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Fuzzy Logic Model for Prediction of Properties of Fiber Reinforced Self-compacting Concrete

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A fuzzy logic prediction model for fresh and hardened properties of self-compacting concrete (SCC) containingfly ash and polypropylene fibers has been developed. Materials studied experimentally contained 0 %, 10 %, 20 % and 30 wt. % fly ash replacing cement, with four fiber contents at 3, 6, 9 and 12 kg/m^3 in each concrete. Water/cement ratio and superplasticizer content were kept constant at 0.40 % and 1.0 % of cement content, respectively. In our models, properties of fresh and hardened concrete containing fibers, fly ash and cement content were predicted for fresh as well as a function of time for hardened concrete.The results obtained from the fuzzy logic prediction model were compared with the average results of the experiments and were found to be remarkably close to one another. Polypropylene fibers provide a reinforcement, the use of fly ash lowers environmental contamination, while satisfactory properties are obtained.

Keywords: fuzzy logic, self-compacting concrete, fly ash, polypropylene fibers.

1. INTRODUCTION

Concrete, one of the principal structural materials and widely used around the world, is a heterogeneous material consisting of cement, water, sands and aggregates [1 – 7]. Although its heterogeneous structure causes some undesirable effects [8] concrete remains an indispensable construction material – while allowing engineers to incorporate many materials into it. Therefore, developments in the construction industry throughout the world along with the necessity for new concrete applications have led to many studies on types of concretes [9, 10].

Self-Compacting Concrete (SCC), a new kind of High Performance Concrete (HPC) with excellent deformability and segregation resistance, was first developed in Japan in 1986. It is a special kind of concrete that can flow through and fill the gaps around reinforcement and in corners of molds without any need for vibration and compaction during the placing process [11, 12]. Due to this property, SCC's use in civil engineering has gradually increased over the last several years [13]. Generally, SCC is produced using a new generation of superplasticizers to reduce the water/binder ratio. Additionalcementitious or inert materials such as limestone powder, natural pozzolans or fly ash can be used to increase the viscosity and fresh concrete workability and also to reduce the cost of SCC.

The term “fiber-reinforced concrete” is defined by American Concrete Institute in their standard ACI 116R, Cement and Concrete Terminology, as a concrete containing dispersed randomly oriented fibers. Inspired from the ancient applications of techniques of natural fibers (straws, chips, horse tails, goat hair, plumes, etc.), artificial fibers are commonly used in order to improve mechanical properties of concrete [14]. Many different kinds of fibers such as metallic, polymeric, coated, uncoated or modified by irradiation, have been used in concrete technology because of their specific advantages [15 – 20]. Especially, steel fibers have improved several concrete properties. Thus, tensile, flexural, impact andfatigue strength, wear resistance, deformation capability, load bearing capacity after cracking and toughness properties of concrete have been significantly improved by the use of steel fibers [21 – 26]. The reason is simple,steel fibers have high elastic modulus and stiffness. Steel fiber reinforced concretes (SFRCs) have been used in several areas of infrastructure and industrial floors, overlays, and channel lining; laboratory tests and field applications have shown SFRCs to be more durable than plain concrete subjected to high water flow [8, 27]. However, steel fibers easily appear at surface concrete and suffer from rusting, this apart from electric conductivity and magnetic field problems. If a SFRC is used in the

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runway of an airport, in high speed railway systems, or in nuclear power plants, safety problems might appear [18, 23]. Moreover, steel fibers increase the unit weight of concrete.

Recent progress in polymeric materials involves the use of polypropylene (PP) fibers. Thus, a new generation of PP fibers may be a potential replacement for steel fibers since the former have good ductility, fineness, and are dispersible easily – so they can restrain propagation of cracks [18]. We note that apart from linear fibers also two-dimensional PP fiber mats find good uses [28].

On the other hand, it is well-known that incorporation of the fibers into the concrete reduces the workability of concrete, a handicap for on-site applications. Thus, one of the ways to compensate for the workability loss associated with the inclusion of the fibers is by combination of SCC, fibers and fly ash (FA).

The use of fly ash reduces the demand for cement, fine fillers and sand that are required in SCC [29, 30]. Fly ash, a by-product of coal power plants, has been reported to improve mechanical properties of concrete such as freeze-thaw resistance, sulphate resistance, weaken alkali-silica reaction, enhancedurability and abrasion resistance. Also shrinkage, permeability [31], chloride penetration, corrosion [32] and wear loss of hardened concrete [33] are decreased. The usage of industrial waste materials in concrete, in regards to both environmental pollution and the positive effect on a country's economy, is beyond dispute. Utilization of waste material in construction industry reduces certain technical and environmental problems of plants and decreases electric costs – apart from reducing the amount of solid waste, greenhouse gas emissions and enhancing conservation of existing natural resources. In Turkey, the annual fly ash production is about 18 million tons – more than the rest of all industrial wastes created in the country [34]. Unsalvaged FA causes environmental pollution and its storage costs is very high [31].

An area that has not been extensively examined previously is the fiber additions on the mechanical and durability properties of SCC with fly ash. Researchers have studied fly ash concrete and fiber reinforced concrete separately; clearly investigation of reinforcing fibers together with fly ash in concrete is an area that deserves an investigation.In this situation, we have studied effects of incorporating 10 %, 20 % and 30 % FA and 3, 6, 9 and 12 kg/m^3 monofilament polypropylene hybrid fibers into the SCC on physical and mechanical properties of fresh and hardened concretes.

In 1965, Zadeh [35] pioneered the development of fuzzy logic (FL). Aristotelian logic has two possibilities only. Zadehprovided a mathematical tool which enables us to describe and handle imprecise notions such as "a set of all real numbers which are much greater than 1", "a set of beautiful women," or "a set of tall men". In this work we have used also the FLapproach to develop a method of estimating properties of concrete, fresh and hardened. In our model, cement content, fly ash content and PP fiberscontent constitute input.Slump flow (S), t_{500} flow time (T), V-funnel (V) and J-ring (J) values of the fresh concrete are predicted.

2. MATERIALS AND EXPERIMENTAL TECHNIQUES

Dry and clean natural river sand (NRS), crushed stone I (Cst-I) and crushed stone II (Cst-II) were used in concrete mixture. The CSthad 12 mm maximum aggregate size with 0.93 % water absorption value and its density at saturated surface dry (SSD) condition was 2.70 g/cm^3. The water absorption values of the NRS and CS sands used were 3.02 % and 2.91 % and their densities at SDD condition were 2.67 g/cm^3 and 2.69 g/cm^3, respectively. The gradations of aggregates and the grading of the mixed aggregate are presented in Table 1.

Table 1. The gradations of aggregates and the grading of the mixed aggregate

	NRS	Cst-I	Cst-II	Mixture
75 μm	1	0	0	7.7
150 μm	5	0	0	11
300 μm	18	0	0	15.5
600 μm	32	0	0	21.9
1.18 mm	53	0	0	30.7
2.36 mm	81	0	1	43.5
4.75 mm	96	0	1	61.6
9.5 mm	100	50	12	87.2
12.5 mm	100	100	100	100
Fineness modulus	4.1	7.5	7.9	5.2

The cement used in concrete mixtures was Portland cement, CEM I 42.5 R. Physical and mechanical properties and chemical analysis of cement are presented in Tables 2 and 3, respectively.

Table 2. Physical and mechanical properties of Portland cement

Compressive strength (MPa)			Flexural strength (MPa)		
2 Days	7 Days	28Days	2 Days	7 Days	28Days
22.5	36.6	47.8	3.7	5.6	6.9

Initial setting time (minute)	Final setting time (minute)	Le Chatelier (mm)	Specific gravity (g/cm^3)	Blaine (cm^2/g)
145	195	1	3.15	4150

Table 3. Chemical analysis of Portland cement and fly ash (weight %)

Compound	Portland cement	Fly ash
Total SiO_2	22.90	57.2
Al_2O_3	5.32	25.53
Fe_2O_3	3.63	6.01
CaO	55.83	1.14
MgO	1.99	2.42
SO_3	2.62	0.16
Cl	0	0.014
LOI*	4.20	1.12
Free CaO	0.82	0.12
Total Admixture	19.45	–

* Loss of ignition.

The class of FA used in this study was classified as F fly ash according to ASTM C 618 [36]. Its chemical composition is presented in Table 3. The Blaine fineness was 5230 cm^2/g. Specific gravity was 2.1 g/cm^3. The increment of the cement paste in SCC is very important because it is an agent that carrier the aggregates [37].

We have applied a novel modified polycarboxylic ether superplasticizer (SP). The admixture is light brown in color, with a specific gravity of 1.08, pH value = 5.7 and solid content = 40 wt. %. In developing a SCC, usually a new generation polycarboxylic based superplasticizers are used together with either some chemical or mineral admixtures that provide viscosity values in the appropriate range.

The PP monofilament fibers used are wavy-shape, 45 mm long with 1 mm of diameter, and density = 0.91 g/cm^3. Their elastic modulus is 5.88 GPa, and the tensile strength is 320 MPa.

Concrete compositions studied are listed in Table 4. Binder content and water-binder ratio was 450 kg/m^3 and 0.35, respectively. Fly ash was replaced with cement at 10 %, 20 % and 30 % ratios. The dosage of superplasticizer was 1.0 % of the binder content of concrete. The fibers were incorporated into the concrete in the content of 3, 6, 9 and 12 kg/m^3.

Table 4. Mixture proportions of the concrete (kg/m^3)

Codes	Cement	FA	Water	SP	Fiber	Fine aggregate	Coarse aggregate
A1	450	0	158	4.5	0	967	807
A2	450	0	158	4.5	3	964	804
A3	450	0	158	4.5	6	959	799
A4	450	0	158	4.5	9	955	796
A5	450	0	158	4.5	12	950	792
B1	405	45	158	4.5	0	961	801
B2	405	45	158	4.5	3	957	797
B3	405	45	158	4.5	6	952	793
B4	405	45	158	4.5	9	947	790
B5	405	45	158	4.5	12	942	786
C1	360	90	158	4.5	0	954	795
C2	360	90	158	4.5	3	949	791
C3	360	90	158	4.5	6	945	787
C4	360	90	158	4.5	9	940	783
C5	360	90	158	4.5	12	935	779
D1	315	135	158	4.5	0	947	789
D2	315	135	158	4.5	3	942	785
D3	315	135	158	4.5	6	937	781
D4	315	135	158	4.5	9	932	777
D5	315	135	158	4.5	12	928	773

The concrete mixtures were prepared in a laboratory mixer with the capacity of 60 dm^3. In a typical mixing procedure, the materials were placed in the mixer in the following sequence: first course aggregates and fine aggregates and fibers together, followed by cement, initially dry material mixed for 1 minute, then addition of 90 wt. % of water. After 1.5 minutes of mixing, the rest of mixing water together with the SP was added. All batches were mixed for a total time of 5 minutes. Specimens for the testing of the hardened material properties were prepared by direct pouring of concrete into molds without compaction.

From each concrete mixture, six specimens were cast in cylindrical molds of 150 mm diameter and 300 mm height. Three 150 mm cubes were cast. The cubes were used for the compressive strength testing. The cylinders were used for elasticity modulus and splitting tensile strength tests. After demolding, the specimens were placed in a saturated limewater bath until the time of testing. Curing was performed in accordance with ASTM C511 [38] standard. It is well known that adequate curing of concrete is very important not only to achieve the desired compressive strength but also to make durable concrete. Compressive strength tests were carried out in accordance with ASTM C39 [39]. Splitting tensile strength tests were performed according to ASTM C496 [40]. Flexural strength and elasticity modulus were determined according to ASTM 293 [41] and ASTM C469 [42], respectively.

Numerous methods are available for determination of rheological behavior of materials with or without fiber reinforcement - including those used earlier by some of us [43 – 45]. One can perform rheological testing [46], which for SCC is applied to determine viscosity and yield strength in the plastic state. Rheology, however, is laboratory oriented and not very convenient for field use. Therefore, other field-oriented test methods are used in quantifying properties and workability of fresh SCC. We have determinedself-compaction abilities of the mixtures according to standards of Self Compacting Concrete Committee of European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC) [47].

We have performed three types of workability tests on fresh concrete mixtures, namely slump flow test, J-ring test and V-funnel test.

The slump flow test is used to evaluate the horizontal free flow (deformability) of SCC in the absence of obstructions. The test method is very similar to that for ordinary concrete. The difference is that, instead of the loss in height, the diameter of the spread concrete is measured in two perpendicular directions and recorded as slump flow. The higher the slump flow, the greater is the concrete's ability to fill formworks. During the slump flow test, the time required for the concrete to reach a diameter of 500 mm is also measured and recorded as t_{500}. This parameter is an indication of the viscosity of concrete and indicates how stable the concrete is. A lower time points to a greater fluidity or smaller workability loss.

J-ring test is used to determine the passability of the concrete. It is an extension of the slump flow test in which a ring apparatus is used with the inside diameter h_1 and the outside diameter h_2. The flow of mix is obstructed by the bars, thereby creating a difference of levels in the concrete. This gives an indication of the passing ability and restricted deformability of concrete [47].

The V-funnel test is used to determine the fluidity or viscosity of concrete. The V-funnel is filled with concrete; the time it takes for the concrete to flow through the apparatus is measured. Clearly good flowable and stable concrete would take a short time to flow out. The V-funnel test results are related to material viscosity [47].

3. EXPERIMENTAL RESULTS

3.1. Fresh concrete

Properties of fresh SCC as a function of fly concentration and fiber content are presented in Fig. 1.

We shall now look for possible correlations between different properties. Slump flow might be a decisive property.In Fig. 2 we demonstrate a relationship between slump flow and the other properties. The correlation parameter $R^2 = 1$ would represent a perfect agreement of calculated and experimental values.

3.2. Hardened concrete results

Several properties are presented in Table 5 as a function of time in days.

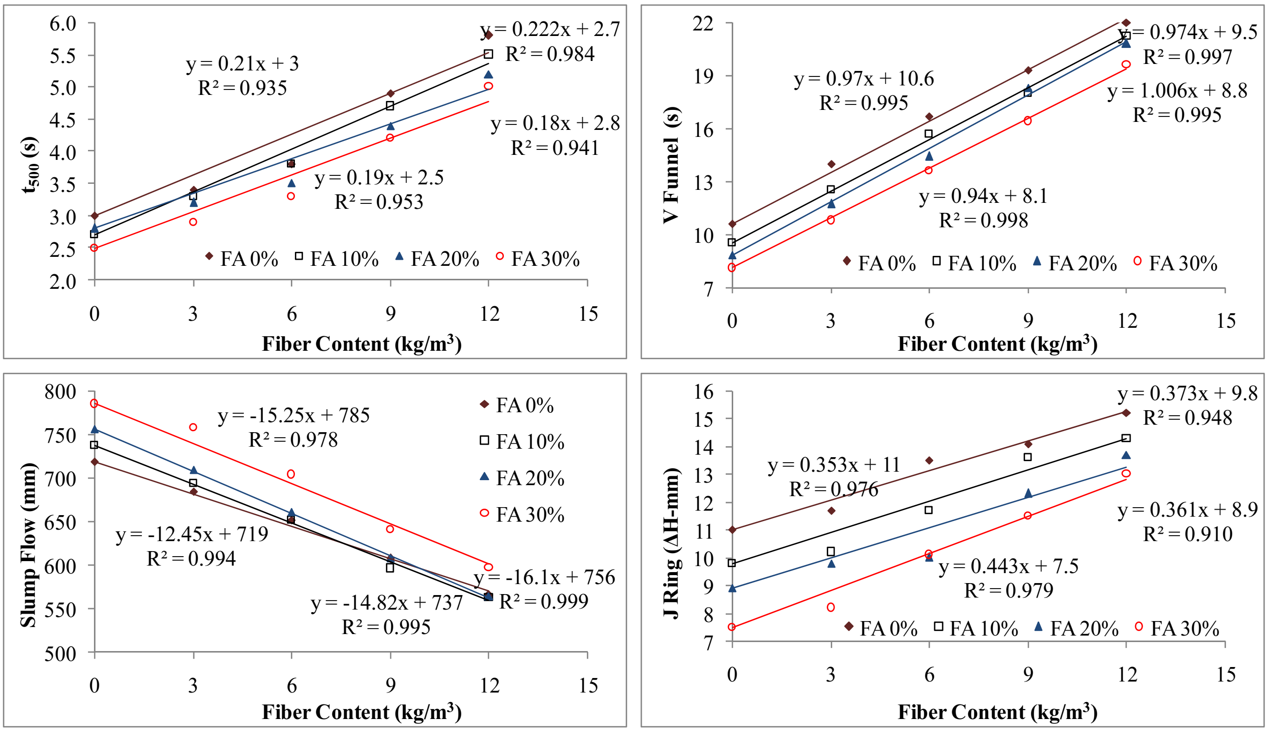
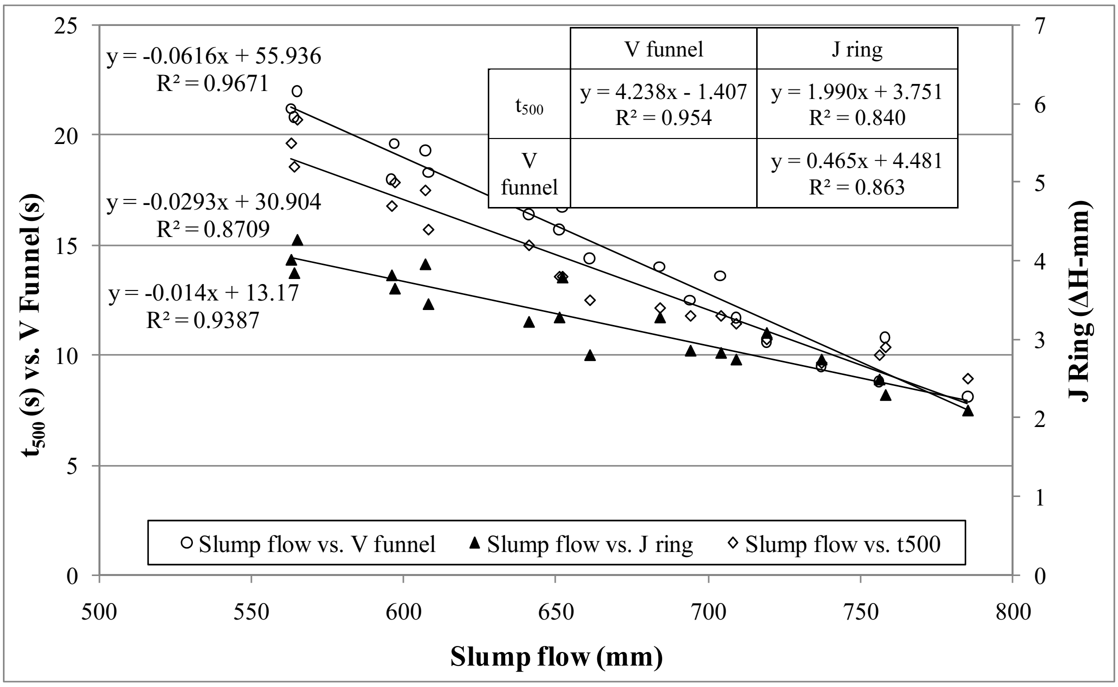


Fig. 1. Effect of fiber content and fly ash replacement on the fresh properties of concrete



	V funnel	J ring
t_{500}	y = 4.238x - 1.407 R² = 0.954	y = 1.990x + 3.751 R² = 0.840
V funnel		y = 0.465x + 4.481 R² = 0.863

Fig. 2. Relationship between slump flow and other fresh concrete tests

Table 5. The results of hardened concrete properties of SCC

Codes	Comp. Str. (MPa)			Flexural			Splitting			E mod		
	days 7	days 28	days 90	days 7	days 28	days 90	days 7	days 28	days 90	days 7	days 28	days 90
A1	62.1	76.4	85.6	7.5	7.7	8.1	4.1	5.9	6.8	43.6	46.8	48.7
A2	65.4	78.2	88.1	7.8	8.1	8.2	4.4	6.2	7.3	45.1	46.2	48.9
A3	63.6	80.4	90.3	8.0	8.7	9.2	4.3	6.5	7.7	44.3	47.3	49.6
A4	65.7	79.8	89.7	8.4	9.1	10.1	4.5	6.3	7.4	45.5	47.0	49.2
A5	62.6	78.0	87.6	9.5	10.6	11.6	4.2	6.0	7.0	44.7	46.7	48.3
B1	57.4	68.6	78.2	6.8	6.9	7.2	3.8	5.0	6.3	42.8	44.9	47.3
B2	57.9	70.3	79.5	7.1	7.5	7.9	3.8	5.3	6.5	43.3	45.0	47.8
B3	58.5	71.4	80.4	7.8	7.9	8.0	3.9	5.6	6.4	44	45.8	48.1
B4	60.2	73.8	82.6	8.0	8.5	8.7	4.1	5.7	6.7	43.8	46.2	48.3
B5	59.7	72.7	81.0	8.7	9.0	9.3	4.0	5.5	6.5	44.3	45.6	47.9
C1	53.8	65.2	72.4	6.3	6.5	6.8	3.6	4.8	5.0	41.5	44.7	46.3
C2	54.6	67.2	74.7	6.6	6.8	6.9	3.8	5.1	5.4	43.2	45.6	47.1
C3	54.0	66.4	74.8	6.9	7.1	7.2	3.6	4.9	5.7	42.9	44.8	46.8
C4	55.1	67.8	76.1	7.2	7.4	7.4	4.0	5.1	6.0	43.8	45.2	47.5
C5	54.5	66.3	75.0	7.7	7.8	7.9	3.7	5.0	5.6	43.7	44.5	47.3
D1	50.3	60.9	68.3	5.9	5.9	6.0	3.4	3.9	4.5	40.8	42.7	44.3
D2	51.5	62.3	69.6	6.4	6.6	6.8	3.6	4.3	4.7	41.7	43.2	44.5
D3	53.1	64.7	71.0	6.7	6.9	6.9	3.8	4.7	5.0	41.8	43.8	44.9
D4	52.6	63.1	72.8	6.9	7.2	7.4	3.6	4.6	5.3	42.3	42.9	45.2
D5	49.8	61.8	69.3	7.2	7.5	7.6	3.3	4.3	4.7	41.4	43.6	44.8

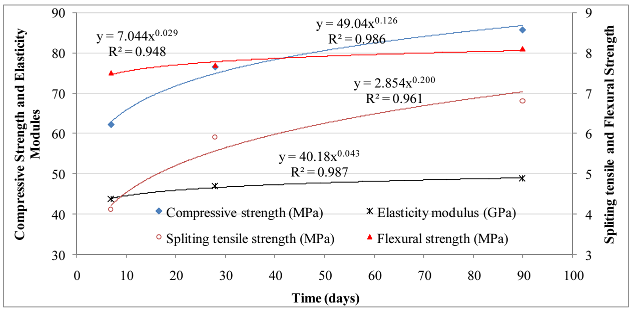


Fig. 3. Changes of hardened properties with time for A1

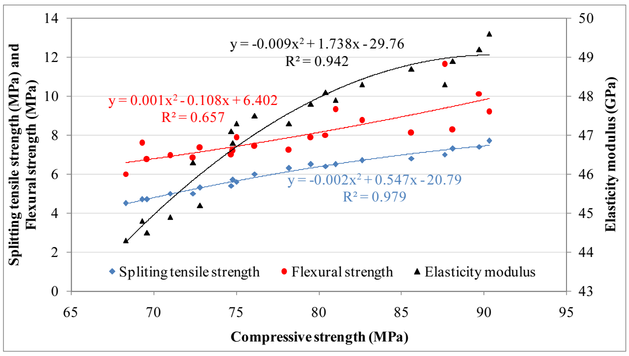


Fig. 4. Relationship between parameters of 90-days concretes vs. compressive strength

An example of relationships between concrete strength and concrete age are presented in Fig. 3 for the A1 material. Similar results have been obtained for other materials but are not included for brevity. In all cases the correlation coefficients R^2 are as good as those displayed in that Figure.

Compressive strength of concrete is known as the most important parameter representing the material quality. While there is no doubt that the splitting tensile strength, flexural strength and modulus of elasticity all increase with increase in the compressive strength, there is no agreement on the precise form of the relationships. Our attempt to provide such relationshipsfor SCC is presented in Fig. 4.

4. FUZZY LOGIC APPROACH

4.1. Basics of the approach

The main idea of fuzzy set theory is quite intuitive and natural: instead of determining the exact boundaries as in an ordinary set, a fuzzy set allows no sharply defined boundaries because of generalization of a characteristic function to a membership function [48, 49]. Fuzzy logic concept provides a natural way of dealing with problems in which the source of imprecision is the absence of sharply defined criteria rather than the presence of random variables. Fuzzy approach considers cases where linguistic uncertainties play some role in the control mechanism of the phenomena concerned. Here uncertainties do not mean random, probabilistic and stochastic variations, all of which are based on the numerical data. Zadeh was motivated in his work on fuzzy logic by the observation that the key elements in human thinking are not numbers but levels of fuzzy sets. Further, he saw each linguistic word in a natural language as a summarized description of a fuzzy subset in a universe of discourse representing the meaning of the word. In consequence, he introduced linguistic variables as variables whose values are sentences in a natural or artificial language[50].

Since practitioners of Materials Science and Engineering, Mechanics and related disciplines are not necessarily familiar with the fuzzy set theory, before presenting our own contributions we discuss basic tenets of this approach. The basic elements of each fuzzy logic system are, as shown in Fig. 5, rules, fuzzifier, inference engine, and defuzzifier.

Input data are most often crisp values. The task of the fuzzifier is to map crisp numbers into fuzzy sets (cases are also encountered where inputs are fuzzy variables described by fuzzy membership functions). Models based on fuzzy logic consist of "If-Then" rules. A typical "If-Then" rule would be:

IF the value of dosage is "low" and the value of fly as is "low" and the value of fiber is "middle" THEN the result X_n is "value of output" The fact following "If" is called a premise or hypothesis or antecedent. Based on this fact we can infer another fact that is called a conclusion or consequent (the fact following "Then"). A set of a large number of rules of the type: "If premise Then conclusion" is called a fuzzy rule base.

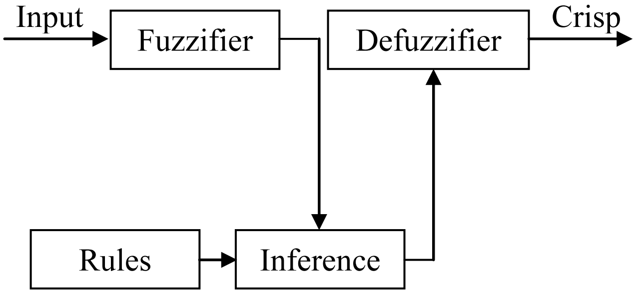


Fig. 5. Basic elements of a fuzzy logic [49]

We would like to note that - in classical expert systems – rules are derived exclusively by human experts. In fuzzy rule-based systems, the rule base is formed with the assistance of human experts; recently, numerical data has been used as well in a combination of numerical data with human experts. An interesting case appears when a combination of numerical information obtained from measurements and linguistic information obtained from human experts is used to form the fuzzy rule base. In this case, rules are extracted from numerical data in the first step. In the next step this fuzzy rule base can (but need not) be supplemented with the rules collected from human experts. The inference engine of the fuzzy logic maps fuzzy sets onto fuzzy sets. A large number of different inferential procedures are found in the literature. In most papers and practical engineering applications, a minimum inference or product inference is used. During defuzzification, one value is chosen for the output variable. The literature also contains a large number of different defuzzification procedures. The final value chosen is most often either the value corresponding to the highest grade of membership or the coordinate of the center of gravity [49].

The fuzzy approach considers the cases where linguistic uncertainties play some role in the control mechanism of the phenomena concerned [51]. The key idea in fuzzy logic is allowance of partial belongings of any object to different subsets of the universal set - instead of belonging to a single set fully. Partial belonging to a set can be described numerically by a membership function which assumes values between 0 and 1 inclusively. For instance, Fig. 6 shows a typical membership function for small, medium and large class size in an universe U. Thus, these verbal assignments are fuzzy subsets of the universal set. In Figure 6 set values less than 2 are considered "small"; those between 4 and 6 are "medium"; while values larger than 8 are definitely "large". However, intermediate values such as 2.2 partially belong to the subsets "small" and "medium". In fuzzy terminology 2.2 has a membership value of 0.9 in "small" and 0.1 in "medium", but 0.0 in "large" subsets. The literature is rich with references concerning the ways to assign membership values or functions to fuzzy variables. Among these ways are intuition, inference rank ordering, angular fuzzy sets, neural networks, genetic algorithms, inductive reasoning, etc. Especially, the intuitive approach is used rather commonly because it is simply derived from capacity of humans to develop membership functions through their own innate intelligence and understanding. Intuition involves contextual and semantic knowledge about an issue; it can be also involve linguistic truth values about this knowledge [50].

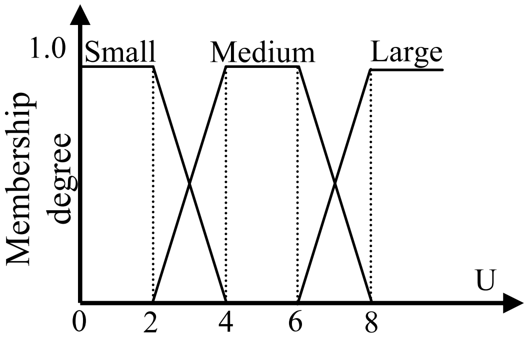


Fig. 6. Fuzzy subsets [50]

Even if the measurements are carefully carried out as crisp quantities, they can be fuzzified. Furthermore, if an uncertainty arises because of imprecision, ambiguity or vagueness, then the variable is fuzzy and can be represented by a membership function. Unlike the usual constraint where, say, the variable in Fig. 6 must not exceed 2, a fuzzy constraint takes the form as saying that the same variable should preferably be less than 2 and certainly should not exceed 4. This is tantamount in fuzzy sets terms that values less than 2 have membership of 1 but values greater than 4 have membership of 0 and values between 2 and 4 would have membership between 1 and 0. In order to simplify the calculations in practical applications, usually the membership function is adopted as linear. The objective then can be formulated as maximizing the minimum membership value; this has the effect of balancing the degree to which the objective is attained with degrees to which the constraints have to be relaxed from their optimal values [51]. Fuzzy has recently been used and successfully applied in a wide range of scientific areas by many researchers, and it is obtained optimal results [49 – 55].

4.2. Model Construction

We have developed a fuzzy logic model prediction for V-funnel, t_{500}, J-ring, slump flow and slump diameter testing results. SCCs containing different cement, fly ash and fiber contents were considered – fresh concretes as well as hardened ones so that time is a variable in the latter case.

Experimental results were used to train modelsin the design of fuzzy systems. To use sample data and derive the necessary rule base by the fuzzy inference procedure is a very common method in defining the fuzzy rule base. A small numbers of membership functions have been used because the model becomes exponentially more complex as the number of variables or membership functions increases.

Concentrations of fibers, fly ash and cement were used as input variables to predict fresh concrete properties – such as slump flow, V-funnel, t_{500} and J ring values as output parameters. Then fresh SCCs properties were used as input parameters to predict hardened concrete properties including compressive strength, flexural strength, splitting tensile strength and elasticity modulus.

In the models, membership functions of cement, fly ash and fiber were 4, 4 and 5, respectively. For prediction of fresh concrete properties, 10 membership functions of output parameters were defined as $X_1, X_2, ..., X_{10}$ to ensure sufficient accuracy ofthe output. For hardened concrete properties we have 12 membership functions of output, that is$X_1, X_2, ..., X_{12}$. The number of membership functions was determined according to accuracy of the model and range of data exchange.After selection of membership functions, 80 (4×4×5) rules were formed in modeling.

For control purposes, fuzzy sets can be used to set up rules as follows:

Rule$_1$: IF “dosage” is very high and “fly ash” is low and “fiber” is very low THEN X_1;

Rule$_2$: IF “dosage” is high and “fly ash” is low and “fiber” is low THEN X_2;

Rule$_3$: IF “dosage” is high and “fly ash” is very high and “fiber” is very high THEN X_3;

Rule$_n$: IF “dosage” is n and “fly ash” is n and “fiber” is n THEN X_n.

A block diagram used in fuzzy modelling of fresh concrete properties, a block diagram used for fuzzy modelling of hardened concrete properties and a block diagram used for fuzzy modelling of hardened concrete properties from fresh SCCs properties are presented respectivelyin Figs. 7 – 9.

4.3. Fuzzy logic results for fresh concrete

The results from the use of our fuzzy model are compared with experimental ones for fresh concrete in Fig. 10. Prediction results with fuzzy logic of fresh concrete properties are similar to experimental results and found remarkably close to each other.

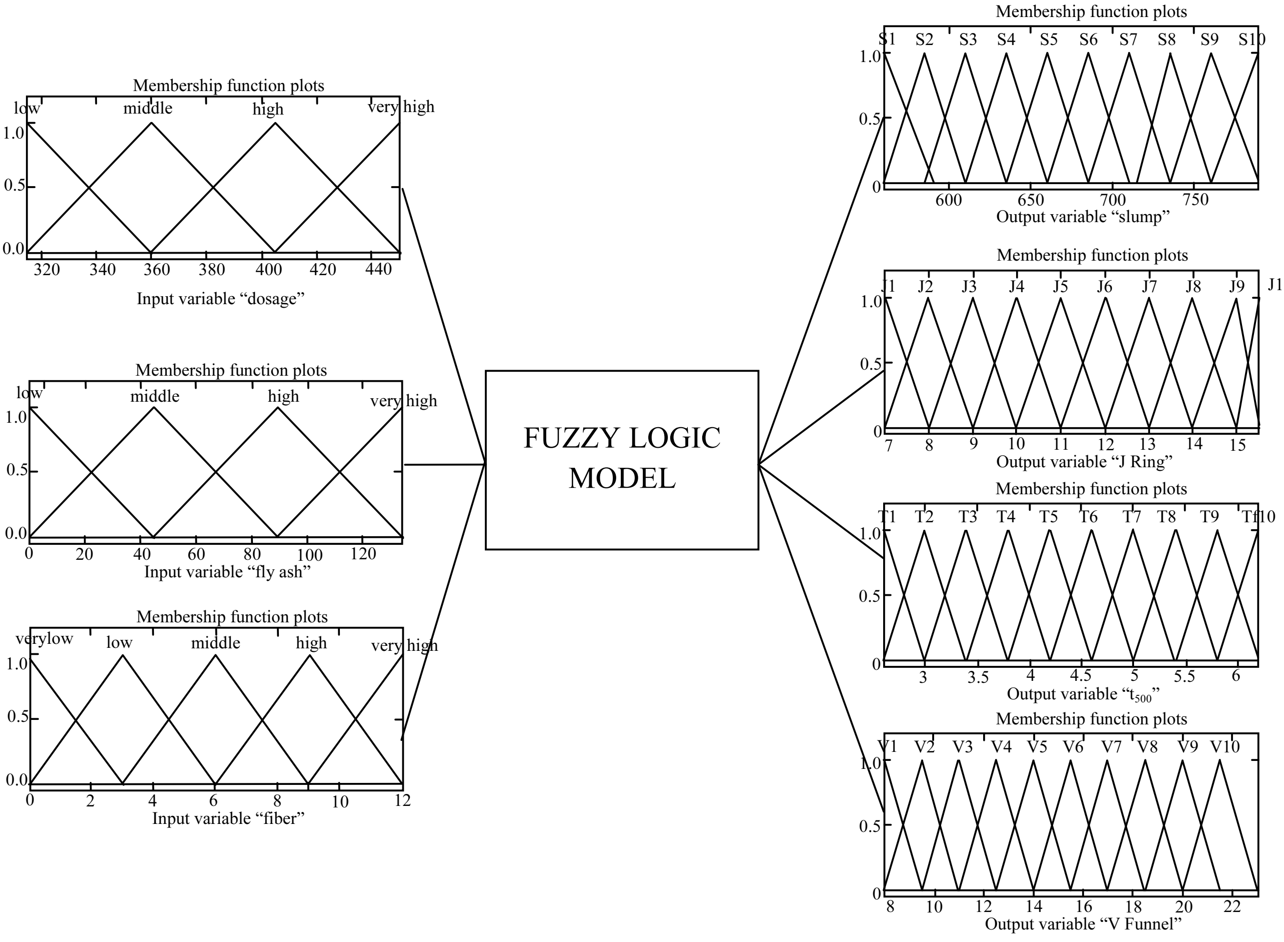


Fig. 7. Block diagram used for fuzzy modelling of fresh concrete properties

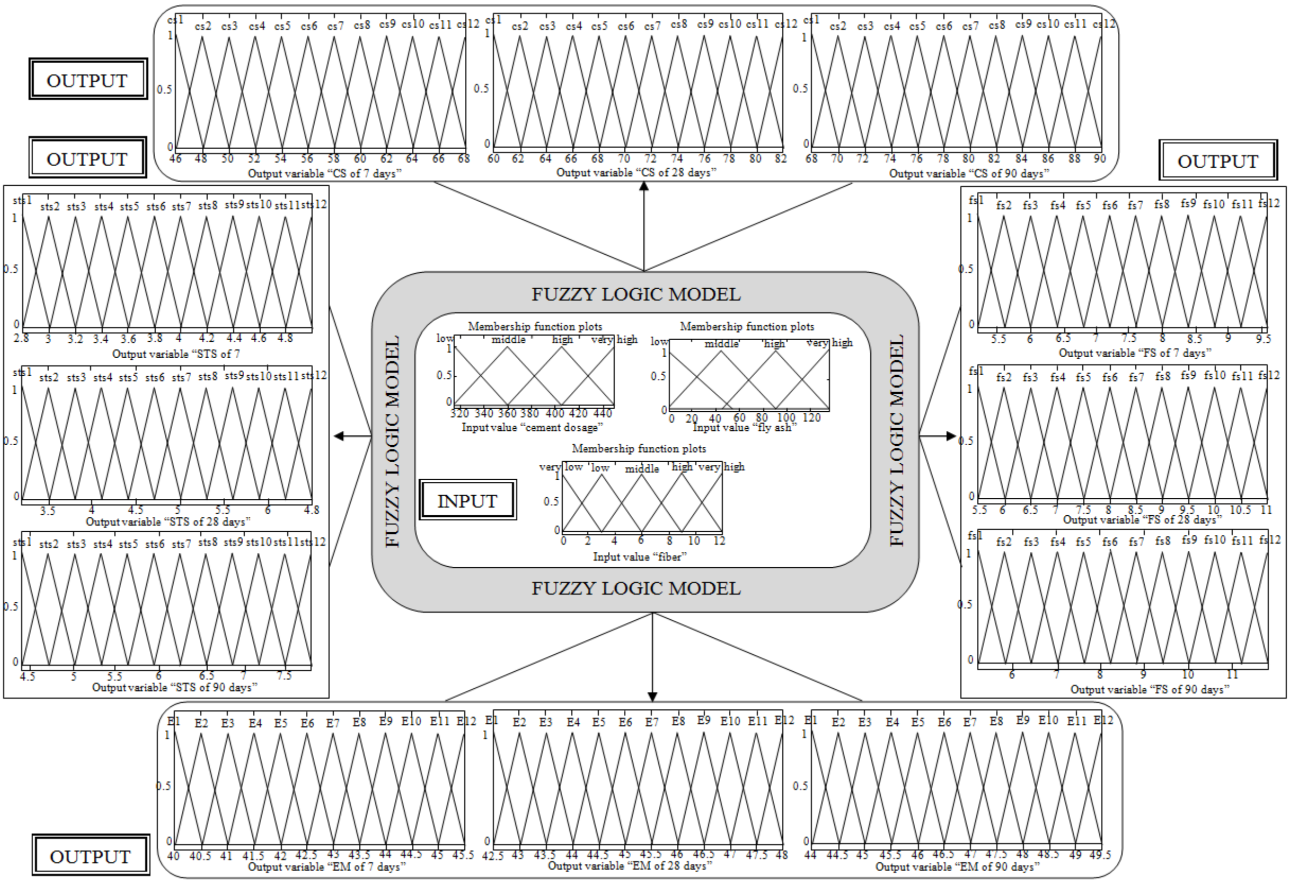


Fig. 8. Block diagram used for fuzzy modelling of hardened concretes properties

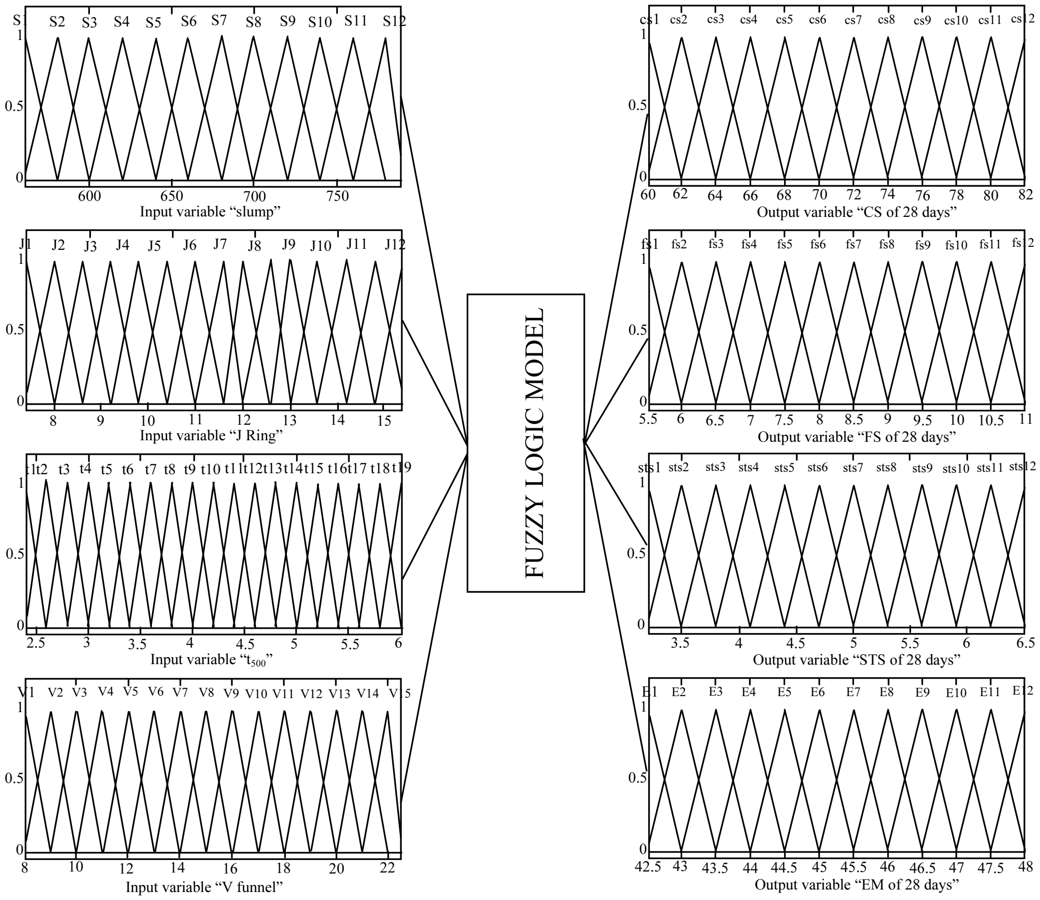


Fig. 9. Block diagram used for fuzzy model prediction of hardened properties from fresh concretesproperties

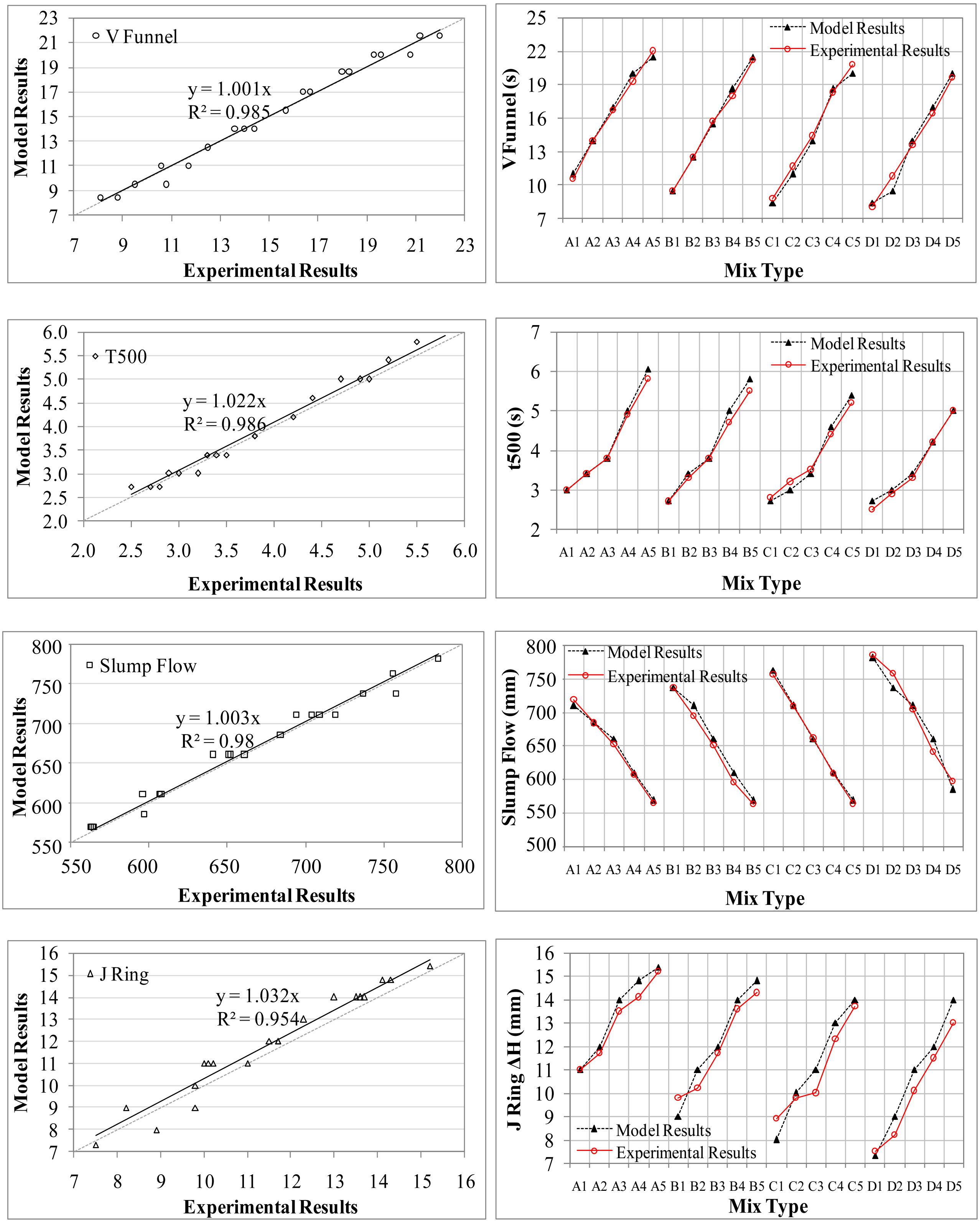


Fig. 10. Fuzzy model predictions and experimental results for fresh concretes

4.4. Prediction results for hardened concretes

Properties of fresh concretes can be used also as indicators of performance of hardened concretes and their durability. Needless to say, properties of concretes as a function of hardening time provide the 'real' information. Comparison of predictions from our fuzzy model with experimental ones is presented in Fig. 11.

As easily seen in Fig. 11, our model provides results in good agreement with experimental values of all parameters that have been measured.

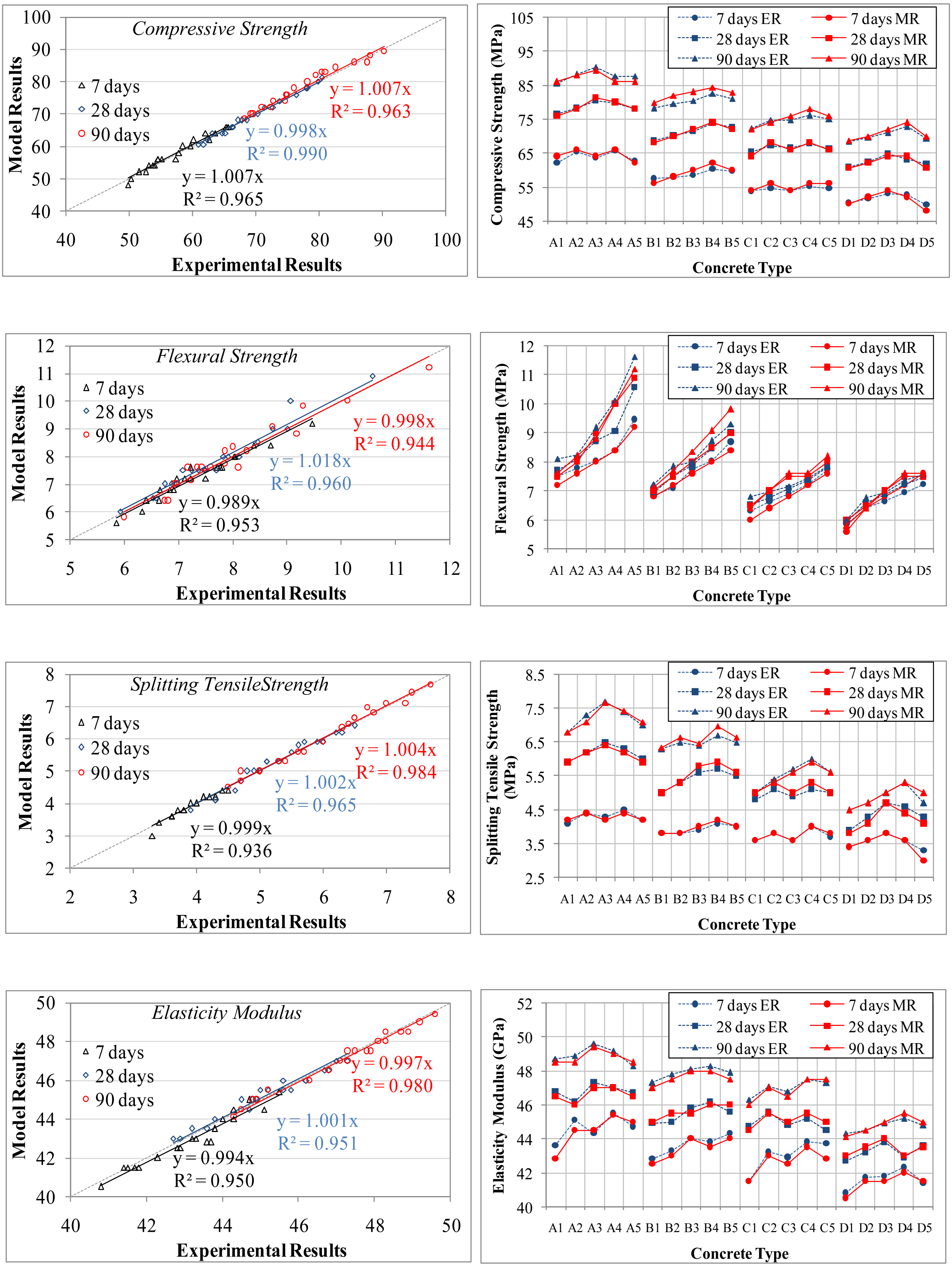


Fig. 11. Predicted and experimental results for hardened concretes

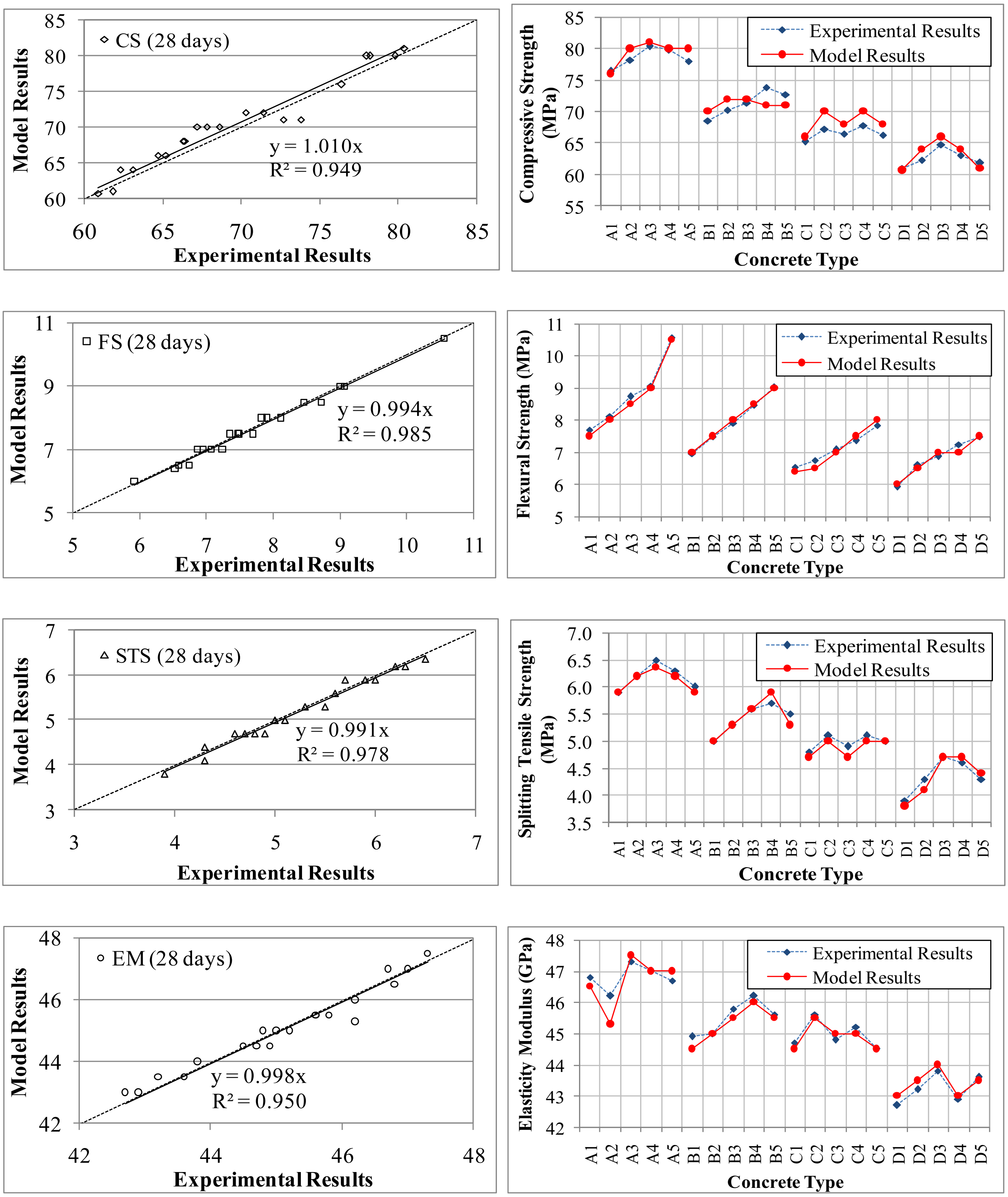


Fig. 12. Comparisons of experimental and developed model results for hardened concrete properties

4.5. Prediction of propertiesof hardened concretes from those of fresh concretes

Results of those predictions are displayed in Fig. 12. Agreement with the experimental results is comparable to that in Fig. 11. The correlationcoefficients R^2 rangein Fig. 11 between 0.951 and 0.990, while in Fig. 12 that range is between 0.949 and 0.985.

5. CONCLUSIONS

The combination of SCC + fibers + FA has provided sufficient strength characteristics of concrete and improved workability. Inclusion of fly ash, an industrial waste material, lowers environmental pollution and has a positive effect on economy.

We have used fuzzy logic approach to predict fresh concrete properties from variables representing the concrete mixture, to predict similarly hardened concrete properties, and finally hardened concrete properties from fresh concrete properties. The advantage of the proposed approach is that the behavior of concrete can be predicted without lengthy trial-and-error experiments that increase material waste and also increase production costs. We have thus predicted from our fuzzy logic approach several properties quite successfully: slump flow, V-funnel, J-ring and slump diameter – all on the basis of fly ash content (%), cement content (kg/m^3) and fiber content (kg/m^3).

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