Operations Research and Engineering Letters
Vol. 1, No. 1, 2022, pp. 1-9
ISSN: 2812-9318

Estimation Strength Properties of UHPC Using Rough Set Algorithms

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Article Info

Article history:

Received February 12, 2022
Revised March 20, 2022
Accepted March 22, 2022

Keywords:

Rough set,
Ultra high performance,
Concrete,
estimation strength properties.

ABSTRACT

During the hydration of cement, a heterogeneous structure is created within its composite materials and the properties of the material in a hardened state vary during the production period even though the mass proportion of the component materials in the concrete does not change. The rough set theory represents an advanced technique for treating the problems of uncertainty, ambiguity and inaccuracy, and it is suitable for assessing the attainment of the required mechanical properties of the composite based on its properties in early ages. This paper shows the results of tests completed on 12 mixtures of ultra-high performance concrete. The water/binder ratio and the content of silica fume and steel fibers are varied. By applying rough sets in the program solution Rosetta, an analysis of the parameters is carried out and the rules are given for deciding which of them can help in the process of making a choice as to the proportions of the component materials in the concrete mixture in relation to the required and attained mechanical properties.

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1. Introduction

The development of modern civil engineering is based to a large extent on a permanent search for high quality materials and on bettering and perfecting the characteristics of existing materials. The aim of current research is the development of materials which have high mechanical properties, satisfactory resistance to a variety of aggressive agents (durability) and whose use can be justified economically (Balaguru & Shah, 1992), (Bentur & Mindess, 1990). Alongside this, in the research and development of materials in civil engineering, the generally accepted concept of sustainable development has a strong influence, which together with sociological and economic aspects includes saving energy, environmental protection and the preservation of unrenewable natural resources (Marinkovic, Radonjanin, Malešev & Ignjatovic, 2010).

High and ultra high performance concrete came about at the end of last century through modification of the existing rules for deciding on the combination of component materials (Skazli, Bjegovic & Mrakovcic, 2004). In some cases the characteristic strength of this concrete is over 200 MPa, depending on the regime applied, care of the samples and quantity of highly reactive material in the mixture (Yunsheng, Wei, Sifeng, Chujie, & Jianzhong, 2008),(Yazıcı, Yardımcı, Yigiter, Serdar Aydın & Turkel, 2010). With this, is its notably improved performance when applying pressure which induces tensile stress, also its stiffness and durability when compared with other types of concrete (Cwirzen, Penttala & Vornanen, 2008), (Yang, Millard, Soutsos, Barnett & Le, 2009), (Feylessouf, Tenoudji, Morin & Richard, 2001). In France in 2002, based on many years of research, the first recommendations were made for the use of this type of composite (AFGC Interim Recommendations, 2002).

The rough set theory is an advanced mathematical concept for dealing with inaccuracy, ambiguity and uncertainty in the analysis of data, which was introduced at Warsaw University in 1982 (Pawlak, 1982). The problem of determination or assessment of strength in UHPC on the basis of testing the mechanical properties of concrete in early ages is characterised by an incomplete and insufficient body of information, and by virtue of this, falls into the domain where the rough set theory is highly applicable.

Since its initial introduction, the rough set theory has found an important role in expert systems, systems for supporting decision making, shape recognition and solving different problems in civil engineering (Cirovic & Plamenac, 2005), (Cirovic & Cekic, 2002), (Ali et al., 2021). By using these methods in soft programming Attoh-Okine introduced a system for supporting decision making in the repair and maintenance of road constructions (Attoh-Okine, 1997). Also, Kim,Y.M. et. al. (2009) suggested determining the categories of cracks in reinforced concrete structures.

This paper shows an analysis of experimental test results, with the purpose of showing that the use of rough sets can help in the decision making process, that is that on the basis of the mechanical properties of ultra-high performance concrete in early ages, the mechanical properties of a composite 28 days old can be worked out. In order to calculate the relevant characteristics of the data in tables and to generate rules for classification, the software solution Rosetta was used (Rosetta, n.d.). The software is designed to support the process of gaining new knowledge, processing data and generating rules in the context of rough set theory. The experimental data shown in this study is part of a defended Master's thesis (Nikolic, 2010).

2. Brief Overview of Rough Set

A basic assumption in rough set theory is that each item (object) in the discussion is associated with some particular information (data). This means that each object is displayed with the help of specific information about it. More objects which can be described by the same information are similar to each other, that is they cannot be different to each other with regard to the available information. Relations generated in this way are known as indiscernibility relations, and they represent the mathematical basis for the rough set theory.

The goal of achieving the mathematical formulation of a rough set begins with a data table. It is understood that the term attribute is used rather than the term criterion since the first term is much more general than the second. It is also understood that the data table is a quadruple data group (Figure 1.):

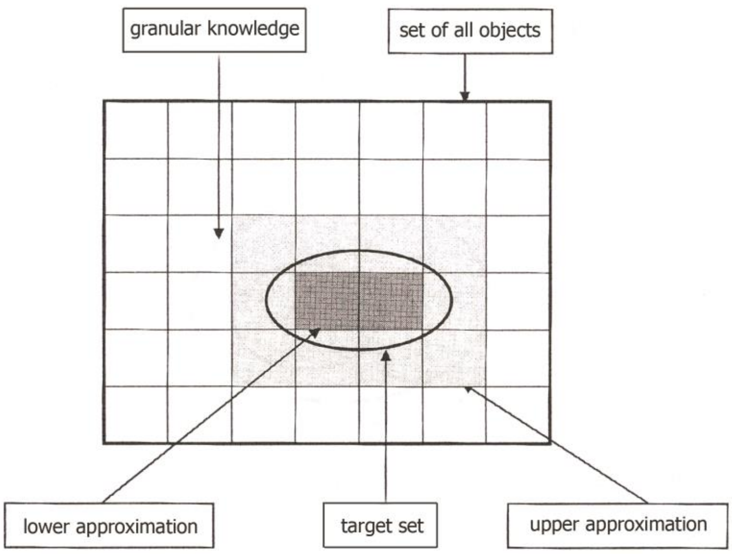

Figure 1. A graphic representation of Rough set theory

$$S = (U, A, V, f) \quad (1)$$

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:

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

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 ($B \subseteq A$).

The following operations on sets are defined:

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

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

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

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

Boundary region of X is the set

$$BN_B(X) = B*(X) - B*(X) \quad (5)$$

If the boundary region of X is an empty set:

$$BN_B(X) = 0 \quad (6)$$

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

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

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

3. Experimental Program

3.1. Overview

In the experimental program, only component materials available in Serbia were used. In previous laboratory tests the compatibility of the cement with the chemical additives was confirmed. When making the mix, water from the town water supply was used.

In the experimental program, ordinary Portland cement was used CEM I 52.5R, and as an aggregate, quartz sand with a granule size of 0-0.5mm was used. When testing its granulometric composition, 70.2% of the aggregate grains were between 0.2 and 0.4 mm. Enough polycarbosilane based superplasticizer was used to make it possible to have a very low water/binder ratio. As a mineral supplement, extra fine silica fume was added. Flat steel fibers were used (length/diameter=8/0.15 mm) with strain resistance □ 3000 N/mm2. The steel fibers were coated with brass in order to increase durability and resistance to corrosion.

3.2. Mix proportions

The experiment was carried out altogether on 12 different concrete mixtures. The composition of the mixtures is shown in Table 1. Each individual mixture was prepared three times in order to show the repeatability of the experiment results for each of the properties. The composition of the mixture was chosen on the basis of previous research in order to reach the compressive strength of ultra-high performance concrete. The volume proportion of steel fibers moved within a range of 2.5 to 4.2%. All mixtures were prepared in a standard 5l cement and plaster mixer. The fresh mixture was poured into steel molds (4x4x16cm). Samples were pressed on a vibrotable at a frequency of 150 Hz.

Table 1. Concrete mix proportions

No.	Cement [kg]	Aggregate [kg]	Silica fume [kg]	Additive [kg]	Steel fiber [kg]	Water	w/c*1	w/b*2
C1	850	1180	100	20,0	195	207,0	0,24	0,20
C2	850	1160	100	23,0	195	212,0	0,25	0,20
C3	950	1045	110	35,4	195	226,6	0,24	0,20

C4	850	1095	170	35,4	195	204,6	0,24	0,20
C5	900	950	200	34,6	330	198,4	0,22	0,18
C6	900	950	200	36,4	330	179,6	0,20	0,16
C7	850	1050	185	39,0	330	164,0	0,19	0,16
C8	1050	900	230	28,6	300	180,4	0,17	0,14
C9	900	1050	200	42,1	230	240,9	0,27	0,22
C10	850	1020	185	34,5	330	168,5	0,20	0,16
C11	850	1020	185	39,5	330	169,5	0,20	0,16
C12	850	1020	185	37,8	330	162,2	0,19	0,16

*1 – water/cement ratio, *2 – water/binder ratio

3.3. Compressive and flexural strength

The experiment was carried out on concrete in fresh and hardened states. All 12 mixtures were class consistency S1. The temperature of the concrete in a fresh state was measured at between 22 and 25□. The density of fresh concrete was from 2560 to 2630 kg/m3. Its flexural strength was determined through tests using prisms of 4x4x16 cm, and the compressive strength by a modified cube method (examination surface 4x4 cm). Table 2 shows the test results of the mechanical properties of concrete.

Table 2. Experimental results

Concrete	Compressive strength [N/mm2]			Flexural strength [N/mm2]		
	2 days	7 days	28 days	2 days	7 days	28 days
C1	86,1	123,8	146,9	15,2	22,5	26,7
C2	82,4	113,1	136,3	17,1	23,3	23,9
C3	77,4	96,3	131,3	17,6	20,3	28,7
C4	82,3	128,1	148,2	14,7	24,8	29,5
C5	97,4	125,6	153,1	24,9	28,7	29,8
C6	95,3	125,6	155,0	21,8	24,3	25,9
C7	96,1	132,5	153,1	18,8	25,6	26,2
C8	93,9	123,8	154,4	16,8	21,1	21,9
C9	82,6	97,8	128,1	16,5	18,3	22,8
C10	83,9	96,9	146,9	18,9	23,6	32,6
C11	89,6	115,6	159,4	21,4	25,9	29,5
C12	78,5	93,8	170,9	19,2	25,3	30,1

4. Decision Algorithm for Estimating Category of Strength Properties

As well as showing the mechanical properties, table 3 also gives the values of the water/binder ratio and the volume proportion of steel fibers in the 12 concrete mixtures. The table represents a table of attributes and a decision table. The columns in the table are marked by the attributes (properties of the mixture), and the rows are marked by objects (the experimental mixtures), while the values in the table are the attribute values.

Table 3. Decision table

No.	f_c^2	f_s^2	f_c^7	f_s^7	w/b	C_{sf}	O
C1	86,1	15,2	123,8	22,5	0,20	2,4	no
C2	82,4	17,1	113,1	23,3	0,20	2,4	no
C3	77,4	17,6	96,3	20,3	0,20	2,4	no

C4	82,3	14,7	128,1	24,8	0,20	2,4	no
C5	97,4	24,9	125,6	28,7	0,18	4,0	yes
C6	95,3	21,8	125,6	24,3	0,16	4,0	yes
C7	96,1	18,8	132,5	25,6	0,16	4,0	yes
C8	93,9	16,8	123,8	21,1	0,14	3,7	yes
C9	82,6	16,5	97,8	18,3	0,22	2,8	no
C10	83,9	18,9	96,9	23,6	0,16	4,0	no
C11	89,6	21,4	115,6	25,9	0,16	4,0	yes
C12	78,5	19,2	93,8	25,3	0,16	4,0	yes

7 criteria were adopted for the evaluation of variant solutions:
- f_c^2: compressive strength at 2 days old
- f_s^2: flexural strength at 2 days old
- f_c^7: compressive strength at 7 days old
- f_s^7: flexural strength at 7 days old
- f_c^{28}: compressive strength at 28 days old
- f_s^{28}: flexural strength at 28 days old
- w/b: water/binder relationship
- C_{sf}: volume proportion of steel fibers in 1m3 of composite.

These criteria represent attribute conditions, and the solution applicable (or non-applicable) composition of the designed concrete mixtures represents the attribute decision. The values of the attributes expressed are numerical. For the required mechanical properties at 28 days old (compressive strength >150 N/mm^2 and flexural strength >25 N/mm^2), the concrete also needs to fulfil the necessary workability requirements in order for fresh concrete to be added.

Discretization of the values of the attribute conditions was inspired by the need to describe numerical values in linguistic terms rather than precise values. Presentation of the data grouped in intervals secures more correct processing of the data as it reduces the influence of deviation of some of the data at particular intervals of the experimentally acquired values. In this way, part of the excess data can be identified and then removed. The values of the attribute conditions are divided into three intervals of equal length and shown in Table 4.

Table 4. Decision Table after discretization

No.	f_c^2	f_s^2	f_c^7	f_s^7	w/b	C_{sf}	O
C1	1	0	1	0	1	0	no
C2	0	1	1	1	1	0	no
C3	0	1	0	0	1	0	no
C4	0	0	2	1	1	0	no
C5	2	2	2	2	1	2	yes
C6	2	2	2	1	0	2	yes
C7	2	1	2	2	0	2	yes
C8	2	0	1	0	0	1	yes
C9	1	0	0	0	2	1	no
C10	1	1	0	1	0	2	no
C11	1	2	1	2	0	2	yes
C12	0	2	0	2	0	2	yes

With:
fc2: [*, 82.5)→0; [82.5, 91.8) →1; [91.8, *)→2;
fs2: [*, 17.0) →0, [17.0, 19.1) →1, [19.1, *)→2;
fc7 [*, 105.5) →0, [105.5, 124.7) →1, [124.7, *)→2;
fs7 [*, 22.9) →0, [22.9, 25.1) →1, [25.1, *)→2;
w/b [*, 0.17) →0, [0.17, 0.21) →1, [0.21, *)→2;

Csf [*, 2.6) →0, [2.6, 3.9) →1, [3.9, *)→2;

The question is often asked as to whether some of the data can be removed from the decision table on the condition that its basic characteristics are kept. Reductors represent a minimal subset of attributes which makes the same classification of elements of the universe possible as a complete set of attributes. In other words, attributes which do not belong to the reductors are excess in terms of the classification of elements in the universe. Determining the reductions is an essential task in the rough set theory. A flexible set of algorithms for processing data is available in the software solution Rosetta. In this paper, a genetic algorithm reducer is used for reducing data and generating rules for decision making as an effective tool for finding the reduction of rough sets.

A presentation of the function and purpose of algorithms, and also a method of deciding on the minimal subset of attributes is given in detail in a study by Vinterbo and Øhrn (Vinterbo & Øhrn, 2000).

The decision making rules from the first reduced groups of attributes { f_c^2, f_s^7} have the following form:

f_c^2 ([82.5, 91.8)) AND f_s^7 ([*, 22.9)) => no
f_c^2 ([*, 82.5)) AND f_s^7 ([22.9, 25.1)) => no
f_c^2 ([*, 82.5)) AND f_s^7 ([*, 22.9)) => no
f_c^2 ([91.8, *)) AND f_s^7 ([25.1, *)) => yes
f_c^2 ([91.8, *)) AND f_s^7 ([22.9, 25.1)) => yes (8)
f_c^2 ([91.8, *)) AND f_s^7 ([*, 22.9)) => yes
f_c^2 ([82.5, 91.8)) AND f_s^7 ([22.9, 25.1)) => no
f_c^2 ([82.5, 91.8)) AND f_s^7 ([25.1, *)) => yes
f_c^2 ([*, 82.5)) AND f_s^7 ([25.1, *)) => yes

On the basis of the given rules for decision-making, it is possible to evaluate whether the mechanical properties of the composite achieve the required values at 28 days old, and within the given parameters.

5. Results of Sensitivity Analysis and Discussion

The compatibility of the component materials is confirmed during the preliminary examination using a variety of cement types and a variety of chemical additives from different suppliers. There is a possibility of a large deviation in the results for the mechanical properties if the component materials are not compatible with each other or if the declared chemical and mineralogical composition changes during cement production.

The key parameters adopted for assessing the compressive strength and the flexural strength are the compressive strength at 2 days old and the flexural strength at 7 days old { fc^2, fs^7} . After applying a Genetic Algorithm in the reduction of attributes, a second group of reductors represents the compressive strength and the flexural strength at 7 days old and the volume proportion of reinforced steel fibers. The rules from the second reduced groups of attributes { fc^7, fs^7, C_{sf} } are:

fc^7 ([105.5, 124.7)) AND fs^7 ([*, 22.9)) AND C_{sf} ([*, 2.6)) => no
fc^7 ([105.5, 124.7)) AND fs^7 ([22.9, 25.1)) AND C_{sf} ([*, 2.6)) => no
fc^7 ([*, 105.5)) AND fs^7 ([*, 22.9)) AND C_{sf} ([*, 2.6)) => no
fc^7 ([124.7, *)) AND fs^7 ([22.9, 25.1)) AND C_{sf} ([*, 2.6)) => no (9)
fc^7 ([124.7, *)) AND fs^7([25.1, *)) AND C_{sf} ([3.9, *)) => yes
fc^7 ([124.7, *)) AND fs^7 ([22.9, 25.1)) AND C_{sf} ([3.9, *)) => yes
fc^7 ([105.5, 124.7)) AND fs^7 ([*, 22.9)) AND C_{sf} ([2.6, 3.9)) => yes

On the basis of (8) and (9) it is possible to make an assessment of the mechanical properties of this type of composite on the basis of early hardness, whilst noting that the decision-making rules shown cannot be adopted as a model for the behaviour of the material. There are many factors which influence the properties of concrete with high mechanical properties (water/binder ratio, silica fume content, physical-mechanical properties of the cement properties, type and compatibility of chemical additives etc.) (Neville, 1994), (Yunsheng et al., 2008), (Yazıcı et al., 2010). For this reason it is very important for the composite materials to remove all excess attributes by reduction, and then on the basis of the final number of experimental research results present a model framework for the composite and make predictions regarding some of the properties of the material.

In addition to these decision-making rules, figures 2 and 3 show the dependence of compressive strength on the value of the water/binder ratio, and the influence of the percentage proportion of steel fibers on the fc/fs ratio. In figure 2 a definite fall in the compressive strength can be seen with a rise in the water/binder ratio. By rising the quantity of steel fibers there is an increase in the value of the flexural strength, which is also evident in the results of the experimental research and in the research of other authors. Figure 3 shows the growth of the relationship between compressive strength and flexural strength depending on the volume proportion of steel fibers and the age of the composite and it is evident that a growth in this relationship increases with an increase in the quantity of steel fibers.

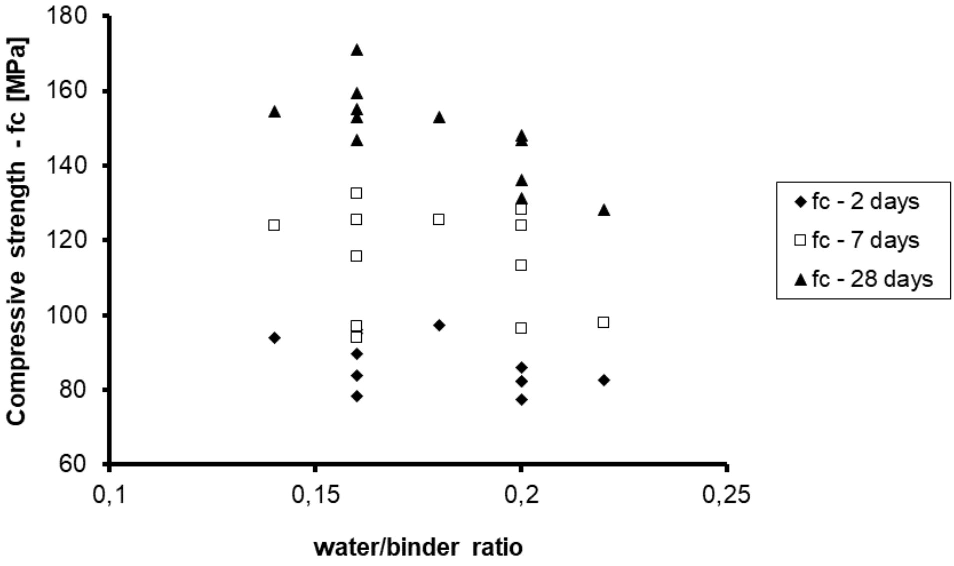

Figure 2. Influence of water/binder ratio on compressive strength

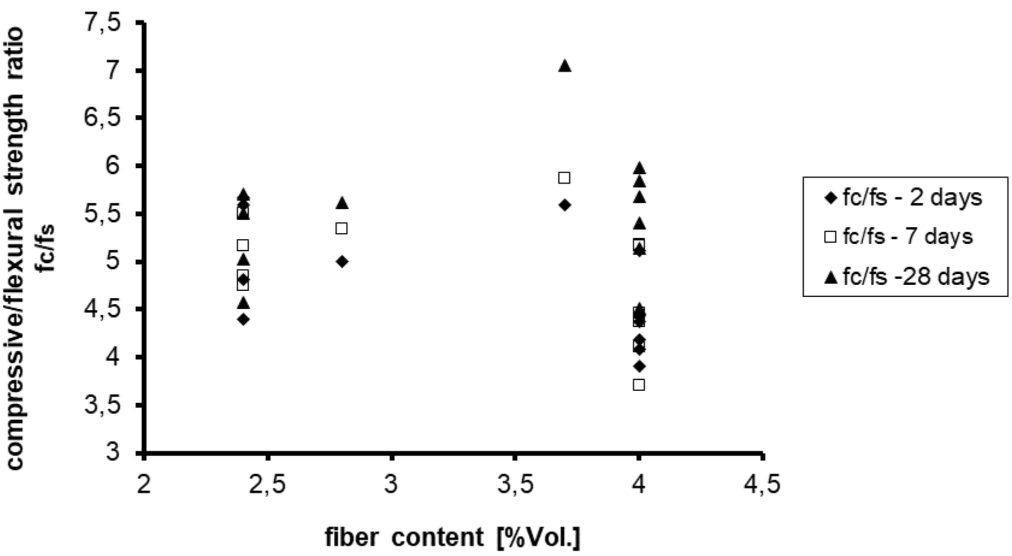

Figure 3. Influence of percentage proportion of steel fibers on fc/fs ratio

6. Conclusions

On the basis of early hardness, it is very important in the production process of prefabricated elements of composite materials with a cement matrix to anticipate whether recently produced elements fulfil the required quality standard. Concrete is a heterogeneous material, as a consequence of which there can be a definite deviation in the compressive strength achieved at 28 days old, even though the elements are prepared from the same class and type of concrete.

This paper pointes out the importance of assessment of the hardness of ultra-high performance concrete in relation to the required values due to a lack of research on this type of composite prepared with component materials available on the domestic market. In the experimental study, 12 mixtures were prepared in a laboratory with the purpose of showing that it is possible to produce cement composite material with extremely high mechanical properties with local materials.

By using rough sets, suggestions can be made to the decision maker as to possible problems in the production itself. The function of rough belonging has a probabilistic character, so with this kind of analysis, based on attributes that reflect measurable properties, conditions and experience as well as by using several groups of attributes, an objective decision can be made.

On the basis of experimental results it is possible to draw the following observations:

- It was shown that a compressive strength of over 150 MPa and a flexural strength of over 30 MPa can be achieved with component materials available on the domestic market without the use of hydrothermal processing. Getting ultra-high performance concrete with a compressive strength of over 200 MPa is conditional on the use of concrete mixtures with notably higher quality cements which are not available on the domestic market and by using steam curing or autoclave curing.

- The experimental results were analysed by using rough sets and the decision making rules were presented, on the basis of which it is possible to work out whether the ultra-high performance concrete fulfils the required properties primarily on the basis of the mechanical properties in early ages. This does not mean that the decision making results introduced do not apply to a composite made from other component materials, but they certainly differ depending on the quality of the composite materials used.

- In figure 1 it can be seen that mixtures with a water/binder ratio of over 0.2 cannot reach a compressive strength of over 150 MPa and what needs to be kept in mind is that designing the concrete mixtures for this type of composite is without the use of hydrothermal processing.

- The growth of the value of the fc/fzs ratio in relation to the age of the composite in this experimental research can only be seen when the volume proportion of steel fibers is increased. In figure 2, growth in the fc/fzs ratio at 28 days old compared with 2 and 7 days old can only be seen when using 4% of steel fibers in the concrete mixture.

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