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Concrete Crack Analysis in RC Elements Using Rough Set Theory

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ABSTRACT

The rough set theory is a relatively recent mathematical approach to definition and analysis of vagueness, ambiguity and uncertainty, and it is suitable tool in data mining system. The paper presents a decision rule modeling for classification and analysis the cause of concrete cracking in relation to time (in fresh or hardened concrete) and physical, chemical, thermal and load impact in uncertain environment. The model is based on stochastic approach and decision table is obtained by considering cracks characteristic as attribute set. It is shown that the objective decision rules for given parameters related to cracks classification can be formulated.

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1. Introduction

The presence of cracks in reinforced concrete (RC) structures is an almost inevitable phenomenon. The formation of microcracks is possible even in the early period of concrete hydration due to partial segregation or plastic shrinkage of concrete (Sivakumar and Santhanam, 2007). During the period of exploitation of the building, defects in the structure of hardened concrete can occur due to the action of loads, an aggressive environment or some other influence (change in temperature, settlement of supports over time, earthquake).

When considering the durability of RC structures, it is essential to establish the cause of damage in concrete. Depending on the cause of the appearance of the crack, it is necessary to consider whether the mentioned damage can be allowed without the application of remedial measures, and it is necessary to determine the limit of acceptable damage. If the observed cracks in the concrete do not significantly affect the reaching of the limit state of usability, it represents a visible warning. On the other hand, cracks in a concrete structure are less critical than those in a metal structure (Pavišić, 2007).

During natural disasters, the durability and behaviour of the structure will depend on the approach of the building owner during the exploitation period to evaluate the condition and the solution to the resulting problems with the appearance of concrete cracks (Folić, 1991). Furthermore, unpredictable natural disasters (heavy rains, floods, extremely heavy snowfalls, earthquakes) are expected to be more frequent in the coming decades. As a result, reviews and assessments of the condition of RC structures gain additional importance.

Rough set theory has found a crucial role in expert systems, decision support systems, shape recognition, but also in the treatment of various problems in construction (Ćirović and Plamenac, 2005) (Ćirović and Cekić, 2002). By applying this soft programming method, Attor-Okine presented decision support systems for the rehabilitation and maintenance of pavement structures (Attor-Okine, 1997). Also, Min Kim et al. proposed a model for categorizing cracks in reinforced concrete structures (Min Kim et al., 2009).

The paper presents a model of the analysis of the causes of cracks in concrete by applying loss sets based on 21 cases of cracks in the RC structures. The software solution Rosetta was used to calculating the relevant data characteristics in the tables and generate classification rules. The software is designed to support the process of knowledge discovery, data processing and rule generation within rough set theory. In addition, experimental data were collected during the inspection of RC structures by the authors of the paper.

2. Application of Rough Set Theory

Dealing with the problems of uncertainty, vagueness, and imprecision is one of the critical activities in successfully implementing intelligent decision support systems. So far, numerous approaches have been developed to solve this problem, and one of the latest mathematical approaches is provided by rough set theory. It is based on the research of a group of authors headed by prof. Pawlak conducted at Warsaw University, Institute for Computer Sciences at the end of the 80s of the last century (Pawlak, 1982).

An elementary set is any set of all objects that are indistinguishable and represent granules of knowledge about the universe. A sharp (precise) set is any union of some elementary sets; otherwise, the set is rough. The assumption that objects can be "seen" only through the available information about them leads to the view that knowledge structure is granular. Due to the granularity of knowledge, some objects that interest us cannot be recognized and appear as the same or similar. Consequently, unlike precise concepts, fuzzy concepts cannot be characterized by information about their elements.

The rough set theory approach solves this problem by assuming that a pair of concrete terms can describe any indefinite object called a lower and upper approximation. Lower and upper approximation are two basic operations in rough set theory. The lower approximation consists of all objects that belong to the set, and the upper approximation contains all objects that probably belong to it (those that belong and those that cannot be claimed to belong with certainty). The difference between the upper and lower approximation constitutes the boundary area of a fuzzy concept (object) (Ćirović and Plamenac, 2005).

In order to mathematically formulate rough sets, the starting point is the data table. It is understood that the term attribute is used instead of the term criterion because the first term is much more general than the second. A four-fold group of data is understood as a data table:

$$S = (U, A, V, f) \tag{1}$$

where:

U – a finite set of objects

A – a finite set of attributes

For each attribute $a \in A$ there is a set Va of its values or assessments. Each attribute a determines the function f: $U \rightarrow V_a$. For each subset B of A, there is an indiscernibility relation I on U, marked as I(B) and thus defined as:

$$I(B) = \{(x, y) \in U \times U : f_a(x) = f_b(y), \forall a \in B\} \tag{2}$$

Let U be a finite set of objects – a universe and let X exist so that $X \subseteq U$, with $x \in X$. Binary relations B on U are introduced, that is the indiscernibility relation. Let B be a subset of A.

The following operations on sets are defined:

$B*(X)$ - a lower approximation of X is defined as follows:

$$B*X = \{x \in U : B(x) \subseteq U\} \tag{3}$$

$B^*(X)$ - an upper approximation of X defined as follows:

$$B^*X = \{x \in U : B(x) \cap X \neq 0\} \tag{4}$$

Boundary region of X is the set

$$BN_B(X) = B*(X) - B*(X) \tag{5}$$

If the boundary region of X is an empty set:

$$BN_B(X) = 0 \tag{6}$$

the set is crisp (exact) with respect to B, and in the opposite case

$BN_B(X) \neq 0$ (7)

the set X is rough (inexact) with respect to B.

Therefore, the lower approximation of the set is the union of all knowledge granules that are entirely included, i.e. contained in the set. The upper approximation is the union of all granules that have a non-empty intersection with the set. The boundary region is the difference between the upper and lower approximations.

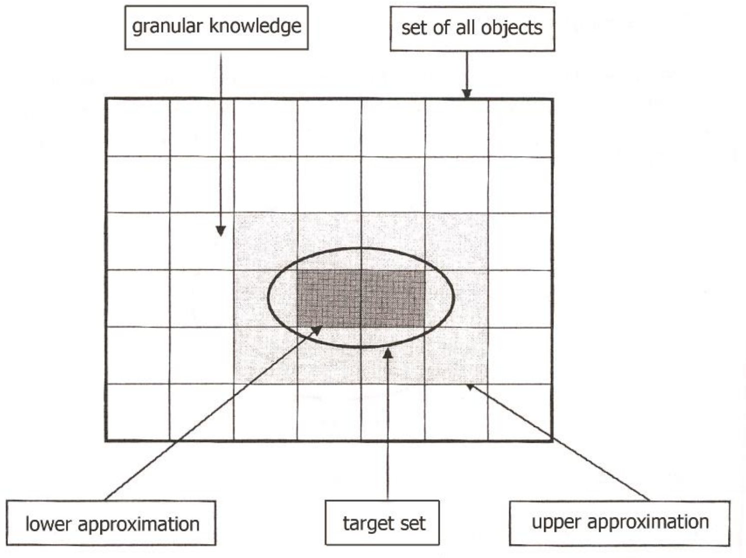

Figure 1. Knowledge granules, sets and approximations

Four basic classes of rough sets can be defined, i.e. four categories of imprecision:

1. $B*(X) \neq 0$ *and* $B*(X) \neq U$, *iff is X roughB* - determined
2. $B*(X) \neq 0$ *and* $B*(X) \neq U$, *iff is X internalB* - undetermined
3. $B*(X) \neq 0$ *and* $B*(X) = U$, *iff is X externalB* - determined
4. $B*(X) \neq 0$ *and* $B*(X) = U$, *iff is X totalB* - undetermined

In the theory of rough sets, elements (objects) of the universe cannot be classified with certainty as elements of a particular set which constitute a rough set. Therefore, to define the uncertainty problem, we need to introduce a function of membership of elements to a rough set, which is called a function of rough membership.

$$\alpha_B(X) = \frac{|B*(X)|}{|B*(X)|} \quad \text{whereby } 0 \leq \alpha_B(X) \leq 1 \qquad (8)$$

where $|X|$ is the cardinality of the set X, $X \neq 0$. The coefficient $\alpha_B(X)$ is the accuracy of the approximation of the term X.

If: $\alpha_B(X) = 1$ the set is sharp compared to B, and if: $\alpha_B(X) < 1$ the set is rough compared to B.

The rough membership function of an object x to a rough set is defined as follows

$$\mu_X^B(x) = \frac{|X \cap B(x)|}{|B(X)|} \quad \text{whereby } 0 \leq \mu_X^B(x) \leq 1 \qquad (9)$$

3. Decision-Making Algorithms for Assessment of the Causes of Crack Appearance

Table 1. shows the values of condition attributes and decision attributes for selected parameters, which were used to analyze the possibility of cracking in RC elements due to inadequate installation or care of the concrete. Ten criteria were adopted for the evaluation and analysis of a specific case:

- crack appearance time (A)
- crack shape (B)
- the place of occurrence (C)
- the quality of component materials (D)
- water-cement factor of embedded concrete (E)
- hydrometeorological risk factor when installing wet concrete (F)
- aggressive environment factor (G)
- confirmed correct reinforcement (H)
- influences from the external load (I)
- temporary overload (J)

The mentioned parameters represent condition attributes, and concrete parameters' improper pouring and curing represent a decision attribute. Therefore, two discrete values were adopted for the decision attribute (1-concrete pouring and curing is the cause of cracks; 2- concrete pouring and curing is not the cause of cracks).

Table 1. Decision table

	Condition Attributes										Decision attribute
	A	B	C	D	E	F	G	H	I	J	K
1	-	1	2	2	2	1	1	1	1	1	1
2	2	2	2	1	1	1	1	1	3	1	2
3	1	3	1	1	3	3	1	1	1	1	1
4	2	3	1	1	1	1	1	1	2	1	2
5	2	1	2	2	3	3	1	1	1	1	1
6	2	1	2	2	3	3	1	1	1	1	1
7	3	1	2	2	3	3	1	1	1	1	1
8	-	3	1	3	3	1	1	2	3	1	2
9	2	1	1	1	2	2	1	1	1	1	1
10	3	3	3	1	-	1	2	1	3	1	2
11	1	1	2	2	2	1	1	1	1	1	1
12	2	3	3	1	1	2	1	1	3	1	2
13	2	3	2	1	3	3	1	1	1	1	1
14	2	3	1	1	1	1	1	1	1	1	1
15	2	3	2	1	2	3	1	1	1	1	1
16	1	3	2	1	3	3	1	1	1	1	1
17	2	3	2	1	3	3	1	1	1	1	1
18	3	3	2	2	3	1	1	1	3	1	2
19	2	2	1	1	1	2	1	1	1	1	1
20	2	3	3	1	2	1	2	1	2	1	1
21	1	1	2	1	-	2	1	1	1	1	1

A - *crack appearance time*: describes the time when cracks appeared, and three discrete values were adopted (1-less than 24h; 2-from 1 to 10 days; 3-over ten days). When the crack appearance time was unknown, the field in the table is marked with '-'.

B - *crack shape*: defines the shape of the crack, where three discrete values are given (1-formed network of cracks on the surface; 2-line cracks on the surface; 3-line cracks in the concrete structure)

C – *place of occurrence*: describes the area or surface where the crack was observed. Three discrete values were adopted (1-local, only on the part of the RC element; 2-along the entire RC element; 3-over the entire construction)

D - *the quality of component materials*: the condition attribute mentioned considers the possibility of cracking due to the use of aggregates with properties that are not suitable for use in concrete, but also in rare cases when the quality of cement or water is not satisfied. Three discrete values are adopted (1-confirmed quality; 2-properties of component materials have not been tested; 3-component materials are a potential cause of cracks)

E - *water-cement factor*: defines three discrete values for the water-cement factor (1-for w/c<0.4; 2-0.4<w/c<0.5; 3-w/c>0.5)

F - *hydrometeorological risk factor during the installation and care of concrete*: this condition attribute considers the influence of air temperature during transport, installation and care of concrete, wind speed, and precipitation. Three discrete values were adopted (1- risk is not present; 2- risk exists; 3-risk is pronounced)

G - *environmental aggressiveness factor*: describes the possibility of cracking due to the action of chemical agents on concrete. Two discrete values were adopted (1- there is no impact; 2- there is an impact)

H - *confirmed correct reinforcement*: the mentioned attribute considers the possibility of a crack appearing due to inadequate reinforcement, i.e. placing the reinforcement in a position different from the designed one. Two discrete values are adopted (1-correct reinforcement confirmed; 2-correct reinforcement not confirmed)

I - *influences from external load*: this attribute is primarily used to analyze the impact of the appearance of cracks due to the exploitation load within the permitted limits but also considers the influence of concrete flow on the possible appearance of cracks. Three discrete values were adopted (1-external influences are not relevant; 2-external influences are present; 3-external influences are pronounced and may cause cracks to appear)

J - *temporary overload*: defines the possibility of a crack appearing due to temporary overload (1-no; 2-yes).

It is often asked whether removing some data from the decision table while preserving its essential characteristics is possible. Reducers represent a minimal subset of attributes that allows the same classification of elements of the universe as a complete set of attributes. In other words, attributes that do not belong to reducers are redundant in classifying elements in the universe. Finding reductions is an essential task in rough set theory. A *genetic algorithm reducer* was used for data reduction and the generation of decision rules.

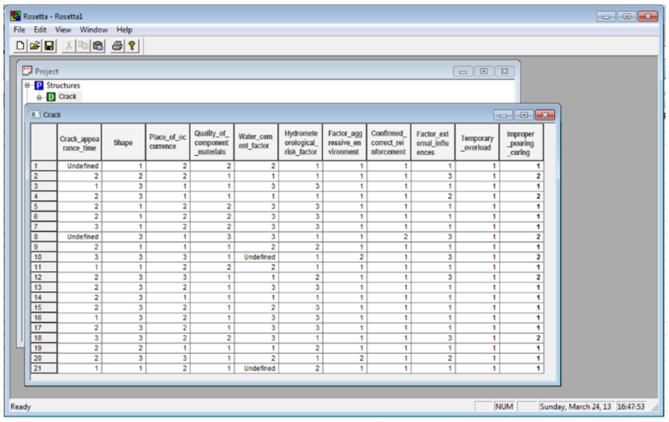

Figure 2. Decision table - Rosetta

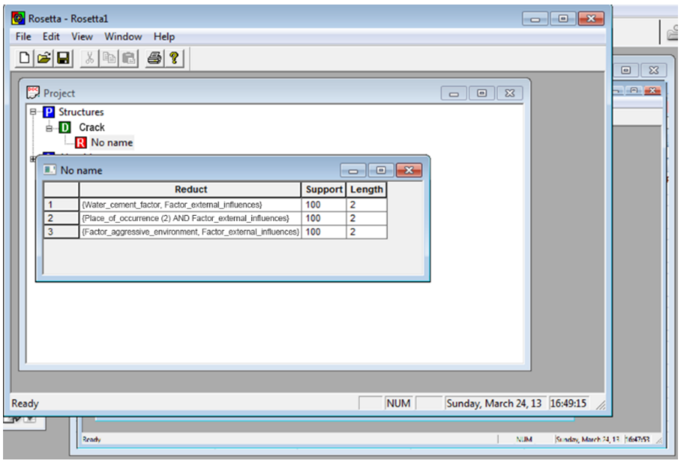

Figure 3. Attributes after reduction - Rosetta

The display of the algorithm's objective functions and the method of selecting the minimal attribute subset are detailed in Vinterbo and Øhrn (2000) work. After applying the *genetic algorithm reducer*, three groups of reduced attributes were obtained (Water_cement_factor, Factor_external_influences); (Place_of_occurrence, Factor_external_influences); (Factor_aggressive_environment, Factor_external_influences). The generated decision rules, as the ultimate goal of modelling, have the following form:

Water_cement_factor (2) AND Factor_external_influences (1) => Improper_pouring_curing (1)
Water_cement_factor (1) AND Factor_external_influences (3) => Improper_pouring_curing (2)
Water_cement_factor (3) AND Factor_external_influences (1) => Improper_pouring_curing (1)
Water_cement_factor (1) AND Factor_external_influences (2) => Improper_pouring_curing (2)
Water_cement_factor (3) AND Factor_external_influences (3) => Improper_pouring_curing (2)
Water_cement_factor (1) AND Factor_external_influences (1) => Improper_pouring_curing (1)
Water_cement_factor (2) AND Factor_external_influences (2) => Improper_pouring_curing (1)
Place_of_occurrence (2) AND Factor_external_influences (1) => Improper_pouring_curing (1)
Place_of_occurrence (2) AND Factor_external_influences (3) => Improper_pouring_curing (2)
Place_of_occurrence (1) AND Factor_external_influences (1) => Improper_pouring_curing (1)
Place_of_occurrence (1) AND Factor_external_influences (2) => Improper_pouring_curing (2)
Place_of_occurrence (1) AND Factor_external_influences (3) => Improper_pouring_curing (2)
Place_of_occurrence (3) AND Factor_external_influences (3) => Improper_pouring_curing (2)
Place_of_occurrence (3) AND Factor_external_influences (2) => Improper_pouring_curing (1)
Factor_aggressive_environment(1) AND Factor_external_influences (1) => Improper_pouring_curing (1)
Factor_aggressive_environment(1) AND Factor_external_influences (3) => Improper_pouring_curing (2)
Factor_aggressive_environment(1) AND Factor_external_influences (2) => Improper_pouring_curing (2)
Factor_aggressive_environment(2) AND Factor_external_influences (3) => Improper_pouring_curing (2)
Factor_aggressive_environment(2) AND Factor_external_influences (2) => Improper_pouring_curing (1)

4. Conclusion

The possibility of applying rough sets to support decision-making in analyzing the appearance of cracks in RC structural elements is shown. The model is based on a stochastic approach where the data were analyzed under imprecision and uncertainty with missing data. Decision rules based on expert decisions are presented, which contributed to the interpretation, analysis and classification of crack occurrence patterns, i.e. the influence of concrete placement and maintenance on the occurrence of cracks in RC construction.

Rough sets are a suitable method for analyzing quantitative and qualitative parameters when, due to an insufficient number of empirical or experimental data, conventional statistical methods are not applicable. Moreover, one of the modern techniques of soft programming shows exceptional success in treating problems in everyday engineering practice.

The decision table shows the attributes of the conditions and the attributes of the decision, with a note that during modelling, it was not necessary to know the probability distribution for the adopted attributes and prior knowledge of mutual relations. After attribute reduction, critical groups of attributes (Water_cement_factor, Factor_external_influences); (Place_of_occurrence, Factor_external_influences); (Factor_aggressive_environment, Factor_external_influences) were singled out, which were analytically shown to have the most significant influence on the decisions made. After applying the rough set, it is interesting to compare experts' opinions on the attributes of the conditions after the reduction.

Based on the generated decision rules, it is possible to generate decision attributes for the defined condition attributes, with a note that by expanding the number of analyzed events, there is a possibility of changing the data structure and the condition attributes after reduction.

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