PREDICTION OF THE RISKS OF DESIGN AND DEVELOPMENT OF NEW BUILDING MATERIALS BY FUZZY INFERENCE SYSTEMS

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We dealt with a process of design and development of new building materials based on the secondary raw materials. The secondary raw materials can, due to their variable properties, unpredictably influence physico mechanical characteristic of the resulting material. In order to eliminate these risks, many preventive methods are applied. The best-known method is FMEA (Failure Mode and Effects Analysis). The work was performed in two parts. The first part deals with mathematical models of tensile cohesion in dependence on percentage substitution of fly ash for milled limestone using fuzzy logic theory. In the second part the possibilities of an extension of FMEA methodology by using fuzzy inference systems (FIS) is shown. Practical applications show that using FIS for modelling of physico-mechanical properties of materials with secondary raw substances and for quantification of risks is acceptable.

INTRODUCTION

Together with the increasing lifestyle demands there are also the demands on industrial production which is a substantive producer of waste materials. Disposal and liquidation of these materials are very difficult both from the viewpoint of environment and economy. Recycling of the waste materials and their utilisation as secondary materials to produce building materials is one of the solutions to these problems.

Production of building materials and elements is able to fabricate a huge volume of waste materials and not only the building ones. Nevertheless, the secondary raw materials may cause many problems that should be considered in the process of design and development. This paper deals both with the utilisation of fly ash for the production of polymer-cemented adhesive agents as the substitution for a filler mass for ceramic tiling and with calculation modelling of tensile cohesion of these materials using fuzzy interference systems. The risks quantification in connection with fly ash utilisation will be also discussed.

Utilisation of fly ash for production of adhesive agents for ceramic tiling elements

Ceramic tiling is a typical multilayer element in which materials of different properties are joined. Co-action of these materials is influenced especially by temperature and moisture expandability. One of the conditions of the ceramic tiling serviceability is a good and stable anchoring to a base which is influenced by the state of the base, the character of the back face of the tiling element, the type of adhesive agent and by external factors, respectively.

Recently, the most used adhesive agents have been polymer-cemented mortars. They are based on cement with special polymer additives. Essential input materials are: filler, binder and additives. From the viewpoint of the characteristics of adhesive materials, it is necessary to differentiate the so-called technological properties which influence the actual implementation of tiling works, and physico-mechanical properties of hardened mortar which influence especially the long-terms behaviour of the whole ceramic tiling with reference to its serviceability. Decisive functional properties requirements are specified in a standard [1].

This paper deals with the most monitored characteristic of these materials - tensile cohesion. Testing methods and requirements for this characteristic are presented in Table 1.

Table 1. Examined characteristics of adhesive agents.

Characteristic	Requirement	Testing method
Initial tensile cohesion	≥ 0.5 MPa	EN 1348:1997 [2]
Setting time: tensile cohesion after not less than 20 minutes	≥ 0.5 MPa	EN 1346 [3]

Setting time and structure of adhesive of tiles are the most important properties for the value of tensile cohesion. It`s very important to describe the influence and risks of using fly ash as a substitution for milled limestone. The theory of fuzzy sets seems to be acceptable for characterization of these problems.

Fuzzy inference systems

Fuzzy inference systems (FIS) are one of the frequent applications of theory of fuzzy sets in practice. Recently, they have been utilised in decisions, operation and modelling of the processes in which quantities, that either cannot/can be described with difficulty and thus expensively by virtue of conventional calculation methods. An advantage of FIS is the utilisation both of quantitative and qualitative knowledge about a modelled system.

In particular, it is not necessary to introduce simplified precondition that can cause many problems in practical applications. The simplification is indeed presented with regard to the vagueness of conceptions. Nevertheless, this uncertainty is compensated with the fact that the modelled system is elaborated in its entire complexity.

General structure of FIS is described in more detail in [4] and [5]. It implies: phase of fuzzyfication, inferential process, database, rules database and a phase of defuzzyfication.

Theory of fuzzy sets is based on the classical theory of sets where the element belongs into the set or not. In the theory of fuzzy sets the membership function is defined. This function of a fuzzy set is a generalization of the indicator function in classical sets (crisp sets). In fuzzy logic, it represents the degree of truth (the number of $<0;1>$) as an extension of valuation. Degrees of truth are often confused with probabilities although they are conceptually distinct because fuzzy truth represents membership in vaguely defined sets, not likelihood of some event or condition. In technical applications, triangular and trapezoidal membership functions are frequently used (see [4] and [5]).

A very important term is a linguistic variable defined as a variable which takes verbal values. Verbal values are represented by fuzzy sets, thus by membership functions. The inputs of the fuzzyfication phase are strict values of input variables that are determined by their universes, i.e. by referential sets. The output of the fuzzyfication phase is a membership function of the fuzzy set that subsequently enters the inferential process. Then by virtue of databases and rules database a solution is calculated.

The output of the inferential process is a fuzzy set determined by its membership function. However, for practical reasons the output in a form of the fuzzy set is incompetent, so it is necessary to convert it into the crisp value. This is a role of the defuzzyfication phase.

The rules database consists of conditional *if - then* rules (see [4] and [5]) which form the FIS base. All information about the character of these rules and about the input and output variables is saved in the database.

Let $x_1, x_2, ..., x_n$ are input variables defined on the universes $U_1, U_2, ..., U_n$ and y is output variable defined on the universe V. Thus FIS has n input variables and one output variable. Each universe Ui is covered by the system of fuzzy sets $A_i^1, A_i^2, \ldots, A_i^{ni}$ and universe V is covered by the system of fuzzy sets $B^1, B^2, \ldots, B^m$. Individual fuzzy sets represent verbal values of linguistic variables $x_1, x_2, ..., x_n$ and y. Hereafter, the set of conditional rules if - then is considered:

$$R^{(k)} : \textit{if}\ (x_1 = A_1^{(k)})\ \textit{and}\ (x_2 = A_2^{(k)})\ \textit{and...}\ \textit{and}\ (x_n = A_n^{(k)})\ \textit{then}\ (y = B^{(k)}) \tag{1}$$

where $k = 1, 2, \ldots, R$ is indication of a rule. Input vector $x = (x_1, x_2, ..., x_n)$ is then defined on Cartesian product $U = U_1 \times U_2 \times \ldots \times U_n$. Each rule $R^{(k)}$ represents as a matter of fact fuzzy implication (see [4] and [5]), i.e. fuzzy relation among the fuzzy sets $A^{(k)}$ and $B^{(k)}$, where $A^{(k)} = A_1^{(k)} \times A_2^{(k)} \times \ldots \times A_n^{(k)}$, which is defined on $\mathbf{U} \times V$ with membership function $\mu_{R(k)}(\boldsymbol{x},y)$, where $\boldsymbol{x} \in \mathbf{U}$ and $y \in V$.

The rule type (1) are the base of FIS of *Mamdani´s* type. By modification of the consequent (the part of rule behind then) the rules type *Takagi* - *Sugeno* (*Sugeno*) are obtained:

$$\textit{if}\ (x_1 = A_1^{(k)})\ \text{and}\ (x_2 = A_2^{(k)})\ \textit{and...}\ \textit{and}\ (x_n = A_n^{(k)})\ \text{then}\ (y = f_k(x_1, x_2, ..., x_n)) \tag{2}$$

This type differs from the (1) only by the fact that the function of input variables is just in the consequent. With regard to the demand factor of the computing process, the function fk is appointed as either constant or linear one and so.

$$f_k\ (x_1, ..., x_n) = a_{0k} + a_{1k} x_1 + ... + a_{nk} x_n \tag{3}$$

An advantage of FIS Sugeno is the possibility of utilisation of historical, i.e. previously measured data for extraction of every readings about both input and output variables and about the conditional rules, i.e. for extraction of the data base and base of rules. Many methods are utilised for this purpose. The most known and mostly applied is the so-called ANFIS method (Adaptive Neuro - Fuzzy Inference System). It is an adaptive forward neuron network for training of which a hybrid teaching method is used. More details about this method can be found e.g. in [6].

For defuzzyfication of the output values, i.e. for the conversion of the fuzzy set to a strict value, weighted average of the output functional values of the functions fk for individual rules is used in FIS, i.e.

$$y = \frac{\sum_{k=1}^{r} w_k f_k(x_1, ..., x_n)}{\sum_{k=1}^{r} w_k}, \tag{4}$$

where w_k is the so-called *weight* of k-th rule which is determined by an intersection of already fuzzyficated values entering FIS and the verbal values of linguistic variables in the individual rules - fuzzy sets $A_1^{(k)}, A_2^{(k)}, \ldots, A_n^{(k)}$.

EXPERIMENTAL

Three types of the mixtures with input compounds presented in Table 2 were tested. Filler - milled limestone - was gradually replaced by fly-ash in each mixture, so as to make it possible to examine the influence of this by-product on the resulting characteristics of the mixture. Fly ash substitution was in all cases 0, 20, 40, 60 and 80 %.

These mixtures were tested both on the initial and tensile cohesion in dependency on setting time (see Table 1). Average measured data of all mixtures are in Table 3. You can find more information about structure of mixtures in [7].

Table 2. Composition of mixture.

Filler	Milled lime-stone	Omyacarb 40; firm Omya a.s.
	Fly-ash	Power plant of Chvaletice; originated by combustion of lignite
Binder	Cement	CEM I 52,5 R; cement factory Hranice
Additives	SB	For common adhesive materials
	SC	For adhesive materials of higher adhesion
	SF	For adhesive materials of higher adhesion and elasticity

Evaluation of physico-mechanical properties of adhesive mixtures

The objective of this part of contribution is to set up mathematical models using fuzzy inference systems (FIS) that would enable an observation of tensile cohesion of adhesive materials in dependence on setting time and on percentage substitution of fly ash for filling agent. The design of FIS was realised in MATLAB environment using *Fuzzy logic toolbox*. This tool enables either by command prompt or by graphical user interface to a complete and processed database together with data rules for FIS of types Mamdani and Sugeno. The advantage of FIS utilisation form modelling of these problems is the fact that by the fuzzy logic it is possible to record and describe varied properties of secondary raw materials.

Three FIS have been set up - one for each of the above described mixture (Table 2) by selected additives. Setting time and percentage substitution of fly ash for milled limestone volume were chosen as input variables of all FIS. Furthermore, it was necessary to design a number of linguistic variable values. Finding of optimal set up of these parameters was derived from the mean deviation of the resulting model and reality. After this analysis, the value 3 was chosen as the most appropriate number of the verbal values of all variables, mainly with regard to simplicity of the resulting models.

Verbal values (membership functions) are shown in Figures 1 and 2. Modalities of verbal values for input variables were adjusted to the Gaussian shape with the level of intersection 0.5 [4,5]. The range for input variables in all FIS was 0-80 % and 0-30 minutes.

Output variable is thus tensile cohesion of an adhesive mixture to the sub-base and to lining. The range of this variable was different for every FIS:

– SB: 0.25 – 1.91 MPa;
– SC: 0.29 – 2.61 MPa;
– SF: 0.38 – 2.80 MPa.

Regarding the character of the measured data, the type Sugeno with defuzzyfication by weighted average was chosen to be the more suitable one (see equations (2) and (3)). For every combination of verbal values of inputs variables, the if - then rule was created. On consequents of if - then rules linear functions were used:

$$f_k (x_1,x_2) = a_{0k} + a_{1k}x_1 + a_{2k}x_2, \qquad (5)$$

where x_1 and x_2 are input variables, $k = 1, \ldots, 9$ is the index of rule and $a_{0k}, \ldots, a_{2k}$ are coefficients designed by ANFIS method with using measured data (see Table 4).

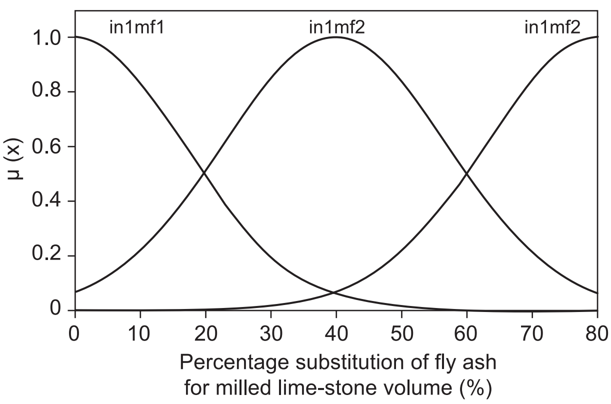

Figure 1. Verbal values of percentage substitution of fly ash for milled lime-stone.

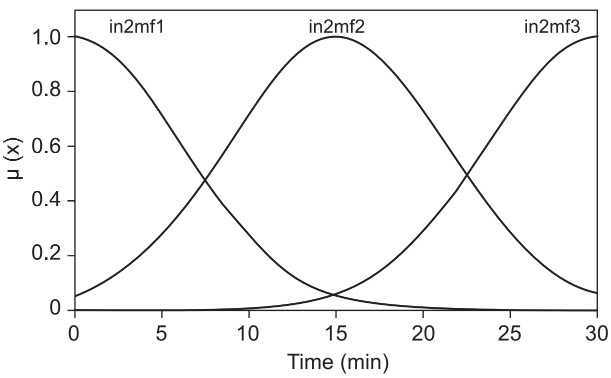

Figure 2. Verbal values of setting time.

Figure 3 shows the base of conditional if - then rules of the FIS for the mixture SB. Since the rules were set up in a grid system, i.e. Cartesian product of universes of input variables $\mathbf{U} = U_1 \times U_2$ was uniformly divided on reciprocally disjunctive subareas in dependence on number of the linguistic values of the input variables; the overall number of the rules is 9. Each of these rules characterises the behaviour of the modelled system in the relevant subarea.

The weight w_k of every rule is determined as minimum from intersections of the first two parts of the rule and fuzzyficated input values. Since the fuzzyfication is realised in a form of the so-called singleton [4,5], the input values are symbolised by a line (see Figure 4).

In Figures 5-7 functionality surfaces of three designed FIS are shown. These surfaces give approximative functionality dependence of tensile cohesion on setting time and percentage substitution of fly ash for milled lime stone volume. The continuance of surfaces is very similar for all involved mixtures.

Quantification of the risks by expert systems

Since the environmental and safety risks of fly ash application are minimal (weight activity is examined), we will deal with the description and estimation of qualitative risks.

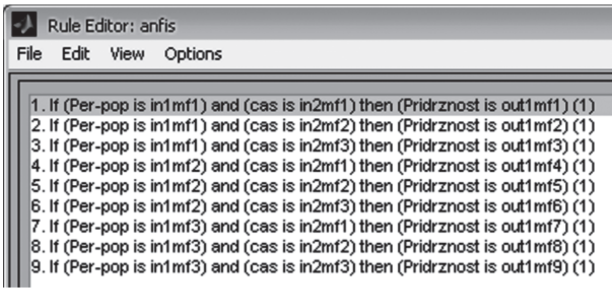

Figure 3. Base of rules in MATLAB environment.

The most significant factors of risks influencing the resulting tensile cohesion of the adhesive mixture are:

a) Various chemical composition of fly ash;
b) Various granulation of fly ash;
c) Various hydraulic activity of fly ash;
d) Reduction of polymeric efficiency due to fly ash application;
e) Increasing absorption of fly ash.

This part of the paper deals with the possibility of amplification of the FMEA method, especially with the task of quantification of the individual risks by means of the fuzzy sets theory.

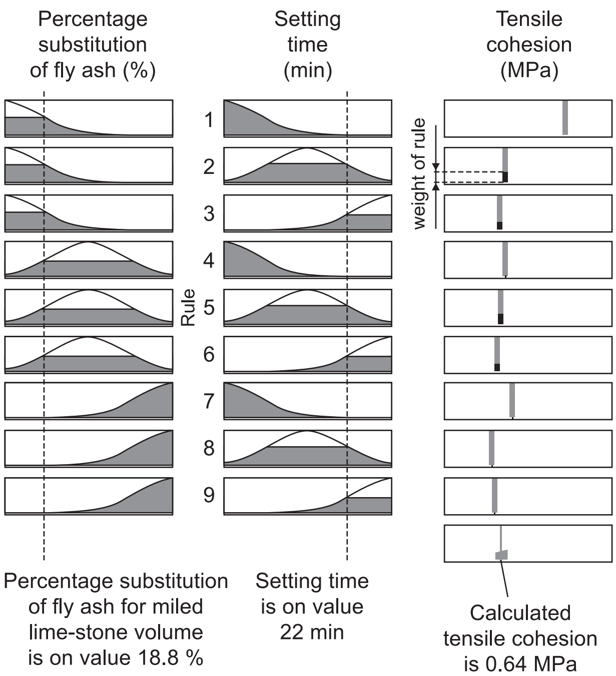

Figure 4. FIS for mixture SB – base of rules and evaluation of specific mixture and setting time.

Table 3. Average measured data.

Specimen	Filler percentage substitution (%)		Initial tensile cohesion (MPa)	Setting time (min) - tensile cohesion (MPa)			
	Milled lime stone	Fly ash		5 min.	10 min.	20 min.	30 min.
SB/R	100	0	1.13	1.91	1.02	1.10	0.58
III/SB/2	80	20	0.35	0.67	0.61	0.54	0.44
III/SB/4	60	40	0.34	0.62	0.57	0.57	0.43
III/SB/6	40	60	0.31	0.59	0.51	0.50	0.43
III/SB/8	20	80	0.25	0.50	0.47	0.44	0.42
SC/R	100	0	1.39	2.61	2.48	1.22	0.97
III/SC/2	80	20	0.41	0.73	0.69	0.61	0.51
III/SC/4	60	40	0.39	0.67	0.62	0.54	0.51
III/SC/6	40	60	0.35	0.62	0.57	0.57	0.50
III/SC/8	20	80	0.29	0.54	0.53	0.49	0.40
SF/R	100	0	1.57	2.80	2.57	1.48	1.07
III/SF/2	80	20	0.45	0.81	0.74	0.71	0.51
III/SF/4	60	40	0.43	0.74	0.70	0.64	0.50
III/SF/6	40	60	0.43	0.62	0.58	0.51	0.50
III/SF/8	20	80	0.38	0.61	0.60	0.52	0.50

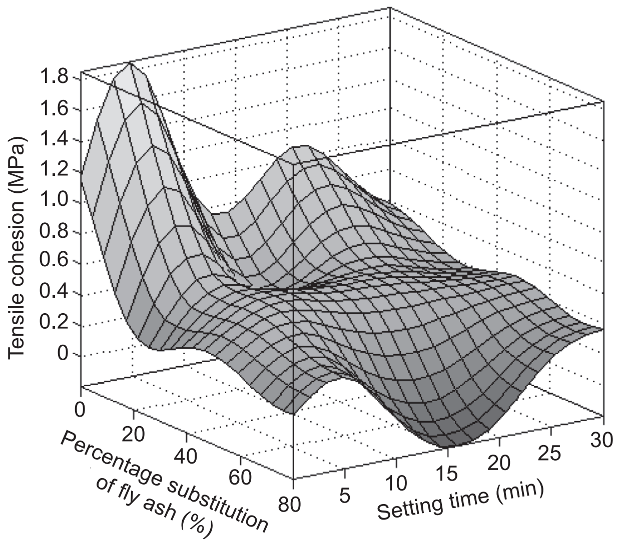

Figure 5. Functionality surface of FIS for mixture SB.

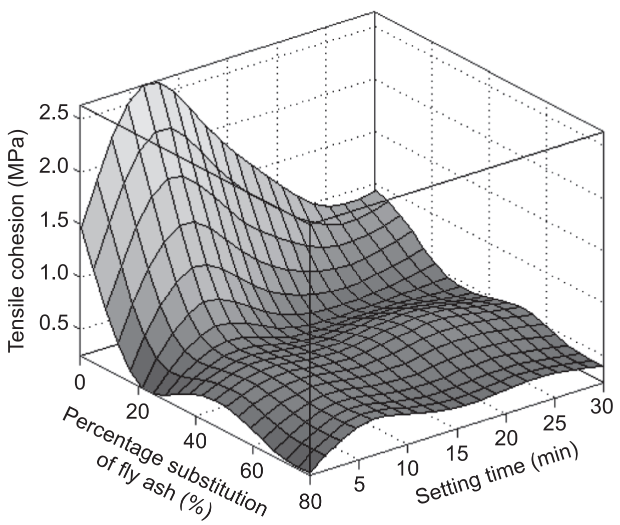

Figure 6. Functionality surface of FIS for mixture SC.

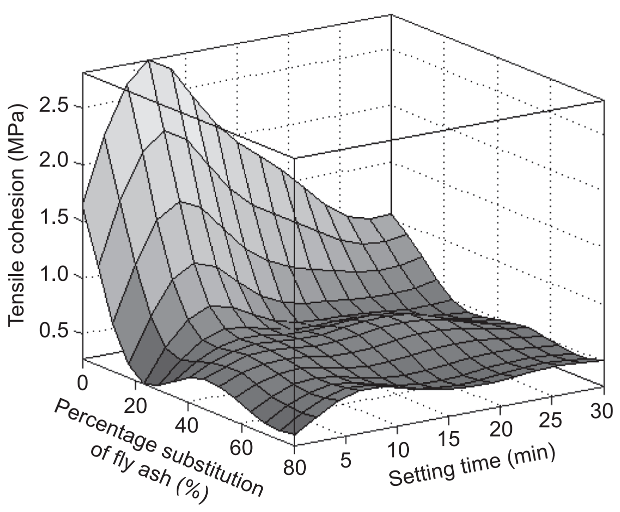

Figure 7. Functionality surface of FIS for mixture SF.

To evaluate severities of the risks, following criteria were set up:

– Probability of the given risk frequency;
– Concern of the interested groups about the risk;
– Possibility of avoidance of the realisation of the risk;
– Assessment of prospective loss.

Each of these criteria takes crisp states. The evaluation is performed by a responsible specialist. After evaluation of each separate criterion, the assessment of the total severity of the given risk is done.

The methodology problem consists in discrete states of the individual evaluated criteria which induce that the responsible specialist has to always tend to some of the given variant. In the result, it may mean either distinctive undervaluation or overvaluation of the given risk. However, in case we introduce individual criteria as the linguistic variables [5] where verbal values will be reciprocally overlapping fuzzy sets, the risk of wrong evaluation will be minimised. Moreover, this generalisation gives to a responsible specialist the possibility to enter the value of criteria in the form of any fuzzy set, which makes possible to consider the variability entering this process. The evaluation procedure of the severity of the risks is then realised by fuzzy inference system of Mamdani type (see above). The structure of this FIS is shown in Figure 8.

The individual verbal values of all linguistic variables were designed so that the calculation model would describe the given problems as correctly as possible. Setting up all membership functions (verbal values) was based on the FMEA methodology. The membership functions are shown in Figures 9-12. Owing to the demanding computing process and to the simplicity of the model, the shapes of triangle and trapezoid were chosen. Input variables except financial loss are designed with no unit. The range of each universe provides the volume of these variables.

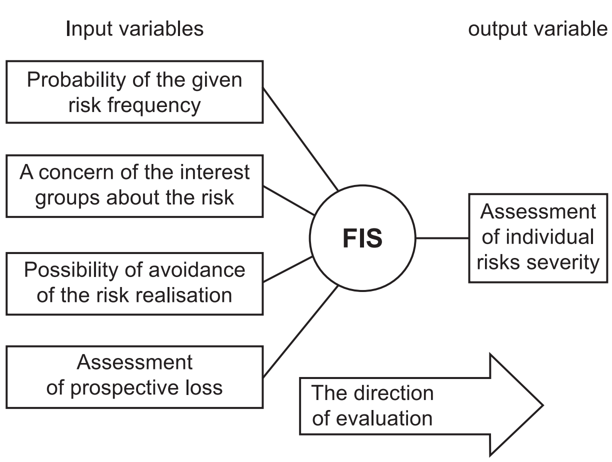

Figure 8. Structure of FIS.

For input variable concern of interested groups, three verbal values, namely low, middle and high concern were chosen (Figure 9). The range of this linguistic variable was determined as an interval <1;3>.

To the variable expressing presumed probability of the risk occurrence 5 verbal values were assigned (Figure 10), namely:

A – Improbable occurrence;
B – Exceptional occurrence;
C – Low occurrence;
D – Frequent occurrence;
E – Permanent occurrence.
The range of this variable is <1;5>.

The same number and shape of all verbal values has a linguistic variable which characterise the possibility of preventing the realization of the risks (Figure 10). It differs in the sense of the individual values:

A – prevention of the risk is easy;
B – provision against the risk occurrence are known and used in standard way;
C – the occurrence of the risk is difficult to predict, the provisions for prevention are known and used;
D – the occurrence of the risk is difficult to predict, the provisions for prevention are known but hard applicable;

Table 4. Coefficients used in *if - then* rules.

FIS	SB			SR			SF		
Rule	a_0	a_1	a_2	a_0	a_1	a_2	a_0	a_1	a_2
1	-0.0514	0.3415	1.3890	-0.0781	0.2917	1.4920	-0.0832	0.3282	1.7230
2	-0.0294	0.1625	-1.9330	-0.0765	-0.0197	2.0160	-0.0934	0.0232	1.4580
3	0.0014	0.0053	0.3331	0.0023	0.0443	-0.3400	-0.0081	0.0427	-0.2370
4	0.0045	0.0334	0.2581	0.0022	0.0412	0.5477	0.0034	0.0430	0.5390
5	0.0015	-0.0004	0.5970	0.0013	0.0319	0.1103	-0.0079	0.0363	0.6169
6	0.0112	0.0030	-0.0953	0.0178	-0.0081	-0.0130	0.0131	0.0008	-0.1031
7	0.0039	0.0882	-0.0910	0.0062	0.0835	-0.2484	0.0071	0.0635	-0.2358
8	0	0	-0.3956	0.0025	0.0093	0.0080	0.0104	-0.0073	-0.2876
9	0.0096	-0.0151	0.0643	0.0105	-0.0164	-0.0041	0.0118	-0.0169	0.0483

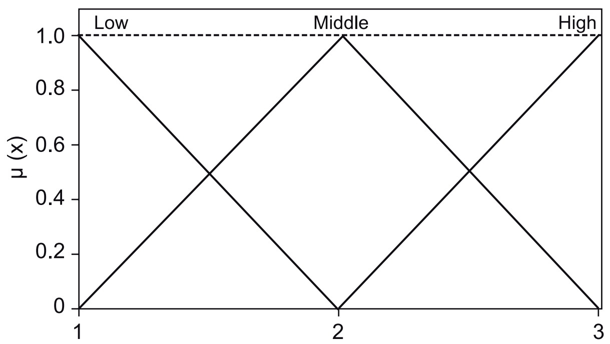

Figure 9. Structure of FIS.

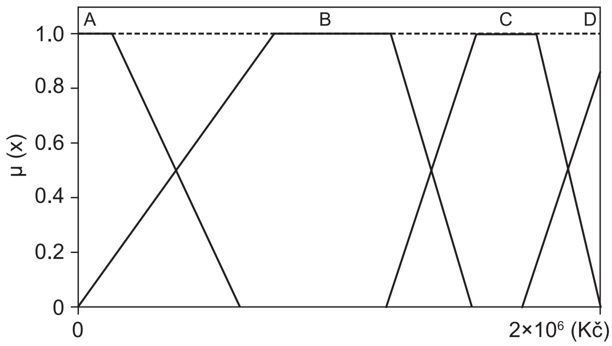

Figure 11. Verbal values (membership functions) of financial loss.

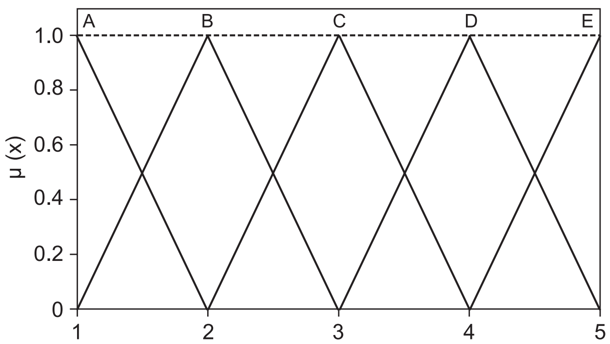

Figure 10. Verbal values (membership functions) of probability of the occurrence of the risk and possibility of risk prevention.

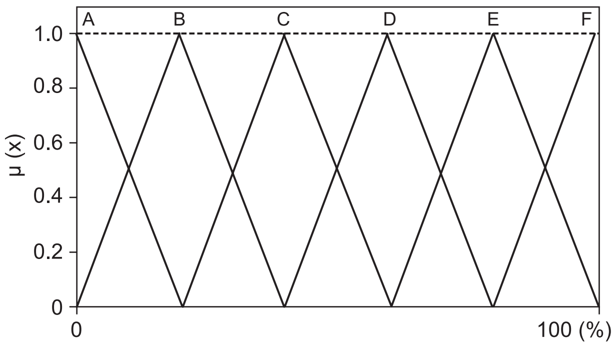

Figure 12. Verbal values (membership functions) of severity of given risk.

E – the provision for prevention of the realisation of the risk and mitigation of consequences are on the level of emergency readiness and reaction, only.

The last input linguistic variable is the estimation of possible financial or other losses when the risk is realized. The verbal values of this variable were designed as follows (see Figure 11):

A – Financial loss up to 100 000,- Kč, eventual administrative procedure;
B – Financial loss up to 1 000 000,- Kč, work injury with defined time of disability;
C – Financial loss over 1 000 000,- Kč, work injury with persistent effects;
D – Work injury with consequence of death.

The output linguistic variable of this process is an estimation of the total risk severity expressed in percentage, i.e. the range is the interval 0-100 %. To this linguistic variable 6 verbal values were assigned:

A – The risk is minimal and it is not looked at by the society;
B – Low severity: The activity, during which the risk originates, fulfils the legislative, normative and other conditions; solution of the problems is not urgent, occurrence of the risk is frequent and easy to predict, the provisions of prevention are known and easily applicable;
C – Middle risk: The risks related to the activity are insignificant, solution of the problems is not urgent, occurrence of the risk is frequent and easy to predict, the provisions of prevention are known and used in the standard way;
D – Significant severity: The risks related to the activity may cause non-fulfilment of legislative regulations, solution of the problems is urgent, occurrence of the risk is predictable, the provisions of prevention are known and used in the standard way, the risk does not cause financial losses, health damage, property and environment damage, making reparations is in organisation's power;
E – Very significant severity: Requirement of the need to control the risks during control at the activities is a priority, the interested parties and groups manifest interest in the given risk, training and control of the workers is necessary. The risks related to the activities may cause non-fulfilment of legislative conditions, occurrence is predictable, the provisions of prevention are known and used, the risk usually causes financial losses, health damage, damage of property and environment, making reparations is in the organisation's power;
F – The risk is critical: The risk related to the activity is from the viewpoint of the organization extremely significant, the need for solution is a priority, the interested parties and groups manifest serious interest in the given risk, training and control of the workers is necessary, the occurrence is predictable, the provisions of prevention are known and used, the risk usually causes financial losses, health damage, property and environment damage, making reparations is not entirely in the organisation's power.

As mentioned above, the evaluating process is performed by FIS of Mamdani type, especially in the order to make it possible to extract conditioned rules from experts´ knowledge and experience. With regard to the character of the problems, defuzzyfication Centroid was chosen (resulting value is gravity centre below the membership function of evaluated fuzzy set, see [4] and [5]). Logic conjunctions *and* and *or* (conjunction and disjunction) were constructed by the maximum and minimum operation (see [4] and [5]).

The conditioned *if - then* rules designed for FIS:

1. *If* (Assessment of losses is D) *or* (Variability of occurrence is E) *or* (Possibility of prevention is E) *or* (Concern of interested parties is high) then (Risk severity is F);
2. *If* (Assessment of losses is A) *and* (Variability of occurrence is A) *and* (Possibility of prevention is A) *and* (Concern of interested parties is low) *then* (Risk severity is A);
3. *If* (Assessment of losses is not C or D) *and* (Variability of occurrence is B) *and* (Possibility of prevention is B) *and* (Concern of interested parties is middle) *then* (Risk severity is B);
4. *If* (Assessment of losses is A) *and* (Variability of occurrence is C) *and* (Possibility of prevention is C) *and* (Concern of interested parties is middle) *then* (Risk severity is C);
5. *If* (Assessment of losses is B) *and* (Variability of occurrence is D) *and* (Possibility of prevention is D) *and* (Concern of interested parties is high) *then* (Risk severity is D);
6. *If* (Assessment of losses is B) *then* (Risk severity is D);
7. *If* (Assessment of losses is C) *then* (Risk severity is E).

In the first rule, that describes high values of criteria (input linguistic values), logic conjunction *or* is used, the other rules are constructed with the conjunction *and*. For the design of this base of rules the expert knowledge not only from the field of building materials but also from the field of risk of management were very important.

RESULTS AND DISCUSSION

The paper is divided by subject matter into two parts. The first part indicates the possibilities of calculation modelling of tensile cohesion of polymer-cemented adhesive materials for ceramic tiling elements, into which fly ash was applied as a filler, by fuzzy inference systems (FIS). The utilisation of these systems seems to be convenient when considering variable properties of fly ash. The models should help to predict the behaviour of adhesive materials.

The type Takagi-Sugeno enabling extraction of the base of rules not only from expert's knowledge and experience but also from experimental data was chosen with respect to the problem solved. Setting time determined by tensile cohesion and percentage substitution of fly ash were specified as input variables. The output variable was tensile cohesion.

After modification of the measured values into the data base, training of the rules base by ANFIS method was done. Resulting FIS were then modified to fulfil required expert demands in the best way. Figure 13 shows the differences between the real measured values of tensile cohesion of a mixture SB and the values calculated by FIS designed for this mixture.

The mean deviations for all designed FIS are:
– SB: 0.04 MPa;
– SC: 0.07 MPa;
– SF: 0.06 MPa.

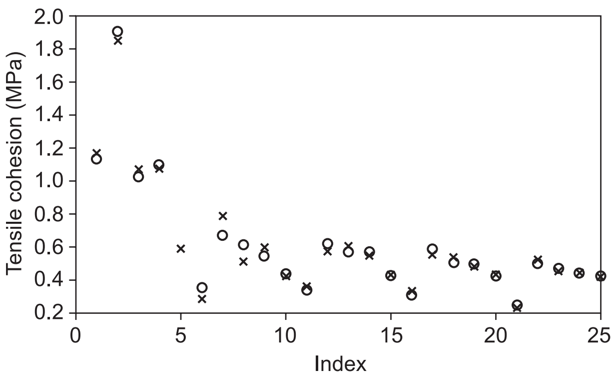

Figure 13. Comparison of measured and calculated values by FIS for mixture with additive SB; ○ – measured values, × – calculated values by FIS.

From these values it can be assumed that designed FIS approximate sufficiently the modelled systems. Let`s have a mixture with substitution 18.8% of fly ash for milled lime stone after 22 minutes of setting with additive SB. Calculated tensile cohesion is approximately 0.64 MPa.

The second part of the paper deals with quantification of the risks related to fly ash application. The resulting severity of each risk was evaluated on the basis of several general criteria expressing the concern of interested parties, possibility of the risk prevention, probability of the occurrence of the risk and assessment of the loss when the risk is realized. For the risk quantification, FIS Mamdani which is more convenient with respect to expert`s experience of the problems was chosen. Eight conditioned rules have been set up. Fuzzyfication was performed by singleton and defuzzyfication by gravity centre method.

On the basis of expert assessment of relevant criteria of all mentioned risks, the Table 4 was compiled. In the last column calculated severity of risk by FIS is given.

From the experts´ assessments of individual criteria and from the calculated severity of risks it results that the most significant risks seems to be the limitation of the efficiency of polymeric admixture due to fly ash application and its inconsistent granulation. On the contrary, the lowest values of the severity were recorded at chemical composition variability of fly ash and increased absorbability.

CONCLUSIONS

The paper shows how to use fuzzy sets and fuzzy inference systems (FIS) for mathematical modelling of physico-mechanical characteristics and for evaluating of risks in the process of development of new materials. Two types of FIS have been shown. The first one, Takagi-Sugeno type, was used for approximative prediction of

Table 5. Assessment of individual risks severity.

Variable / Variant of risk	Concern of interested parties	Probability of occurrence	Possibility of prevention	Assessment of losses	Assessment of individual risks severity (%)
Various chemical composition of fly ash	2.8	2.2	2.0	80 000	63.1
Various granulation of fly ash	2.7	1.8	1.0	200 00	78.5
Various hydraulic activity of fly ash	2.9	2.0	1.9	100 000	74.4
Reduction of polymeric efficiency due to fly ash application	3.0	1.6	1.0	200 000	79.7
Increasing absorption of fly ash	2.8	1.9	1.8	80 000	63.1

tensile cohesion of adhesive agents. It is possible to save economic costs of laboratory testing using designed FIS. These systems enable the insight into the behaviour of tensile cohesion. It must be considered that all models depend on the measured data that were used for the testing base of rules, especially for the design of coefficients a_{0k}, a_{1k}, and a_{2k} (tab. 4). With extension of the testing data, it is possible to upgrade FIS for more accurate description of the surveyed problems.

The second type of FIS (Mamdani) was used for the extension of the FMEA methodology. Using FIS for evaluation of the risk severity seems to be very useful. Designed FIS can be used for the evaluation of the risk severity for almost any problem by changing the verbal values of linguistic variables and *if* - *then* rules.

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