WINDSOR PROBE TESTS: ASSESSMENT OF EQUIVALENT AGGREGATE HARDNESS BY NEURO-FAZZY TECHNIQUES

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Abstract - In this paper a series of non-destructive and destructive laboratory tests has been performed with the purpose to investigate the influence of the aggregate hardness on the result of Windsor probe tests.
A series of specimens fabricated by aggregates having various Mohs'Hardness (inert of fluvial origin) and by aggregates with only a class of Mohs'Hardness (crushed aggregate) has been prepared. During the concrete casting a series of cubical specimens has been prepared. Subsequently the Windsor probe System were applied to estimate the "in situ" strength of specimens. Then, from each specimen a core was extract. Finally, the comparison between penetration tests and cores strength were carried out.
The tables relating the exposed length of the probe with the compressive strength of concrete dependently of the hardness of the aggregates as measured by the Mohs'scale of hardness. The more probable values of mechanicals property are determined by choice of the appropriate hardness of the aggregate. In the practice, the more probable values of mechanicals property of the concrete is determined by choice of the appropriate aggregates hardness.
The more suitable choice of the Mohs'Hardness is carry out by Neuro-Fuzzy techniques. Fuzzy Surfaces Techniques have been exploited in order to reduce the computational complexity and to select the input set of our system.

Keywords: Non-destructive investigations, concrete, Windsor Probe System, Neuro-Fuzzy techniques, aggregate, Mohs'harness.

1 Introduction

This paper detail with to influence of the aggregate hardness on the result of Windsor probe tests. In the practices the tables relating the exposed length of the probe are gave by manufacturing. These tables are compiled for the concrete by aggregate with only a class of Mohs'Hardness.
The concretes generally used in the structures contents aggregates having various Mohs'Hardness (inert of fluvial origin). In this case the compressive strength of concrete, dependently of the hardness of the aggregate, must be estimated by the appropriated choice of an equivalent Mohs'Hardness.
For each exposed length value of the depth gauge, different values for compressive strength of concrete are given, depending on the hardness of the aggregate.
The correlations published by several researches for concrete made with different type of aggregates, having similar Mohs'Hardness, had given different relationships [1,2,3,5]. How previously mentioned, the calibration table furnished with the Windsor Probe equipment not always give satisfactory results [1,2,3,4,5,6]. In this paper the Neuro-Fuzzy techniques is utilized to carry out the more suitable Mohs'Hardness for correlate the probe penetration test results with the compressive strength.

2 Penetration Resistance Methods

Figure 1 shows the instrumentation of the penetration resistance methods.
The parameter that characterizes the method takes the name of penetration index and it is represented from the length of the part of probe not penetrated in the concrete[1, 2, 5, 6].

For every test three probes come fixtures and the result of the test is constituted from the average of the three measures carried out.

Figure 1. Windsor Probe System

3 The Specimes

A total of 6 concrete specimens 600x600x200-mm was designed and fabricated at the Laboratory of the Faculty of Engineering of Mediterranean University of Reggio Calabria.
In particular, 4 specimens (fig. 2), in the following appointed as IF, were prepared by aggregates having various Mohs'Hardness, i.e inert of fluvial origin. For this specimens values from 3 to 7 of aggregate hardness were measured.
2 specimens (fig. 3), following appointed as IS, by aggregate with only a class of Mohs'Hardness, i.e. crushed limestone aggregate were prepared too. Its Mohs'hardness were estimated equal to 4.5.
All specimens were prepared to obtain a characteristic cube strength of 30 MPa.

Figure 2. Specimens IF - Mohs'hardness variable from3 to 7

Figure 3. Specimens IS - Mohs'hardness equal to 4.5

4 The Fuzzy approach

Fuzzy Inference Systems (FISs) are very good tools as they hold the nonlinear uni-versal approximation. They are suitable to handle experimental data as well as a pri-ori knowledge on the unknown solution, which is expressed by inferential linguistic rules in the form IF-THEN whose antece-dents and consequents utilize fuzzy sets instead of crisp numbers. The inputs of the procedure are interpreted as fuzzy vari-ables. Each fuzzy value carried out by a fuzzy variable is characterized by a fuzzy membership function (FMF). Each FMF expresses a membership measure to each of the linguistic properties. FMF are usually scaled between zero and unity, and they overlap. Gaussian FMFs has been used to improve the flexibility of the ap-plied model. A FIS is usually designed according to the following procedure:

1. fuzzification of the input-output variables;
2. fuzzy inference through the bank of fuzzy rules;
3. defuzzification of the fuzzy output variables.

In FIS generation we used the input-output pairs without exploiting the concept of learning: as a result, the estimation accu-racy was found to be invariably not good enough. However, the design of such a "naïve" FIS can turn out to be useful as a first guess model and when real time sys-tems are concerned. Results can be im-proved either by using an algorithm of automatic extraction of FIS from numerical data [17] (MATLAB® GENFIS System) and possibly by introducing learning (MATLAB® ANFIS). A network FIS scheme facilitates the computation of the gradient vector to compute how parameters can be corrected. Once the gradient vector is obtained, a number of optimisation routines can be applied to reduce the error. We model the problem by means of traditional fuzzy systems (rectangular fuzzy patches) and extraction's algorithms (Matlab ® Tool-boxes).
To select the best inputs for the procedure, we exploit the non linear fuzzy curves technique. In particular, it is here proposed as a ranking technique. In order to under-stand how a fuzzy curve works, let us con-sider a Multi-Input Single-Output system (MISO) for which we possess a data base of input-output pairs with possible not relevant inputs. In our problem, the inputs of the model are the ICs, xi (i=1, …, 16) and the considered output, y, is the sEMG signal. We wish determine which ICs are the most important among 3 possible can-didates. We assume that m training data are available, thus xik (k=1, …, m) are the ith co-ordinate of each of m training pat-terns.
The fuzzy curve is defined as:

$$c_i(x_i) = \frac{\sum_k \Phi_{ik}(x_i) y_k}{\sum_k \Phi_{ik}(x_i)}, \qquad k = 1, \ldots, m \qquad (1)$$

where:

$$\Phi_{ik} = \exp\left[-\left(\frac{(x_{ik} - x_i)}{\sigma} \right)^2 \right] \qquad (2)$$

is a Gaussian function (other different local functions could be exploited). We take σ as a fraction (about 20%) of the range for the corresponding input measurement within the data base. The basic idea behind the method is to asses the flatness of the fuzzy curve, ci, characterizing a given input parameter, since the output is scarcely influenced by the input value if the related fuzzy curve is nearly flat. The importance of the input in affecting the estimation of the output is determined on the basis of a figure of merit which is defined as the range of the fuzzy curve, ($c_{i\ max} - c_{i\ min}$). This range is typically a fraction of the range spanned by the corresponding output variable, y, on the whole data set of examples. If the output variable is independent of xi , that is y(xi)=cost, the fuzzy curve ci is also independent of xi and then ($c_{i\text{-}max} - c_{i\text{-}min}$)=0. In the case of a Multiple-Input (MIMO) problem, there is a different fuzzy curve for each input-output variable pair. Regarding our problem, the best input is represented by Mohs5. Table 1 reports the Root Mean Square Error (RMSE) on the training database while Table 2 shows the characteristics of designed Neuro-Fuzzy System for the whole of the inputs.

Table 1: RMSE on training database

#test	**Compressive Strength**	**#rules**	**inputs**
1	10%	11	3
2	13.5%	8	2
3	14.8%	5	1 best input (Specimens IF Mohs'Hardness = 3.15) (Specimens IS Mohs'Hardness = 4.5)

5 The experimental results

The results of penetration tests carried out by Windsor Probe System are showed in Tables 3 and 4 respectively for specimens IF end for specimens IS. In these tables the exposed lengths of the depth gauge and the compressive strength corresponding to different Mohs'Hardness are reported.

Table 2: Characteristics of designed Neuro-Fuzzy System

#Inputs	Three
#Outputs	One
#Rules	11
AndMethod	product (connective)
ImpMehod	minimum (implication)
	maximum (overlapping of the output)
AggMehod	multiple antecedent
Type of Rules	

In the last column the cube compressive strength is reported; it is correlated to the strength of concrete cores by the following relations [2]:

$$R_{ccm} = 2.3 \cdot \frac{f_{car}}{(1.5 + d/l)} \qquad (3)$$

where:

R_{ccm} = mean Compressive Strength expressed in Equivalent Strength of a 150 mm Cube;
f_{car} = Core Compressive Strength;
d = Core Diameter;
l = Core Length.

Table 3: Specimens IF by aggregates having various Mohs'Hardness

[MPa]	Mohs3	Mohs4	Mohs5	Mohs6	Mohs7	Le [mm]	R_{ccm}
IF 1	34.13	29.99	25.68	20.38	15.46	43.00	32.44
IF 2	30.51	26.20	21.72	17.10	12.62	41.00	31.16
IF 3	38.38	34.42	30.28	25.35	20.03	45.33	36.68
IF 4	42.65	39.47	35.61	31.13	26.06	48.00	26.64

Table 4: Specimens IS by aggregate with only a class of Mohs'Hardness

[MPa]	Mosh3	Mosh4	Mosh5	Mosh6	Mosh7	Le [mm]	R_{ccm}
IS 1	36.12	32.06	27.83	22.65	16.88	44.01	31.17
IS 2	32.23	27.92	23.44	18.45	12.68	41.90	28.33

Comparison between Core Strength of specimens IF and "Windsor" Strength, obtained by Windsor Probe Systems for Mohs'Hardness variable from 3 to 7, has shown in figure 4, while in figure 5 the same comparison is related to specimens IS.

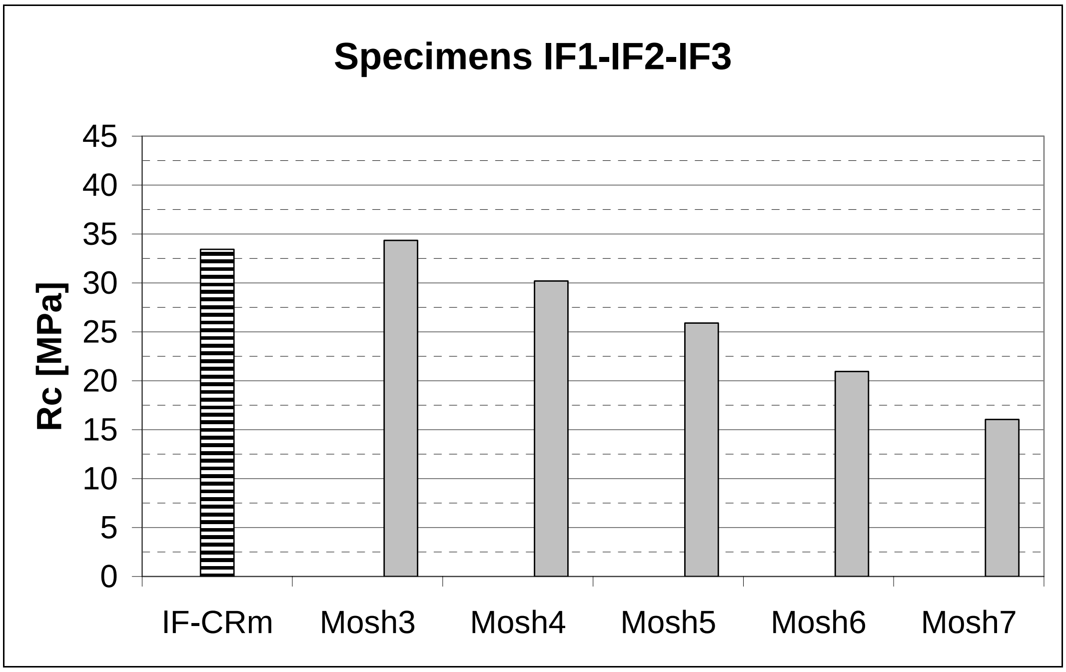

Figure 4. Specimens IF – Correlation between "Windsor Strength" and core strength

The application of the Fazzy techniques have allowed to estimate an equivalent Mohs'hardness of 3.15 in the case of specimens IF, while the same techniques have allowed to estimate a Mohs'hardness of 4.5 in the case of specimens IS. Finally, figures 6 and 7 show the correlation among "Windsor Strength", "Fazzy" Strength and Core Strength for specimens IF ad IS respectively. It is easy to verify how the correlations curve obtained by Fazzy techniques applications are more reliable and consenting to estimate the more probable value of Mohs'Hardness of aggregate contained into the concrete.

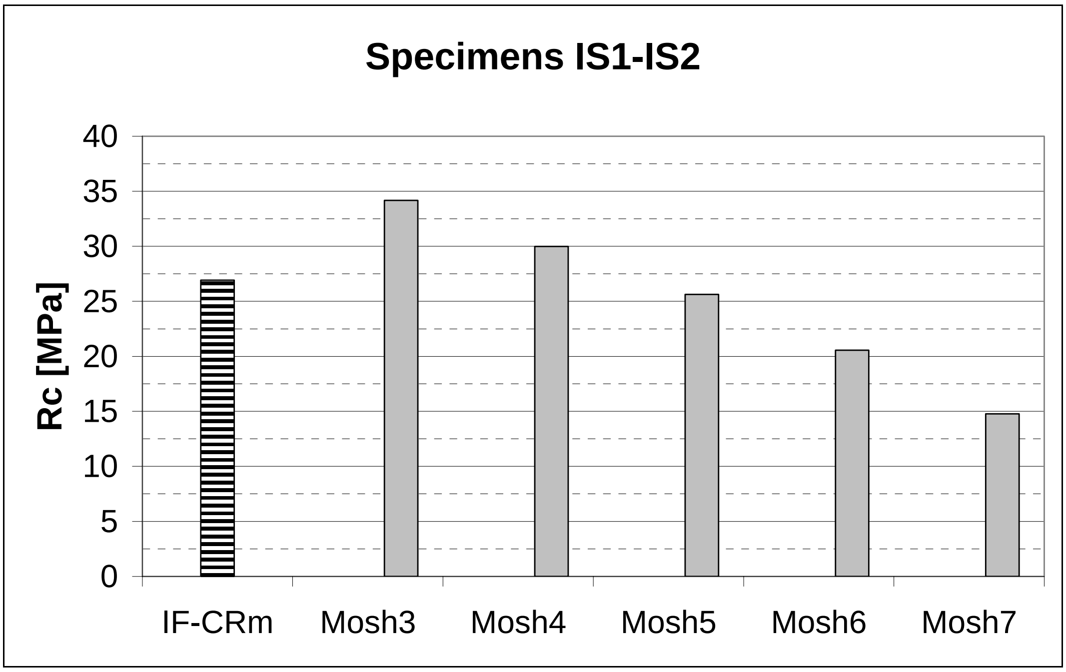

Figure 5. Specimens IS – Correlation between "Windsor Strength and core strength

6 Conclusions

In this paper a series of non-destructive and destructive laboratory tests has been performed with the purpose to investigate the influence of the aggregate hardness on the result of Windsor probe tests.
The study has evidenced that, when a concrete by aggregate of fluvial origin is employed, the hardness of the aggregate assume a important role in the correct evaluation of strength.
The Neuro-Fuzzy techniques consent to obtain the more suitable correlation curves for the type of concrete under investigation.

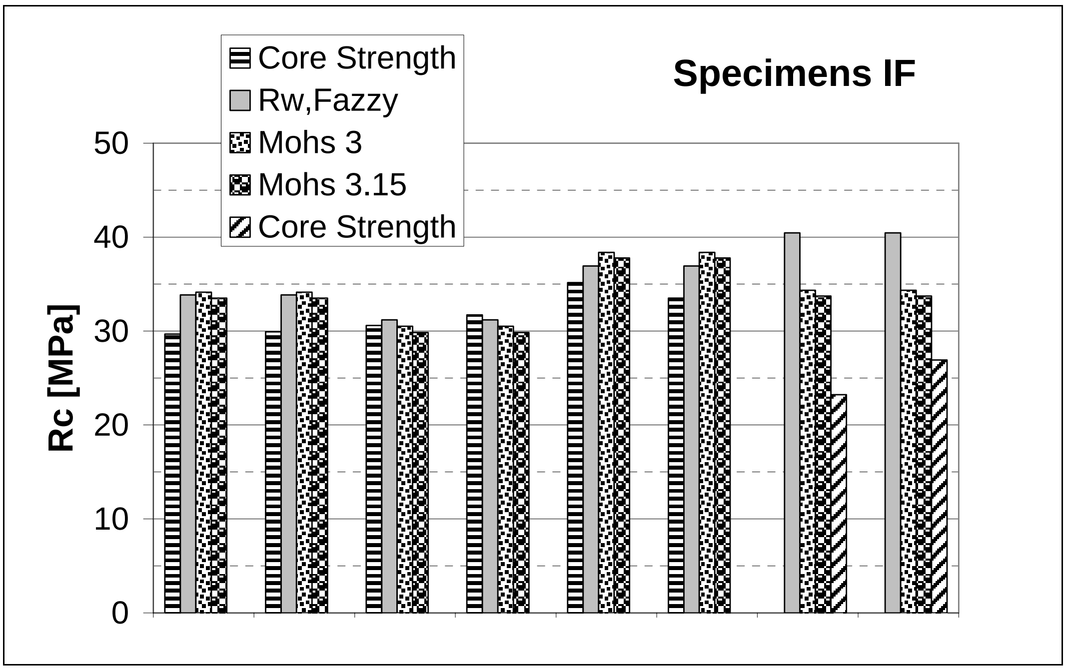

Figure 6. Specimens IF – Correlation among "Windsor Strength", "Fazzy Strength and Core Strength

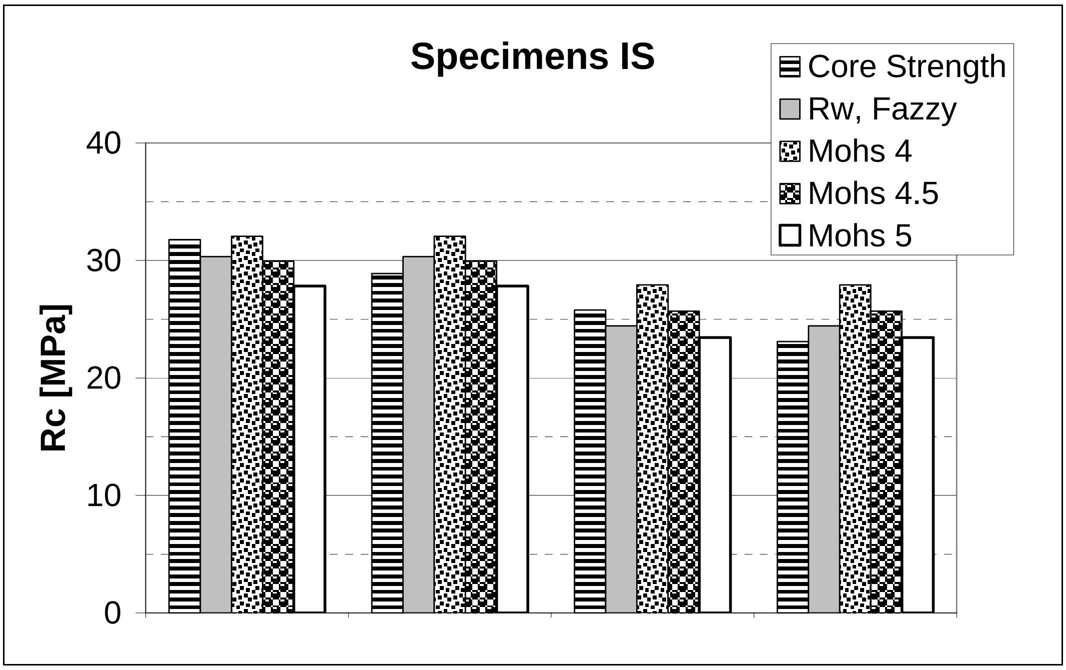

Figure 7. Specimens IS – Correlation among "Windsor Strength", "Fazzy Strength" and Core Strength

The processing have been made by using soft computing approach. By means of qualitative extraction of rules, it is possible evaluate the evolution of the signal. The extracted inference can be improve by means of expert's knowledge. GENFIS approach allows us to estimate and predict ICP values with reduced RMSE and computational complexity.

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