in a rule-based expert system. This procedure works in accordance with the facts in the knowledge base towards the goal or conclusion [42]. Reasoning originates from the given information and then proceeds with it. This approach depends on IF-THEN relationships. That is, if the IF condition is matched in a rule, the action in its THEN part shall be applied. This process can be modelled as IF (condition) THEN (conclusion) [43-44]. Two or more rules can be logically connected by connection terms AND, OR and ELSE to form the combined rule. The connection of combined rules can produce composite rules. Classified knowledge, which represents the core of the proposed system, was prepared in the form of rules coded in a computer environment. The following examples clarify the representation of the knowledge by the rules:

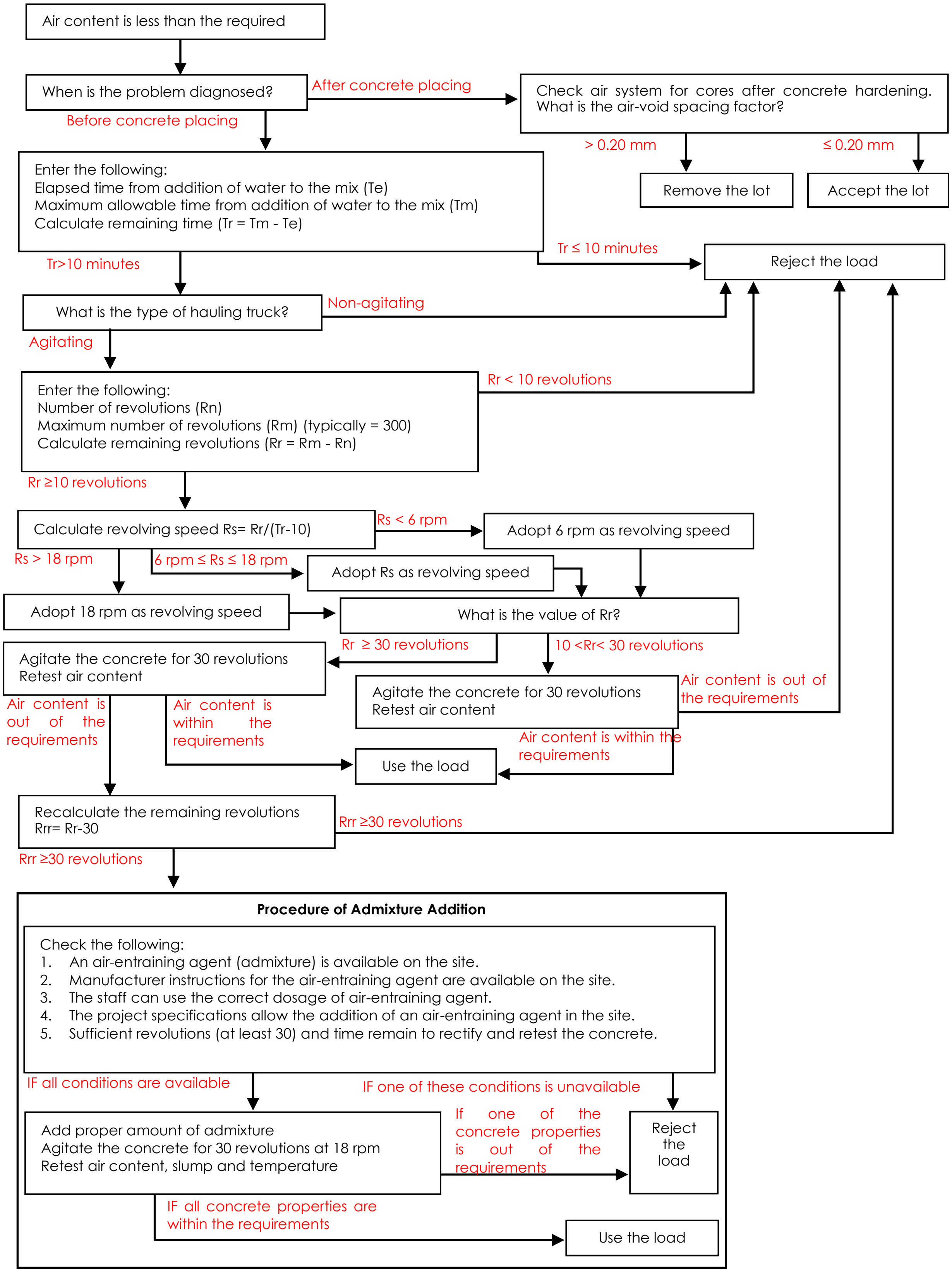


Figure 1 Remedies for low air content in concrete including admixture addition procedure

i. Example 1: Single Rule

IF (a corner crack was diagnosed in a panel) THEN (replace the panel)

ii. Example 2: Two Rules Combined by OR

IF (two or more cracks were diagnosed in a panel) OR (the panel is divided into more than two pieces) THEN (replace the panel)

iii. Example 3: Two Rules Combined by AND

IF (a transverse crack was diagnosed in a panel) AND (a visible vertical displacement is present along the crack) THEN (replace the panel)

iv. Example 4: Multiple Rules Combined by AND

IF (plastic shrinkage cracking was diagnosed) AND (the problem occurred before concrete setting) AND (the cracks are shallow) AND (the cracks are narrow) AND (slip form paving is used) AND (the area under construction is limited or small) THEN (remedy the problem by troweling before concrete setting)

v. Example 5: Composite Rule

[IF (retarder was used in the concrete) AND (32 °C > concrete temperature > 27 °C) AND (32 °C > air temperature > 27 °C)]
OR
[IF (no admixtures were used in concrete) AND (concrete temperature < 27 °C) AND (air temperature < 27 °C) AND (the concrete is hauled by an agitating truck) AND (agitator was on dynamic mode during hauling)]
THEN (maximum allowable time for hauling concrete = 90 minutes)

2.3 Validation of Represented Knowledge

The represented knowledge was validated based on the opinions of two domain experts who did not participate in the knowledge elicitation process. The knowledge contained in the system and knowledge of the experts involved in the validation process was highly compatible. This can be seen in Table 4, where the levels of acceptance were 86% and 93% for Expert 1 and Expert 2 respectively. The system was then operated by four experts to validate its content. The system was found to be valid to an acceptable level, as the scores were equal to or more than 4 on the 5-point Likert scale, as shown in Table 5.Typically, system validation is performed by human experts. For example, Mansyur [22] validated the E-ASSIST system against human expert opinions. The average matching percentage was 69%. In this study, a high level of validity is found, as the average level of acceptance is 89.5% (Table 4) and more than 80% (Table 5).

Table 4 Evaluation by two experts of knowledge contained in the system

Module		Expert 1	Expert 2
Module 1	Effects of bad conditions on concrete	64 %	77 %
Module 2	Imperfections of plastic concrete	69 %	86 %
Module 3	Imperfections in plastic pavement surface and edge	90 %	100 %
Module 4	Early-age cracking in rigid pavement	100 %	100 %
Module 5	Imperfections hardened pavement surface and edge	100 %	100 %
Module 6	Imperfections of joints	90 %	94 %
Module 7	Structural deficiency in rigid pavement	100 %	100 %
Overall		86 %	93 %

Table 5 Evaluation results of the system by four domain experts

	Questions	Scores					
		1	2	3	4	5	Average
1	Data input is adequate for diagnosing				✓✓✓	✓	4.25
2	The system is helpful to provide the remedies				✓✓✓✓		4.00
3	The system is helpful to specify the causes of problems				✓	✓✓✓	4.75
4	The system is helpful to adopt preventive actions				✓	✓✓✓	4.75
5	The system is helpful to specify effects of problems				✓	✓✓✓	4.75
6	The explanations are useful			✓	✓	✓✓	4.25
7	Generally, I am satisfied with the system			✓	✓✓	✓	4.00

2.4 System Structure

The structure of the system consists of a graphical user interface, working memory, inference engine and knowledge base. The system's components work jointly to provide the user with fast, clear and efficient recommendations. The graphical interface is the only component that can be viewed by the user. Through the graphical interface, the user can input data and obtain recommendations. User inputs are contained in working memory via the interface. The inference engine uses inputs via the working memory as well as searching the rules in the knowledge base to match the problem description and provide recommendations. Interface windows were designed to be user-friendly, interactive and clear by using a variety of colours for background and texts. Changes in colours, fonts and other visual effects were used to draw the user's attention to some points. The interface window includes a number of components or controls such as frames, labels, text boxes, images, option buttons (radio buttons), checkboxes, command buttons, windows media player, adobe acrobat reader, combo boxes and message boxes. Each control was designed to perform a specific function. An example of an interface window is shown in Figure 2.

Figure 2 An example of the graphical interface

The working memory resembles a database of conventional programs. The contents of the working memory, sometimes called data structure, change with each problem situation, which makes it the most dynamic component of an expert system, assuming that it is updated. It monitors program status and contains a large amount of data for the given problem. In the proposed system, the working memory typically contains information on a particular instance of the problem addressed. The inference engine is the control mechanism that organises the problem data and searches the knowledge base for applicable rules. The inference engine reaches a conclusion by matching appropriate rules under a set of specific facts. Basically, the system's inference engine operates as follows: IF the premise of a rule is true, THEN the conclusion is true.

The system's inference engine obtains facts from working memory, which in turn obtains information from the user's input data. The user uses the graphical interface to easily feed the system with inputs by selecting options or typing values. When some data are missing, the inference engine cannot respond. However, it orders the interface to notify the user regarding the matter. Notification alerts have two forms, namely alerting by message box or by flashing screen. Either can be applied in accordance with the case. The user can obtain the results in the form of text, images and videos. In addition to reaching conclusions and executing actions, the inference engine can add or delete facts from the working memory.

The proposed system recommends solutions to domain problems and provides the user with probable causes, preventive actions and effects. The recommendations are in the form of text, figures, pictures and videos. Based on the author's knowledge, only this system provides videos to describe the problem and the solution. Other studies covered in the literature review did not refer to video input or output.

2.5 Expert System Verification

Informal and formal testing was conducted for system verification. Informal tests were performed to measure the development progress and to find errors or exceptions. For this type of testing, wide input data ranges were used to assess whether the test data are reasonable for the system. Formal testing, on the other hand, is requirement driven and is performed to verify that the system is ready for its intended use and to demonstrate that the system meets requirements. System verifications were performed prior to the completion of the system. During the development process, the uncompleted system was subjected to frequent informal testing. Whenever a new object (function, class, database, and so on) is developed, the system developer must perform informal tests by using wide test data ranges which aim to capture any error or exception from the newly developed component.

Unit testing involves testing the units one by one in separate testing activities [45]. This testing was continually performed during all stages of the system development to verify that each unit in the system performs its intended function. The internal structure of the system was checked by covering all possible combinations of constants, variables, relationships and source code paths. Errors were diagnosed during the testing process and corrected while the system was still under construction and before transforming it into an executable version. Integration testing was performed to verify that all units operate together as expected. To run the system, the user shall provide the required inputs. Input data are processed in the system to identify suitable recommendations. The interaction between the user and the system was tested. Interaction between the system and the user is illustrated in Figure 3.

Similar to unit testing, integration testing was periodically performed during system construction to verify its capability to execute the intended functions. System verification is performed to guarantee that when all components are put together, they will not produce any errors or exceptions, at least while using the test data ranges covered by the system. The executable version of the system was subjected to this type of testing. Hundreds of tests were performed to cover all possible cases and discover all aspects of the system. In some of these applications, input data were collected from literature. Results were then compared with related literature results.

As a verification step, Dhitivara [20] performed informal testing during system building and complete testing after the system was built. Mansyur [22] tested the nine scenarios included in E-ASSIST one by one and continued testing for sub-module response to verify the system. They debugged the system and corrected all coding errors as part of system verification. Deprizon *et al*. [46] applied several design calculation samples and compared the results with those obtained from manual design procedures; the results were 100% compatible. As previously mentioned, a number of verification methods were performed in the present study. Unit testing was performed during system building to ensure that each unit is functional. Similarly, integrated testing was performed during system building to ensure that all units work together. Debugging was performed to capture and correct any errors in the system code. All errors (syntax, runtime and logic errors) were captured and corrected. Several calculations with different inputs were applied in ES-CCPRP. The same inputs were applied manually. A number of calculation examples were obtained from the literature and applied in ES-CCPRP. The results obtained from ES-CCPRP were 100% compatible with those obtained from manual calculations and examples in the literature. Similarly, calculations of the case study represent another verification method. In addition, a new verification approach was adopted in this study. The system was verified by computer professionals through a questionnaire survey. The literature review did not find any studies that adopted this system verification method. Therefore, it is recommended that the application of this method by expert system developers as a means of evaluating the system interface and code by computer professionals is a good verification method. In addition, feedback from computer professionals can improve the expert system.

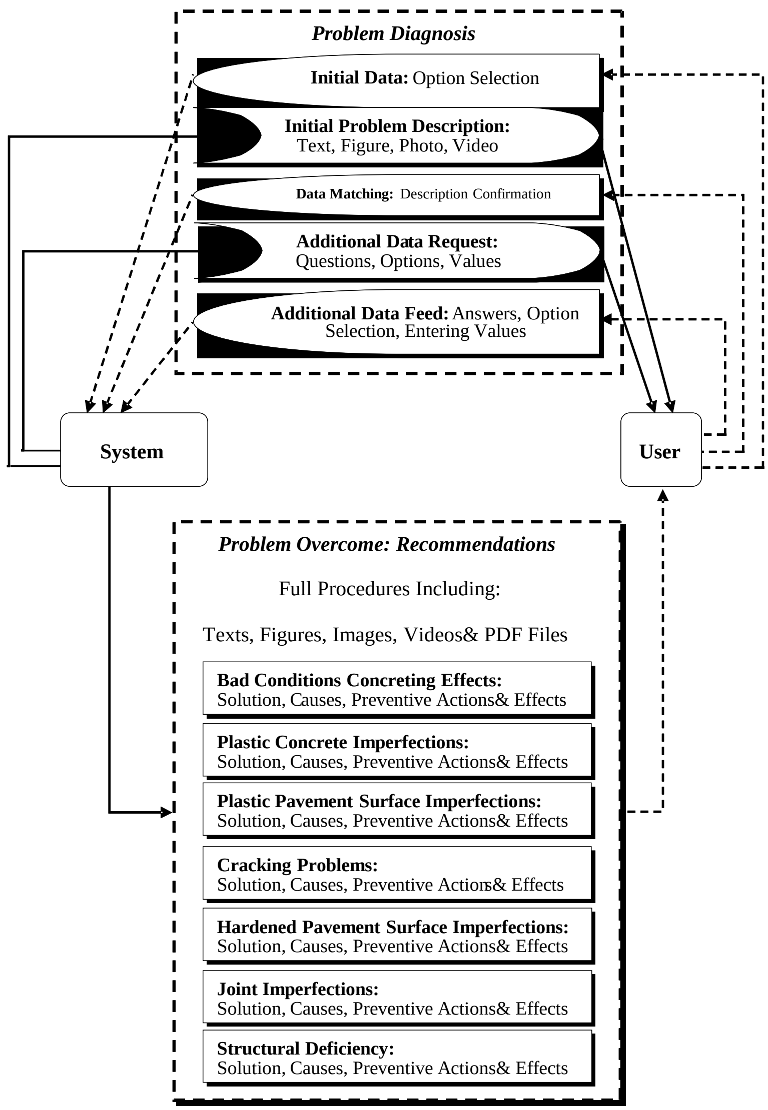


Figure 3 Interactions between user and the system

2.6 System Evaluation

A questionnaire survey was designed to test the satisfaction of different users with the system. Forty-five participants were involved in this stage, including four domain experts, 10 novice engineers, six lecturers in the study domain, 20 students from the department of civil engineering and five computer specialists. The participants evaluated the system by using the questionnaire described in Table 6.

The evaluation reflects their satisfaction through their high ratings (more than 3). The satisfaction of experts indicates that they positively evaluated the user interface; this result also verifies the system. Table 6 summarises the testing and evaluation of the system. The expert systems covered in the literature review were evaluated in similar ways. However, computer professionals, teaching experts and students were involved in this study. On the other hand, no such involvement by these kinds of users was found in the other studies covered in the literature review.

Table 6 Evaluation results of the system by different users

	Questions	Average	Standard Deviations
Q1	The system is easy to use	3.70	0.48
Q2	The system runs quickly	5.00	0.00
Q3	The user interface is user-friendly	4.20	0.79
Q4	The questions are helpful	4.50	0.53
Q5	Presentation of results is clear	4.10	0.53
Q6	Obtaining an explanation from the system is easy	4.30	0.42
Q7	Generally, I am satisfied with the system	4.50	0.57

3.0 CONCLUSION

This paper presents the development of an expert system for remedies for plastic concrete imperfections and their effects on rigid pavement quality to help practising engineers to troubleshoot in this domain. The knowledge was elicited from written sources by literature review and from human experts by interviews and questionnaires. The elicited knowledge involves the imperfections, their effects, their causes, preventive actions and their remedies. This knowledge was represented in the form of rules and coded in computer software using Microsoft Visual Basic. The graphical interface of the system is capable of guiding the user to input data easily and without mistakes. It provides output in the form of text, pictures and videos. The inference engine of the system simulates a human expert to match the correct rule from the knowledgebase based on the inputs. The system was verified and validated by extensive testing. The results of testing proved that the system is built correctly and can efficiently provide effective remedies for the users. The system also has a flexible and friendly user interface based on evaluation by 45 users with different backgrounds. In addition, it can be used as an archive to save the domain knowledge and to distribute highway engineers' experiences and transfer expertise to consecutive generations of engineers.

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