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# A decision support system for diagnosis of distress cause and repair in marine concrete structures

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**Abstract.** Marine Structures are very costly and need a continuous inspection and maintenance routine. The most effective way to control the structural health is the application of an expert system that can evaluate the importance of any distress on the structure and provide a maintenance program. An extensive literature review, interviews with expert supervisors and a national survey are used to build a decision support system for concrete structures in sea environment. Decision trees are the main rules in this system. The system input is inspection information and the system output is the main cause(s) of distress(es) and the best repair method(s). Economic condition, severity of distress, distress situation, and new technologies and the most repeated classical methods are considered to choose the best repair method. A case study demonstrates the application of the developed decision support system for a type of marine structure.

**Keywords:** marine structure; decision support system (DSS); expert database system (EDS); graphic user interface (GUI); cause of distress; decision tree; repair of distress.

## 1. Introduction

Concrete structures have a wide application in sea environment. The major types of these structures are piers, concrete breakwaters and concrete platforms. Piers are common types of concrete structures that are built on posts extending from land to water, used as a landing place for ships, an entertainment area, a strolling place, etc. Breakwaters are applied for the creation of harbor for a safe space in inshore. Some of them are built to refract the waves.

The offshore concrete structures for the oil and gas industry are located in various and very different parts of the world. There are structures in ice infested waters, in seismic zones and in very harsh marine environments, but also in relatively calm areas. Some are located at large water depth, others in shallow areas. The foundation conditions vary from very stiff sand to very soft clays, and some of the structures float permanently. Some of the structures have storage facilities, and all have a hydrocarbon processing plant facility of some kind. Such various conditions for the offshore concrete structure call for different designs. The offshore concrete structures behave very well, and perform their task of supporting the oil and gas processing facility. The oil companies are frequently evaluating the extension of operational life, and modifications to enable further facilities as the

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offshore field may contain additional hydrocarbons (Sandvik 2004).

Gravity-Concrete platforms are applied for petroleum extraction in a very rough sea condition such as North Sea. Although these types of platforms are made of high strength concrete, they cannot withstand all types of destruction and distresses appear on them. The type of distresses is a function of various parameters such as, the type of concrete, location of the platform, the functionality of the platform, the environmental condition such as the wave height and moisture content, the ocean depth and so on. Distresses may appear on the structure at various extents and severity.

An expert system is software that attempts to provide an answer to a problem, or clarify uncertainties where normally one or more human experts would need to be consulted. Expert systems are most common in a specific problem domain, and are a traditional application and/or subfield of artificial intelligence. A wide variety of methods can be used to simulate the performance of an expert, however, common to most or all are: (1) the creation of a knowledge base which uses some knowledge representation formalism to capture the Subject Matter Expert's (SME) knowledge, and (2) a process of gathering that knowledge from the SME and codifying it according to the formalism, which is called knowledge engineering. Expert systems may or may not have learning components but a third common element is that once the system is developed it is proven by being placed in the same real world problem solving situation as the human SME, typically as an aid to human workers or a supplement to some information system.

Expert systems were introduced by researchers in the Stanford Heuristic Programming Project, Edward Feigenbaum, PI, with the Dendral and Mycin systems. Principal contributors to the technology were Bruce Buchanan, Edward Shortliffe, Randall Davis, William vanMelle, Carli Scott and others at Stanford. Expert systems were among the first truly successful forms of AI software (McCorduck 2004, Russell 2003, Luger 2004). The topic of expert systems has many points of contact with general systems theory, operations research, business process reengineering and various topics in applied mathematics and management science.

One of the most powerful attributes of expert systems is the ability to explain reasoning. Since the system remembers its logical chain of reasoning, a user may ask for an explanation of a recommendation and the system will display the factors it considered in providing a particular recommendation. This attribute enhances user confidence in the recommendation and acceptance of the expert system.

Expert system decreases the importance of experts present in the site and a user with any level of information can use this system with the help of system information. Results of this survey are stored in the knowledge based on the availability of this data and reaction to them.

Expert Database System (EDS) is used in a number of different senses:

- A system forms the combination of an expert system with a database system.
- An expert system enhanced with database management facilities or a database system enhanced with a deductive component.
- An advanced database system employing new architecture for knowledge representation.
- Any system lying at the interaction of Artificial Intelligence (AI) and database work.

The Graphic User Interface (GUI) is a system of screens and dialog boxes through which the user interacts with the internal workings of the program. It enables the user to input the data required by the program and receive an output from the program.

A research based upon an evaluation management system (EMS) comprising a database management system (REPCON) alongside visualization technologies and evaluation system (ECON) was developed to produce an innovative platform which would facilitate and encourage the development of knowledge in educational, evolution and evaluation modes of concrete repair by Moodi (2010).

An expert system in flexible airport pavement maintenance and rehabilitation based on *KAPPA-PC* program package was introduced by Ismail *et al.* (2009). The knowledge acquisition in developing the system consisted of several modules that involved interviews with the domain expert and literature review from various literatures. This expert system was developed to help identifying the distress associated with airport pavements and structures, diagnose the cause of deterioration, recommend the rehabilitation treatment and provide information on costing.

Tarighat and Miyamoto (2009) introduced a fuzzy method to deal with the shortcomings from the uncertain data in inspection of structure. The fuzzy bridge deck condition rating method was practically based on both subjective and objective results of existing inspection methods and tools. The parameters of the model were selected as fuzzy inputs with membership functions found from some statistical data and then the fuzziness of the condition rating was calculated by the fuzzy arithmetic rules inherent in the fuzzy expert system.

Ramezanianpour *et al.* (2009) developed an expert system for diagnosis and evaluation of bridge deck structures. Due to structural and environmental effects, the diagnosis assessment of deck slabs was developed based on the cracking in concrete, surface distress and structural distress. Fuzzy logic was utilized to handle uncertainties and imprecision involved. The developed expert system would allow the correct diagnosis of concrete decks, realistic prediction of service life, determination of confidence level, the description of condition and the proposed action for repair.

Yehia *et al.* (2008) prepared a questionnaire form and asked the specialists to fill them out. They developed a decision support system for concrete bridge deck maintenance. They only took into account a few types of distress on their work and offered suitable repair methods for them. They considered corrosion of reinforcement, cracking and delamination and neglected other types.

A computer assisted crack diagnosis system for reinforced concrete structures which aids the non-expert to diagnose the cause of cracks at the level of an expert in the general inspection of structures was proposed by Kim *et al.* (2007). The system presented adapts fuzzy set theory to reflect fuzzy conditions, both for crack symptoms and characteristics which are difficult to treat using crisp sets. The inputs to the system were mostly linguistic variables concerning the crack symptoms and some numeric data about concrete and environmental conditions. Using these input data and based on built-in rules, the proposed system executed fuzzy inference to evaluate the crack causes under consideration.

A fuzzy based assessment system for reinforced concrete building structures which estimated the current state of buildings and presented a guide for future maintenance and management was proposed by Kim *et al.* (2006). The primary assessment categories included the state of building history, environmental conditions, structural capacity and durability. The assessment criteria were estimated based on visual inspection and simply measured data based on the given criteria.

A knowledge-based system used for maintenance planning of highway concrete bridges was proposed by Chassiakos *et al.* (2005). The system included functions for maintenance priority setting among bridges, feasible treatment assessment in each case and maintenance planning for a bridge stock. Maintenance priorities were set using a scoring model with decision parameters appropriately weighted. Feasible treatments were determined based on bridge condition and other factors that accelerate deterioration. Decisions for maintenance planning result from a linear programming model were based on priority ranking, cost and effectiveness characteristics of feasible treatments and existing budget constraints.

A program related to the concrete bridge rating expert system was developed by Moodi (2004). He proposed a knowledge-based system for repair and maintenance of structures by development of U.S. Army Corps of Engineers information. He also offered a suitable repair and maintenance solution for distresses.

It should be considered that an expert system must be comprehensive in the sense that it takes into account all types of distresses and their effects. A structure may loss its performance and functionality due to the neglecting some types of distresses and their effects. It is also vital to take into account the environmental conditions in which the structure is constructed. There are various decision support systems for inland structures. Their application without taking into account the differences with the marine structures may be misleading. The corrosive nature of sea, interaction between structure and different natural causes such as waves should be taken into account. Concrete distresses in sea have more destructive effects than other structures.

As an example, corrosion of reinforcement because of different factors such as Chloride attack, Sulphate attack, sea animates effects etc., has a different mechanism in comparison with land structures and consequently the associated distresses in sea have different values. Some types of distresses in land structures may be ignored while ignoring them in marine structures may cause severe damage. Therefore, it is evident that a special system must be used for marine structures taking into account all types of distresses.

Errors in design process, the external forces or the environmental effects are main causes of distresses for marine structures. The associated distresses are in the form of cracks, surface distresses and miscellaneous distresses. The experts are asked in the era of marine concrete structures to distinguish the different types of distresses and the main causes of them. The marine concrete structure experts have also been consulted to provide the most effective repair methods to fix the faults. Then two types of decision trees are developed. The first type is to relate the distresses with the cause of them. The second type of decision trees is to provide the best repair methods. These two types of decision trees are put in a computer codes. The codes are written in Microsoft Visual Studio 2007 software with a friendly graphical form. The input data are inspection information about the type of distresses that happen on the concrete structures. It is started with several questions from the user. Then based on the answers, this decision support system provides the cause of the distresses and proposes a suitable repair method. The decision support system also provides a number between 0 to100. This number shows a confidence level that indicates the level of trust to the response of the system. The Microsoft Access software is applied to save the output data.

## 2. Concrete structure distresses

Various factors may deteriorate concrete structures. These deteriorations cause different effects on the concrete surface. These effects indicate the type of the distresses. The distresses are classified into 3 main groups: cracks, surface distresses and miscellaneous distresses.

Cracks are divided into 8 groups as given in Table 1, according to (PCA 2001, ACI 2007). This classification is based on appearance and direction of cracks. These crack types have different origins but the most effective one is longitudinal cracks, but random cracks happen more than others on concrete surface.

Another type of concrete structure deterioration is surface distresses. They are classified into 15

Table 1 Classification of cracks in concrete and their associated causes covered by system

| | | |
|---|---|---|
| D-cracking | Definition | Progressive structural deterioration of the concrete beginning in certain types of susceptible coarse aggregate, caused by repeated freezing and thawing after absorbing moisture. |
| | Cause | Excessive force, freezing and thawing, frost attack. |
| Random and Multiple or irregulars over the surface | Definition | It shows several cracks in a reinforced concrete slab without any regular patten |
| | Cause | Ground movement, plastic shrinkage, different types of sulphate attack. |
| Diagonal | Definition | It is caused by loss of foundation support, base erosion and shear stresses, at about 45 degrees to the natural axis of a concrete member. |
| | Cause | Plastic shrinkage, shear forces, ground movement, foundation settlement, drying shrinkage, torsion forces, dead and live loads structural deformation, restraint to load deformation. |
| Pattern or map | Definition | It is fine openings on concrete surfaces in the form of a pattern. |
| | Cause | Unsuitable construction method, unsuitable materials, freezing and thawing action, different types of sulphate attack, plastic shrinkage, drying shrinkage, alkali-aggregate reactivity (AAR), different types of alkali- silica reaction (ASR), different types of alkali-carbonate reaction (ACR), frost attack, pressure of salt crystallization. |
| Crazing | Definition | It is fine and random cracking extending only through the surface. |
| | Cause | Interior tension, atmospheric carbonization, executing problem (improper curing…), climate condition (differential contraction, low humidity, air temperature, hot sun, drying wind). |
| Longitudinal and generally straight | Definition | It develop parallel to the long direction of the member. |
| | Cause | Different types of corrosion of reinforcement, plastic shrinkage, drying shrinkage, plastic settlement, alkali-aggregate reactivity (AAR), different types of alkali-silica reaction (ASR), different types of alkali- carbonate reaction (ACR), frost attack, different types of sulphate attack, creep, compression forces, early thermal contraction, pressure of salt crystallization |
| Transverse | Definition | Develop at right angles to the long direction of the member. |
| | Cause | An overloading condition in combination of dead and live loads, drying shrinkage, compressive stresses. |
| Cracks at joint, edge and opening | Definition | They are Cracks either at or in the vicinity of transverse and longitudinal joints e.g. within the length of dowel or tie bars or immediately adjacent to them. |
| | Cause | Different types of corrosion of reinforcement, lack of expansion joint, compressive failure (blow-up), poor joint construction, thermal expansion, poor load transfer, loss of subgrade, late sawing of joint, corner break, omission of bottom crack inducer, frost attack, different types of sulphate attack, alkali-aggregate reactivity (AAR), different types of alkali-silica reaction (ASR), different types of alkali-carbonate reaction (ACR), pressure of salt crystallization. |

groups as given in Table 2, according to (PCA 2001, ACI 2007). It should be noted that cracks are also kind of surface distresses, but they are usually classified in a separate group because of their importance and variety.

Many other distresses that may cause the impairment of concrete structures are known as

Table 2 Classification of surface distresses and their associated causes covered by system

| | | |
|---|---|---|
| Blister | Definition | Blister is hollow; low profile bumps on the concrete surface. |
| | Cause | Lack of vibration of concrete, poor design of formwork, unsuitable, unsuitable material, fast concrete surface covering, unsuitable troweling. |
| Dusting | Definition | Dusting is formation of powder or chalk at the surface of a concrete slab. |
| | Cause | Poor construction method such as sprinkling water on concrete surface during finishing, new timber formwork. |
| Bug holes and Honeycombing | Definition | Bug holes are voids formed during placement. Honeycombing is the formation of pockets of coarse aggregate during placement. |
| | Cause | Unsuitable construction method, lack of vibration of concrete, poor design of formwork, unsuitable mortar, unsuitable material. |
| Exudation or Stalactite | Definition | It forms on concrete, and on plumbing where there is a slow leak and limestone (or other minerals) in the water supply. |
| | Cause | Mineral material such as calcium oxide and limestone, different types of alkali-silica reaction (ASR). |
| Efflorescence | Definition | Efflorescence is a deposit of salts, usually white in color that occasionally develops on the surface of concrete. |
| | Cause | Poor construction method owing to very permeable concrete, chloride attack, unsuitable curing, dirty concrete, pressure of salt crystallization, dirty aggregate. |
| Delamination | Definition | A splitting, cracking, or separation of a cementitious material in a plane roughly parallel to, and generally near, the surface. Delamination generally affects large areas, and can often only be detected through nondestructive tests such as tapping or chain dragging across the surface. |
| | Cause | Different types of corrosion of steel reinforcement, high amount of moisture and chloride content, the presence of cracks in concrete surface, chloride attack |
| Discoloration | Definition | Gross color changes in large areas of concrete, spotted or mottled light or dark blotches on the surface, or early light patches of efflorescence. |
| | Cause | Poor construction method owing to very permeable concrete, chloride attack, unsuitable curing, dirty concrete, pressure of salt crystallization, dirty aggregate. |
| Spalling & Popout | Definition | Spalling is a process of detachment of a concrete fragment, usually in the shape of a flake, from concrete by the action of weather, by pressure or by expansion within the larger mass. Popout is conical fragment that breaks out of the surface of the concrete leaving a hole. |
| | Cause | Different types of corrosion of reinforcement, chloride attack, different types of sulphate attack, freezing and thawing action, frost attack, weak concrete surface, unsuitable construction method, generating sufficient stresses, alkali-aggregate reactivity (AAR), different types of alkali-silica reaction (ASR), different types of alkali-carbonate reaction (ACR), pressure of salt crystallization. |
| Joint related spalling or faulting | Definition | Faulting is a spall adjacent to a joint. |
| | Cause | Unsuitable construction method, foundation settlement, reinforcement rupture, weak compact concrete, unsuitable reinforcing. |
| Encrustation | Definition | Encrustation occurs when mineral salts are deposited on the surface of the catheter, both internally and externally. |
| | Cause | Different types of sulphate attack. |

Table 2 Continued

| | | |
|---|---|---|
| Abrasion & cavitation | Definition | Abrasion is an external condition only, which is caused by movement of an object or medium across the surface of the concrete, e.g. constant exposure to sea action. Cavitation occurs when high velocity waterflows encounter discontinuities on the flow surface. Discontinuities in the flow path cause the water to lift off the flow surface, creating negative pressure zones and resulting bubbles of water vapor. |
| | Cause | Inadequate construction method, environmental changes, poor abrasion resistance, chemical attack, poor quality of concrete, poor resistance of aggregate, ice erosion, sand storm, abrasion crack, pressure of salt crystallization, hydrostatic pressure. |
| Scaling, disintegration and removal of materials | Definition | Scaling is local flaking or peeling away of the surface layers of hardened concrete. |
| | Cause | Different types of corrosion of reinforcement, chloride attack, different types of sulphate attack, freezing and thawing action, frost attack, weak concrete surface, unsuitable construction method. |
| Pothole | Definition | Pothole is bowl-shape holes of various sizes in concrete pavement surfaces, which when fully developed, are larger than popouts. |
| | Cause | Localized poor concrete, poor consolidation of concrete. |

Table 3 Classification of miscellaneous distress and their associated causes covered by system (ACI 2007 and Moodi 2004)

| | | |
|---|---|---|
| Stain | Definition | Stain is an early sign of reinforcement corrosion. |
| | Cause | Different types of corrosion of reinforcement, Poor concrete. |
| Scouring and leaching | Definition | Scouring is excess water rising in the forms can produce stream-like patterns in the surface of the concrete. |
| | Cause | Poor choice of foundation location, meandering riverbed, inadequate flow area, inaccurate estimation of flood level and its speed, lack of scour prevention measures, improper sizes of riprap protection, improper designed riprap, dissolving water constitutes like calcium hydroxide at crack locations. |
| Dampness and leakage | Definition | Water and dissolved salts attack reinforcing steel, post tensioning tendons, and anchorages; thus they are greatly affecting the capacity of the structure. |
| | Cause | Poor mix properties used and inadequate construction method. |
| Pitting | Definition | It is the development of relatively small cavities in a concrete surface. |
| | Cause | Different types of corrosion of reinforcement. |
| Segregation, Bleeding, and Stratification | Definition | Segregation is the differential concentration of the components of mixed concrete, aggregate, or the like, resulting in non-uniform proportions in the mass. Bleeding channel is the autogenous flow of mixing water within, or its emergence from, newly placed concrete or mortar caused by the settlement of the solid materials within the mass which is also called water gain. Stratification is also the separation of overwet or overvibrated concrete into horizontal layers with increasingly lighter material toward the top. |
| | Cause | Careless in handling and placing concrete, inadequate curing, inadequate and over vibration |
| Temperature changes and Phase conversions | Definition | Phase changes which involved volume changes can cause disruption of concrete. Temperature rises particularly those that occur early, may be responsible for a great deal of early cracking in structures. |
| | Cause | Thermal expansion drying, thermal incompatibility, high temperature, used high alumina cement concrete (HACC) |

Table 3 Continued

| | | |
|---|---|---|
| Strucutral Related Distresses | Definition | Crack locations and directions are indicative of the nature of the structural deficiencies which are caused by overloading, poor construction, deterioration owing to environmental factors, inadequate design detailing, differential settlement of foundations and creep. |
| | Cause | Excessive distress in concrete, overloading beyond the design, poor construction method, environmental factors, deficiencies in shear strength, inadequate flexural strength, bond failure during shrinkage, strain increases with time, temperature changes, reduced internal stresses, impact, moisture. |
| Collapsed Member | Definition | Careless overloading can occur during construction or use, but the direct evidence may have been removed. |
| | Cause | Soil failure, surface rupture, earthquake loads, vessel impact, high temperature on structural materials, fire, wave, tide, tsunami |

miscellaneous distresses. Here, They are classified into 8 groups, according to (ACI 2007, Moodi 2004) as given in Table 3. This type does not deteriorate concrete surface, but they show unsuitable appearance on concrete surface.

## 3. Cause of distresses in concrete structures

Errors can be classified broadly into defect, damage and deterioration. Defects are usually impairments of a structure as a result of improper workmanship, unsuitable materials and unsuitable construction method. Defects often occur early in a structure's life and these impairments are revealed at the first investigation.

Damage is the impairment of a structure caused by external mechanical factors while a structure is in service. Wear and erosion, pounch-out, creep, shrinkage (drying, plastic, aggregate), temperature changes, explosion, overload, impact, ground movement, foundation settlement, earthquake, flood, fire and thermal incompatibility are the main causes of concrete damage.

Deterioration refers to the impairments of a structure due to the environmental condition and the structural weakness due to the improper design. Deterioration in a concrete structure can emerge in the event of structural weakness and usually influences concrete members after the structure has been completed and is in service. It demonstrates the common types of distresses in concrete structures. Deterioration appears in a slower process than defect or damage. They are classified into three categories: physical, chemical and combined physical-chemical causes. Physical causes are insufficient cover, scouring, aggregate D-cracking, joint deterioration, frost attack, differential thermal strains and incomplete curing. Sulphate attack, chloride attack (ingress), carbonation, de-icing salts, high chloride level of additives, soft water attack, sea water attack brine attack, and acidic attack are in group of chemical causes. Physical-chemical causes are freezing and thawing, corrosion of reinforcement, Alkali- Silica Reaction (ASR), Alkali-Carbonation Reaction (ACR) and Alkali-Aggregate Reaction (AAR). Sometimes, physical and chemical factors, both are interfaced to cause a main factor such as corrosion of reinforcement. Environmental factor and chemical material have roles to cause of corrosion of reinforcement.

## 4. Differences between the inland and marine structures

The marine environment has different nature in compared to the inland environment. The differences between these two environments should be specified to be able to design a proper decision support system. Several literatures such as USACE (1995, 1996) and Ramezanianpour (2006) are consulted to find out the differences.

The most important types of causes for structures are corrosion of reinforcement, Alkali reaction and sulphate attack that they briefly discussed.

### *4.1 Corrosion of reinforcement*

Corrosion of reinforcement is the main factor for the concrete structure deteriorations. For inland concrete structures, corrosion of reinforcement is happened due to oxygen in the air or insolvable in the water. There are several factors that may cause corrosion in marine environment. These are:

1-Corrosion of reinforcement due to Oxygen in the air or insolvable in the water.

2-Corrosion of reinforcement due to Chloride attacks in the water of marine.

3-Corrosion of reinforcement due to corrosive chemical materials such as $CO_2$ or $H_2S$.

4-Corrosion of reinforcement due to marine animals, soft bodies and plant attacks.

### *4.2 Alkali aggregate reaction*

Alkali reaction is divided into two groups: Alkali-Carbonate Reaction (ACR) and Alkali-Silica Reaction (ASR). The Alkali-Carbonate Reaction (ACR) is classified for marine structures as:

1-Alkali-Carbonate Reaction due to Carbonate/Dolomite aggregate.

2-Alkali-Carbonate Reaction due to soft body attack content Ammonium Carbonate.

3-Alkali-Carbonate Reaction due to unsolvable Aragonite in the water.

The Alkali-Silica Reaction (ASR) is happened in marine structure as follows:

1-Alkali-Silica Reaction due to silica aggregate.

2-Alkali-Silica Reaction due to hydrostatic pressure of marine water.

3-Alkali-Silica Reaction due to Ettringite and formation of $Mg\ (OH)_2$.

The first reaction in both ACR and ASR is usually happened for an inland concrete structure.

### *4.3 Sulphate attack*

The Sulphate attacks have also different nature in marine structures. They may be classified as:

1-Sulphate attack due to micro organism attacks

2-Sulphate attack due to $H_2S$ and its extension due to corrosion of reinforcement.

3-Sulphate attack due to a contact with petroleum reservoir and pipe.

These classifications are normally applied for marine concrete structures. All of distresses are taken into account to design the decision support system.

## 5. Producing decision trees to diagnose the cause of a distress

A support system should distinguish the cause of a distress and then provide a suitable repair method. To distinguish the cause of a distress, it is necessary to go through the following steps:

1. To specify the distresses;
2. To specify the cause of the distresses;
3. To create decision trees; these decision trees provide relationships between first and second items. Decision trees have a role such as human in a support system. They can distinguish cause of a problem by considering all of specifications.
4. Programming: put the decision trees in a computer code.

The first and the second items have been discussed in previous sections. Creating the decision trees for diagnosing the cause or causes of a distress is an important element of a decision support system.

The occurrence mechanism of each concrete distress due to mentioned factors is very bulky, time-consuming and occasionally vague and indirect. The operator needs to review extensive sources, gather more additional information and use experts' skills to understand its mechanism thoroughly and determine distress factors. It is necessary to diagnose the distress cause. It will help preventing or decrease the occurrence of such a distress in future and also help finding a solution for repair.

At first, it is necessary to obtain and specify the cause or causes of the distresses in a concrete structure. As mentioned, there are three types of distresses: cracks, surface distresses and miscellaneous distresses. The cause of cracks in a concrete structure is given in Table 1 according to (PCA 2001, ACI 2007, USACE 1995, BSI 2008). All types of cracks are mentioned with the various causes that may lead to a crack on the structure. The surface distresses have a various types with different causes. They are classified in Table 2 with the associated causes of them according to (PCA 2001, ACI 2007, USACE 1995, BSI 2008). The miscellaneous distresses with the associated causes of them are given in Table 3, according to (PCA 2001, ACI 2007, USACE 1995, BSI 2008).

As seen in the tables, there are various causes for a specific distress. The appearance of a distress indicates the main cause which can be obtained by using an expert support system.

Decision trees are the important elements of an expert support system that provides the main cause of a distress in a structure.

The production of decision trees can be obtained through the following steps:

(1) Extensive researches in marine and inland structures;

(2) Interview with experts and specialists in the concrete and marine field;

(3) Consult with the existing support systems.

About thirty decision trees are produced for the developed support system for concrete marine structures. All of them can be found in Dehghani *et al.* (2010). As a sample, the decision tree for longitudinal crack is depicted in Fig. 1. The tree begins with a question about the appearance of the crack. The question is "Are the longitudinal crack observed to be directed over the reinforcing steel?". There are two answers for this question. If the answer is yes, then another question will be asked about rust staining. If rust stain is seen near the crack, then corrosion of reinforcement will be the cause. However, different types of corrosion may happen and the remaining questions will provide the type of corrosion.

All of these decision trees are put in a computer program with Graphical User Interface (GUI). The operator can interact with the program to obtain the final answer for the cause of a distress. An operator enters information from the inspection reports of the structure. Since, there may be possibility that the operator is not completely sure about a yes or no answer to a question, an option is also put about the level of confidence for the provided answer to a question. If the operator is 100% sure about the answer, he may insert the word "definitely" and so on. The confidence levels

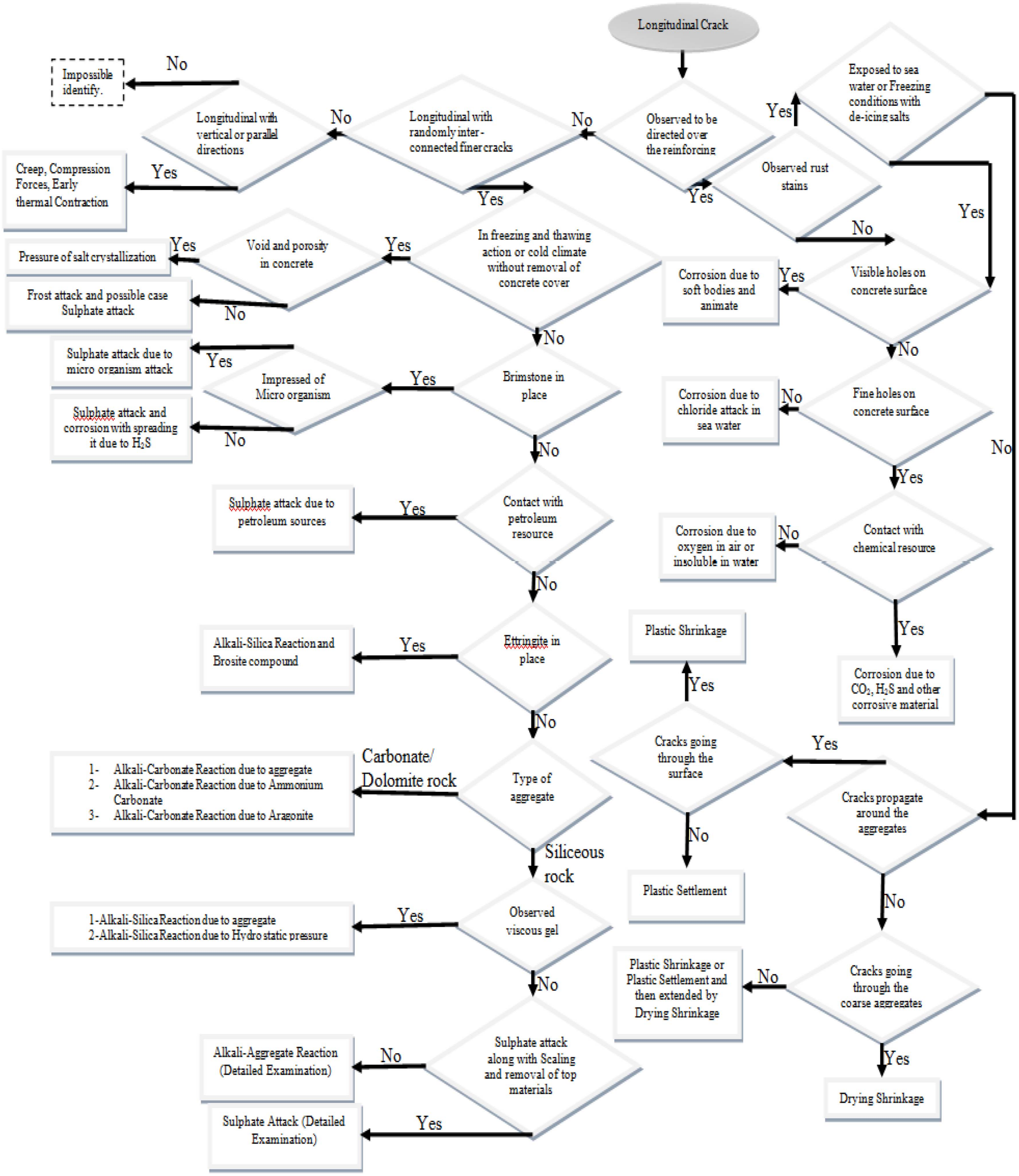


Fig. 1 Decision tree for longitudinal crack

and the associated number to them are shown in Fig. 2. However, there may be several questions to find the final cause for a distress. The program will finally give a number between 0 to 100 for the diagnosed cause for a distress. Fig. 3 shows a sample form of cause diagnosing for a distress in the decision support system.

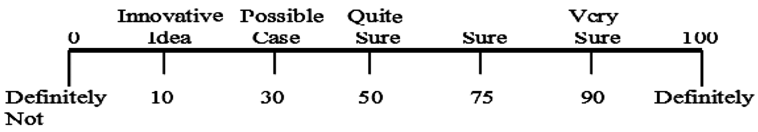


Fig. 2 Confidence Level (CL)

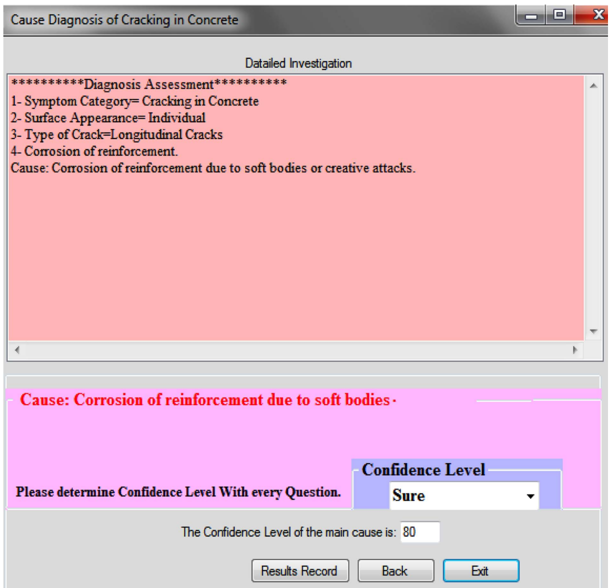


Fig. 3 Sample form for diagnosis of distress cause in the system with confidence level

## 6. Producing decision trees for repair of concrete

The second part of a support system is the recommendation of a repair method. To advise a suitable repair method, it is also necessary to follow these steps:

1. Specifying the most suitable repair methods for concrete marine structures;
2. Creating a decision trees for repairing a specific distress;
3. Programming;

Hence, the available repair method should be put in a computer code. To have a comprehensive support system, experts and literatures are consulted. At first, a questionnaire form is prepared and asked experts who are working in the field of concrete structure to fill them. Majority of the available repair materials and methods are gathered and are put in the form.

Sixteen of them answer to our request and fill the form. They recommend the best and suitable repair materials and methods for marine concrete structures. Responses from the survey are summarized in Tables 4 and 5. It was found that the traditional materials are the predominant materials that are recommended.

Many factors have to be taken into account when choosing an appropriate repair material. These factors depend on the cause and extent of the existing distress, availability, the structural condition, the cost and so on. The repair materials are widely classified to polymer emulsions, resins, prepacked cementitious, pozzolanic materials and fiber materials according to (PCA 2001, USACE

Table 4 Repair materials

| Type | Material | Response % |
|---|---|---|
| Polymer Emulsions | Acrylic Latex, Epoxy Latex, Polyvinyl Acetate, Styrene-Butadiene Rubber (SBR), Co-Polymer Latex, Natural Rubber, Styrene-Acrylic, Vinyl Acetate Ethylene (VAE), Polymthlmethacrylate (PMMA), Magnesium Phosphate Modified, Polyvinyl Chloride. | 10 |
| Resins | Acrylic, Polyurethane, Polyester, Epoxy, Low viscosity Polyester, Low Viscosity Epoxy, Methlmethacrylate (MMA), Polyester-Styrene Co-Polymer, Chlorinated Rubber, Bituminous Materials, Unsaturated Polyester, Silicones, High Molecular Weight Methacrylate (HMWM). | 12 |
| Prepacked Cementitious | Ordinary Portland Cement (OPC), High Alumina Cement (HAC), Magnesium-Phosphate Cement (MPC), Expensive Portland Cement (Types K,M,S), Regulated-Set Portland Cement, Special Blended Cement, Gypsum Cement, Prepacked Patching Materials, Cement Grout. | 52 |
| Pozzolanic Materials | Pulverised Fly Ash (PFA), Blast-Furnace Slag-Cement, Microsilica (Condense Silica Fume), Trass and Diatomite. | 18 |
| Fiber Materials | Steel, Plastic and Glass Fibers. | 8 |

Table 5 Repair methods

| Type | Method | Response % |
|---|---|---|
| Miscellaneous Systems for Replacement, Repair, Strengthening and Protection Methods | Sprayed Concrete; Gunite or Shotcrete, Drilling and plugging, Cathodic Protection, Desalination and Realkalization, Stitching, Reinforcement Replacement, Jacketing, Bonded Steel Plates, Post-tensioning, Infilling and Bracing and Slabjacking. | 42 |
| Cemetitious/Polymeric Systems for Replacement, Repair, Strengthening and Protection Methods | Preplaced Aggregate Concrete, Overlay, Grouting, Dry Packing, Patch/Hand Laid and Concrete Replacement (Fiber Reinforced Concrete (FRC), High Strength Concrete (HSC), Precast Concrete, Conventional Concrete, Polymer Concrete (PC), Polymer Portland Cement Concrete (PPCC), Polymer Impregnated Concrete (PIC), Roller-Compacted Concrete (RCC), Shrinkage-Compensating Concrete, Silica Fume Concrete. | 15 |
| Polymeric Systems for Repair, Strengthening and Protection Methods | Resin Injection, Resin Bonded External Reinforcement, Routing and Sealing, Flexible Sealing, Autogenous Healing, Protective Coating and Rendering, Blanketing, Vacuum Impregnation, Hydrophobation and Gravity Soak. | 33 |
| New technology for Repair of Live Cracks | Mastics, Termoplastics, Elastomers | 10 |

1995, ACI 2007). Most repair projects will have unique conditions and special requirements that must be thoroughly examined before the final repair material criteria can be established.

The repair methods may be classified into four groups according to (PCA 2001, USACE 1995, ACI 2007).

1. Miscellaneous Systems for Replacement, Repair, Strengthening and Protection Methods
2. Cemetitious/Polymeric Systems for Replacement, Repair, Strengthening and Protection Methods

3. Polymeric Systems for Repair, Strengthening and Protection Methods
4. New technology for Repair of Live Cracks

Selection of repair methods can be affected by the nature of the impairment, consideration of durability, availability and compatibility with the existing structure, environment and the cost. A decision tree was developed using the knowledge gained from the literature and the experts. The decision tree proved to be very useful in the development of the rules for the decision support system. The most classical methods and new technologies are used to build the repair decision trees.

The most types of distresses have a unique repair method and it is not necessary to create decision trees for them but the cracks and the spalling are exceptional. Some other types of distresses such as delamination, scaling, disintegration and so on are also the same behavior as the spalling and the developed decision trees for spalling can be used for them. There are several methods and materials for repairing the cracks and spalling and therefore, a pattern should be presented for them. The pattern for a support system is in the form of a decision tree which helps the repair agents to choose the most suitable method for a given situation.

Cracks are divided to two groups:

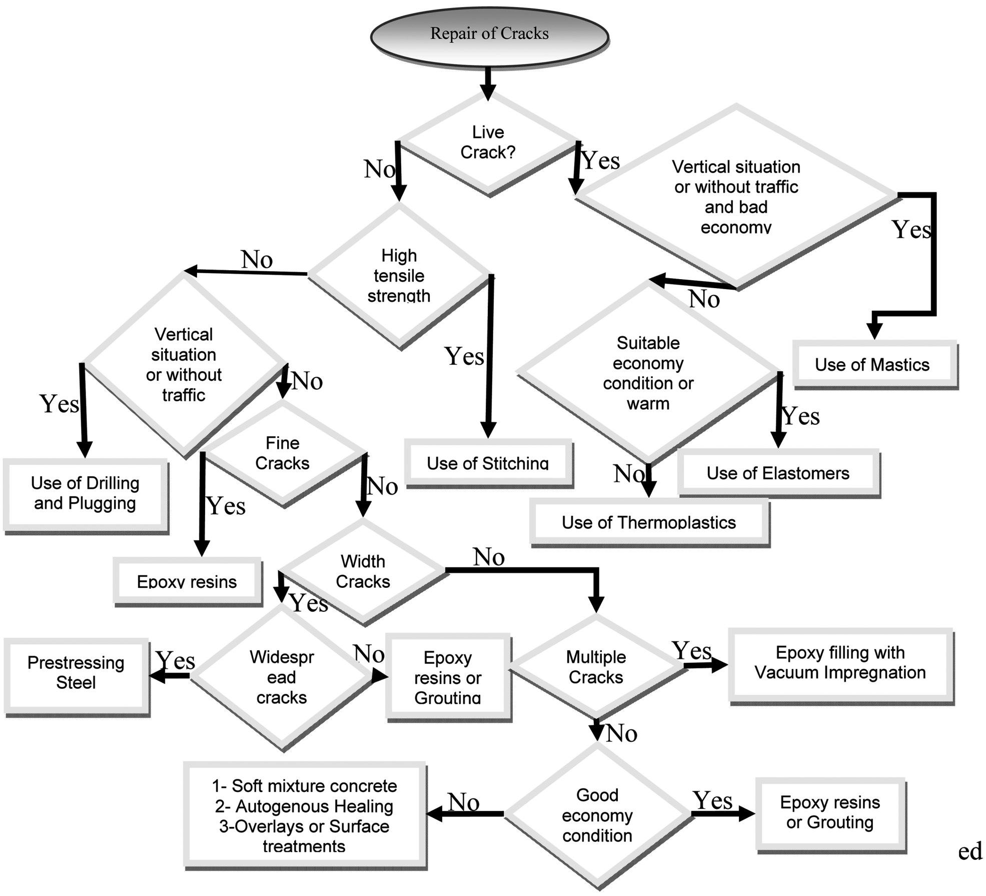


Fig. 4 The repair decision tree for cracking of concrete

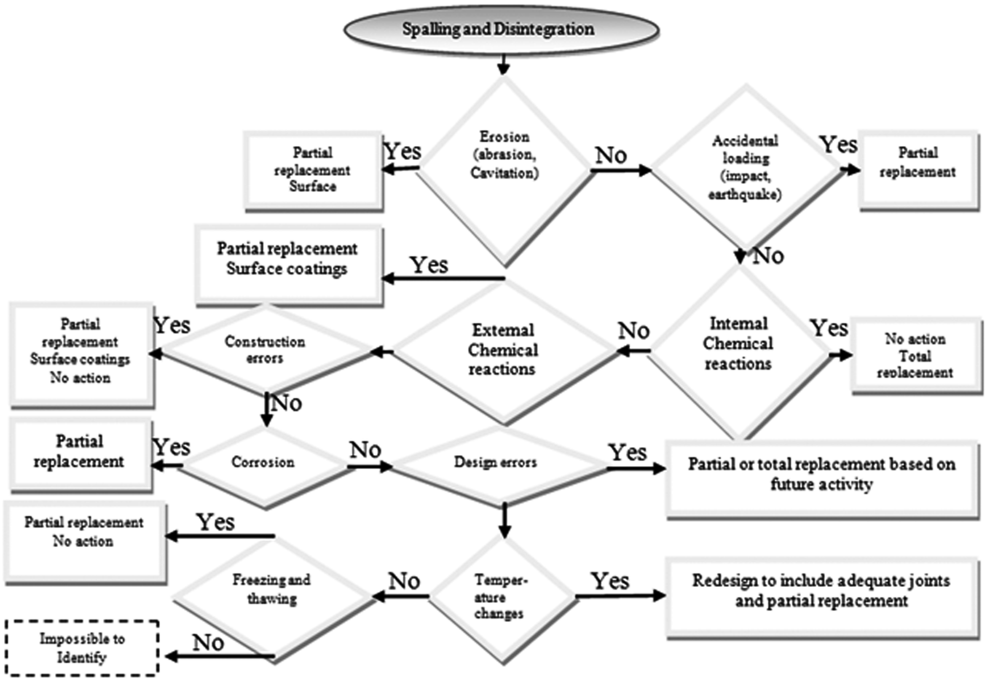


Fig. 5 The repair approaches decision tree for spalling and disintegration

– Live crack: when the crack is growing.

– Dormant crack: when crack has stopped at its place for a while.

Several factors should be considered in creating the decision tree for repairing cracks. These factors are:

(1) New technologies of repair materials;

Table 6 Repair methods for spalling and disintegration

| Repair method | Repair approach |
|---|---|
| Judicious neglect | No action |
| Conventional concrete placement<br>Drypacking<br>Jacketing<br>Preplaced-aggregate concrete<br>Polymer impregnation<br>Overlay<br>Shotcrete<br>Underwater placement<br>High-strength concrete | Partial replacement<br>(replacement of only<br>damaged concrete) |
| Coatings<br>Overlays | Surface coating |
| Remove and replace | Total replacement of structure |

(2) Severity of distresses;
(3) Situation of distresses;
(4) Economic conditions.

Taking into account these basic factors and the repair materials and methods given in Tables 4 and 5, the decision tree for repairing cracks, as shown in Fig. 4, is created for marine concrete structures. At first, the type of crack is asked in the decision tree. When the crack is alive, new technology such as elastomers may be used. If the Type of crack is dormant, the extent, the severity of distress and cost and its situation will be assigned the repair method. For spalling and disintegration a general repair approach can be selected from Fig. 5, which presents a comparison of the possible causes of spalling and disintegration symptoms and the general repair approaches that may be appropriate for each case. Table 6 relates the repair approaches shown in Fig. 5 to specific repair methods.

## 7. Decision support system

The main functions of a decision support system are distinguishing the cause of a distress and advising a suitable repair method. The cause and the most suitable repair method for a distress are obtained by creating the corresponding decision trees. The decision trees for diagnosing the cause and advising the repair method have been presented in previous sections. These decision trees should be put in a computer program to create the decision support system. The Microsoft Visual Studio is applied to put the decision trees in a computer code. The algorithm for the decision support system is given in Fig. 6.

At first, the specification of the structure should be inserted into the program. These include: structure name, structure type, construction type, age, component type, component number, date of evaluation and geometric information.

The distress type is the second input data that should be inserted into the program. Based on the type of the distress, the program will choose the attributed decision tree and asks several questions to obtain the cause of the distress. The program was designed in such a way that it gives also the confidence level for such a decision. Then, the program determines the most suitable repair method for the given distress.

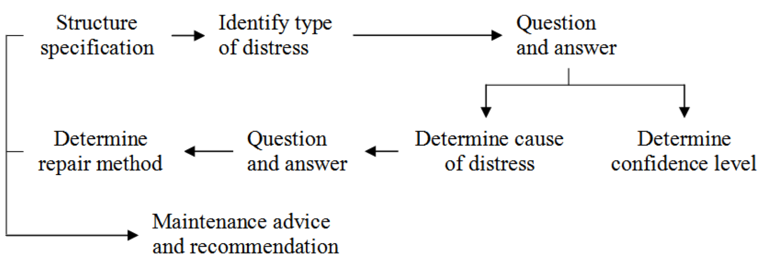


Fig. 6 A complete run stages in the decision support system

## 8. Case study

The decision support system was applied to a pier in *BandarAbbas* in *Iran*. The pier concrete slab was in medium condition but was damaged in some places. The surface of the concrete had crack and efflorescence in major points. The pier is shown in Fig. 7.

The input data are as follows:
– Name: *Eskeleh* Bridge;
– Size: length: 208.4 m, Width: 6.40 m, thickness: 20 cm;
– Location: *Bandar Abbas;*
– Structure type: reinforced concrete bridge;
– Construction type: cast- in-situ;
– Structure age: 15 years;

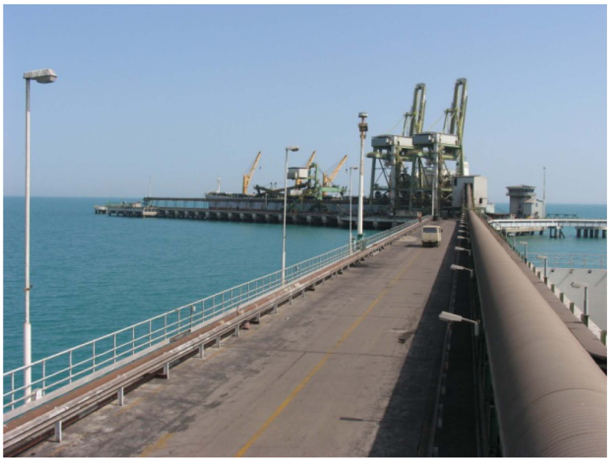

Fig. 7 *Eskeleh* pier in *BandarAbbas*

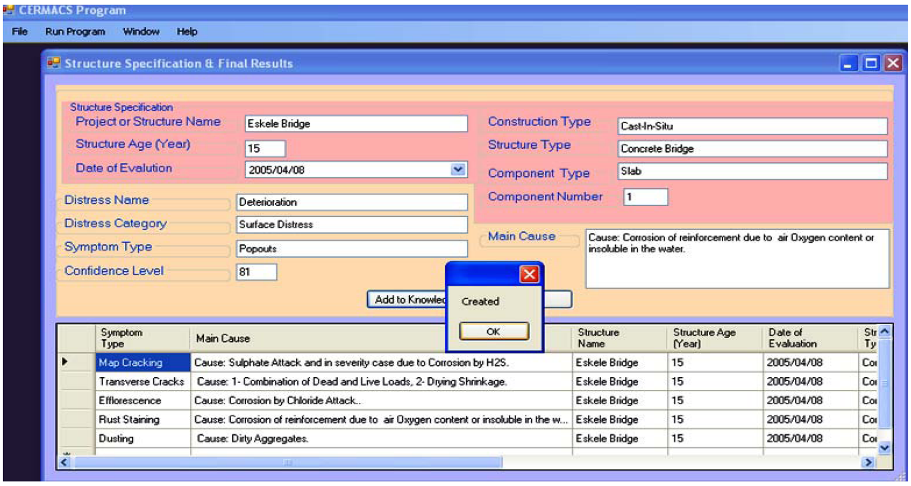


Fig. 8 Final results of the diagnoses of distress causes in decision support systems

Table 7 Cause of distresses gained from decision trees

| Symptom type | Distress category | Main cause |
|---|---|---|
| Map Cracking | Cracking in Concrete | Sulphate Attack and in severity case due to Corrosion by $H_2S$. |
| Transverse Cracks | Cracking in Concrete | 1-Combination of Dead and Live Loads, 2-Drying Shrinkage. |
| Efflorescence | Surface Distress | Corrosion by Chloride Attack. |
| Rust Staining | Miscellaneous Distress | Corrosion of reinforcement due to air Oxygen content or insoluble in the water. |
| Dusting | Surface Distress | Dirty Aggregates. |
| Popouts | Surface Distress | Corrosion of reinforcement due to air Oxygen content or insoluble in the water. |

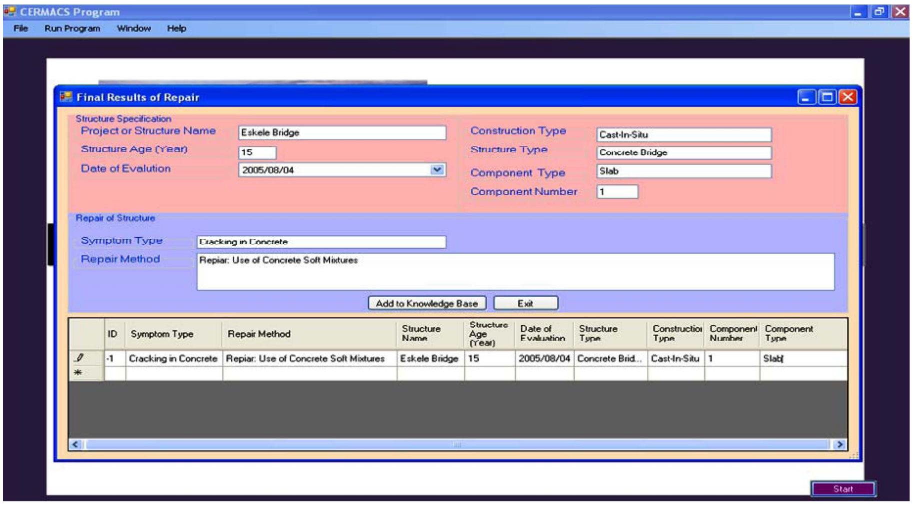


Fig. 9 Final result of diagnosis best method for repair of crack

– Date of evaluation: 2005/04/08;
– Component type: slab;
– Distresses
  • Deep pattern crack with 2 mm wide;
  • Slight efflorescence;
  • Slight dusting;
  • Severe rust staining;
  • Medium popouts; and
  • Through transverse crack with 2 mm wide.

Fig. 8 shows a complete diagnosis of the cause of distress in the database of decision support system.

All diagnosis results of the cause of distress are shown in Table 7.

Fig. 9 shows the suitable repair method for cracking that is taken from decision tree for this case. It recommends using concrete soft mixtures.

## 9. Conclusions

A decision support system was developed for diagnosing of distress causes and advising repair methods for marine concrete structures. At first, all possible distresses on marine concrete structures were listed and the cause or causes of them were obtained by: (1) conducting an extensive literatures review, and (2) consulting with the people who are expert in concrete materials and structures. Then, a set of cause finding decision trees were developed for all possible distresses on marine concrete structures. This set consisted of twenty nine decision trees which eight for cracks, thirteen for surface distresses and eight for miscellaneous distresses. The most important and sophisticated ones were those for longitudinal crack, spalling, popouts and scaling.

It was found out that the salty water, chemical materials and chloride attack are the most important cause and causes that produce distresses on marine concrete structures. It is not the case for inland structure support system and therefore the direct application of such a support system for marine structure will provide erroneous results.

Another set of decision trees were also developed to advise the most suitable and reliable repair methods. These repair-advising decision trees were constructed based on a survey from expert and consulting with literatures. The experts were asked to provide the most suitable materials and repair methods in marine environment. Decision trees for repair method were obtained with consideration of 4 factors: (1) the type of distress and its severity and extent, (2) the economic condition, (3) the most repeated repair method and (4) the new technologies. Because there is a distinct approach for major parts of distresses, two decision trees were proposed for cracks and spalling.

It was observed that the traditional methods and materials could also be used for marine concrete structures. The most important difference is the application of new technologies especially, for live cracks.

The decision support system was applied for a pier in Bandar Abbas port in Iran. The pier had several distresses on the concrete slab. The support system provided the cause of the distress and the most suitable repair method. The consulting with experts indicated on the right decision about the cause and the repair method by the developed decision support system.

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