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THE ESTIMATION OF COMPRESSIVE STRENGTH OF NORMAL AND RECYCLED AGGREGATE CONCRETE

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Abstract. *Estimation of concrete strength is an important issue in ready-mixed concrete industry, especially, in proportioning new mixtures and for the quality assurance of the concrete produced. In this article, on the basis of the existing experimental data of compressive strength of normal and recycled aggregate concrete and equation for compressive strength calculating given in Technical regulation are compared. The accuracies of prediction by experimental data obtained in laboratory as well as by EN 1992-1-1, ACI 209 and SRPS U.M1.048 are compared on the basis of the coefficient of determination. The determination of the compressive strengths by the equation described here relies on determination of type of cement and age of concrete with the constant curing temperature.*

Key words: *compressive strength, estimate strength of concrete, recycled aggregate.*

1. INTRODUCTION

When having stress applied, the response of concrete depends on the stress type, and on influence that the combination of various factors performs on porosity of the different structural components of concrete. The factors include properties and proportions of materials that are used for concrete mixture design, degree of compaction, and conditions of curing [1]. Regarding the strength, the relationship between water-cement ratio and porosity is the most important factor as, by itself, it affects the porosity of both the cement mortar matrix and the interfacial transition zone between the matrix and the coarse aggregate.

Precise models of predicting concrete strength cannot be developed, as direct determination of porosity of the individual structural components of concrete, the matrix and the interfacial transition zone is impractical [2].

Certain number of empirical relations has been estimated for years; they provide indirect information about the influence of numerous factors on compressive strength (com-

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pressive strength is widely used as an index of all other types of strength). Understanding of various factors and their complex interactions is important for understanding the actual response of concrete to applied stress. These factors are usually categorized in three groups: 1.characteristics and proportions of materials, 2. curing conditions, and 3. testing parameters [3]. The selection of proper component materials and their proportions is the first step in concrete mixture design and it provides obtaining the product that would meet the specified strength. Some of the aspects that are important regarding concrete strength are considered here. According to empiric results it should be emphasized that, many mixture design parameters are interdependent and therefore their influences cannot really be separated. Compressive strength depends on concrete components and curing regime. [4,5]

2. Interdependent Parameters and Their Influence on Compressive Strength

2.1. Water-cement ratio

In 1918, after extensive testing performed at the Lewis Institute, University of Illinois, Duff Abrams concluded that there was a relation between water-cement ratio and concrete strength. Today, this inverse relation is recognized as Abrams' water-cement ratio rule; it is represented by the expression (1) where *w/c* represents the water-cement ratio of the concrete mixture and k_1 and k_2 are empirical constants.

$$f_c = \frac{k_1}{k_2^{w/c}} \qquad (1)$$

Typical curves illustrating the relationship between water-cement ratio and strength at a given moist-curing age are shown in Fig. 1. [2]

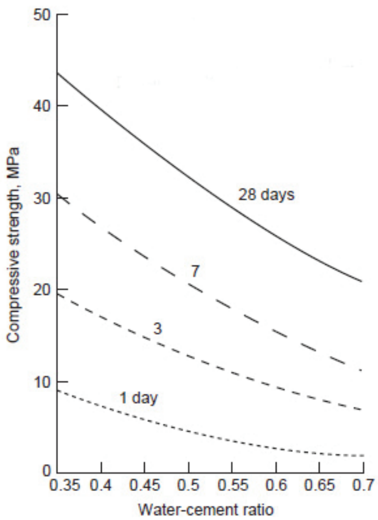

Fig. 1. Influence of the water cement ratio and moist curing age on concrete strength

The factors responsible for the strength of hydrated cement paste and the effect of increasing the water-cement ratio on porosity at a given degree of cement hydration can help understanding the *w/c*-strength relationship in concrete as the natural consequence of a progressive weakening of the matrix, that is caused by increasing porosity following increase in the water-cement ratio [6]. The influence of the water-cement ratio on the strength of the interfacial transition zone is not considered in this theory. In low- and medium-strength concrete designed with normal aggregate, both the interfacial transition zone porosity and the matrix porosity determine the strength, and a direct relation between the water-cement ratio and the concrete strength holds. In high-strength (i.e., very low water-cement ratio) concrete mixtures explanation is different. For water-cement ratios under 0.3, disproportionately high increases in the compressive strength can be achieved with very small reductions in water-cement ratio. A significant improvement in the strength of the interfacial transition zone at very low water-cement ratios is provided and it is considered the main cause for this disproportion. The crystal size of the hydration products is much smaller and the surface area is correspondingly higher, when low water –cement ratio is applied.

2.2. Air entrainment

The porosity of the cement paste matrix at a given degree of hydration is determined mostly by the water-cement ratio. The porosity can be increased when air voids are incorporated into the system as well, either as a result of inadequate compaction or through the use of an air-entraining admixture; thus having the strength of the system decreased.

At a given water-cement ratio, increasing the volume of entrained air influences the compressive strength; this relation is shown by the curves in Fig 2 [2].

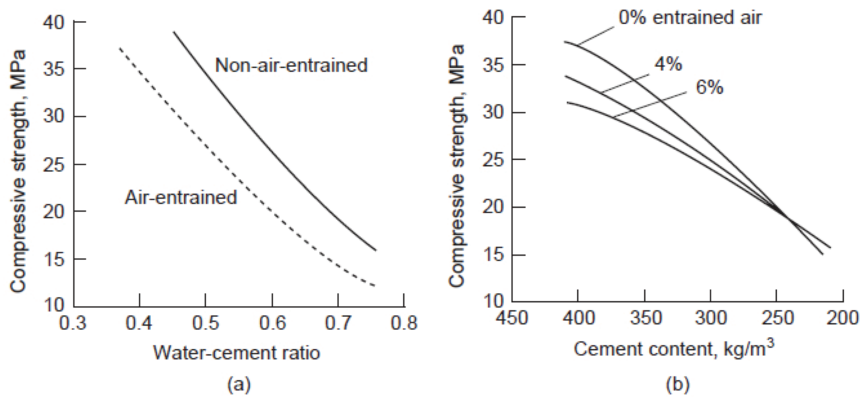

Fig. 2. Influence of the water-cement ratio, entrained air and cement content on concrete strength

The water-cement ratio and cement content affect the response of concrete to applied stress. The explanation can be based on two opposing effects caused by incorporation of air into concrete:

- increasing the porosity of the matrix; entrained air will have an adverse effect on the strength of the composite material
- improving the workability and compactibility of the mixture; entrained air tends to improve the strength of the interfacial transition zone (especially in mixtures with very low water and cement contents) and thus improves the strength of concrete.

In concrete mixtures with low cement content, it can be observed, that when having air entrainment accompanied by a significant reduction in the water content, the beneficial effect on the interfacial transition zone compensates the adverse effect of air entrainment on the strength of the matrix

2.3. Cement type

Fig. 3 shows that the degree of cement hydration has a direct effect on porosity and consequently on strength. At ordinary temperature, rapid hardening Portland cement CEM I, characterized with higher fineness, hydrates more rapidly than other types; therefore, at early ages of hydration (e.g., 1, 3, and 7 days) and at specified water-cement ratio, the concrete containing rapid hardening Portland cement CEM I or ASTM-Type III Portland cement will have lower porosity and correspondingly higher strength. When, compared to rapid hardening Portland cement (ASTM Type I, Type II, and Type III Portland cements), the rates of hydration and strength development at normal hardening Portland cement (ASTM - Type IV and Type V cements) and with portland-slag and Portland pozzolan cements are slower up to 28 days. It is observed that the differences usually disappear after having the similar degree of hydration achieved [3].

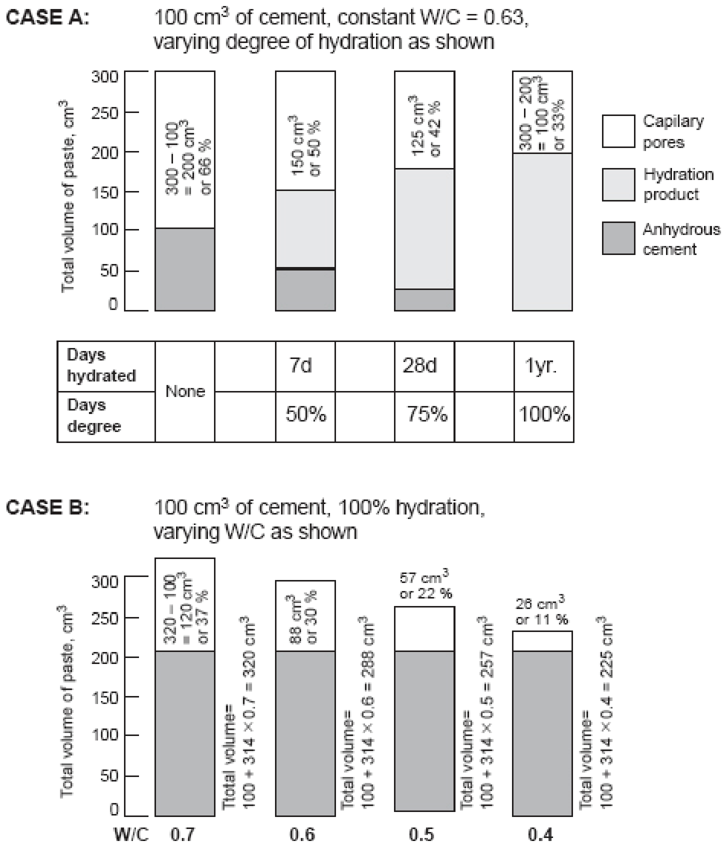

Fig. 3. Changes in the capillary porosity with varying water-cement ratio and degree of hydration.

2.4. Aggregate

In concrete technology, the relationship between water-cement ratio and strength is overemphasized. The influence of aggregate on concrete strength is not generally appreciated. Usually, the aggregate strength is not the relevant factor in normal strength concrete as with the exception of lightweight aggregates, the aggregate particle is several times stronger than the matrix and the interfacial transition zone in concrete. With most natural aggregates the strength of the aggregate is hardly utilized as the failure is determined by the other two phases.

The concrete strength is affected by the other aggregate characteristics, as well: size, shape, surface texture, grading (particle size distribution), and mineralogy, they influence concrete strength in varying degrees. Usually the effect of aggregate characteristics on concrete strength is related to a change of water-cement ratio. Published data supporting the fact that this is not always the case are available. Some theories show that, independently of the water-cement ratio, the size, shape, surface texture, and mineralogy of aggregate particles themselves would influence the characteristics of the interfacial transition zone, thus affecting concrete strength.

When performing the change in *maximum size* of well-graded coarse aggregate of a given mineralogy, two opposing effects on the strength of concrete can be obtained. Under the same conditions (cement content and consistency), concrete mixtures containing larger aggregate particles require less mixing water than those containing smaller aggregate. On the contrary, larger aggregates tend to form weaker interfacial transition zone containing more micro-cracks. Since the interfacial transition zone characteristics have more effect on the tensile strength of concrete compared to the compressive strength, it is to be expected that any changes in the coarse aggregate properties would influence the tensile-compressive strength ratio of the material.

2.5. Mixing water

Water used for mixing concrete, actually its impurities, may affect the concrete strength, setting time, efflorescence (deposits of white salts on the surface of concrete), and the corrosion of reinforcing and prestressing steel. The most of concrete mixtures specifications have the requirement regarding the quality of water included: water should be potable, as municipal drinking waters seldom contain dissolved solids in excess of 1000 ppm (parts per million). In this way, by having low content of impurities, it is provided that mixing water itself is rarely a factor in concrete strength. It does not mean that water that is unsuitable for drinking is not appropriate for concrete mixing. Slightly acidic, alkaline, salty, brackish, colored, or water characterized by inadequate smell should not be rejected outright. This is important because of the water shortage in many areas of the world. Recycled waters from cities, mining, and many industrial operations can be safely used as mixing waters for concrete. The best way to determine the suitability of water is to compare the setting time of cement and the strength of mortar cubes when specimens are made with water with non-specified characteristics and with reference water that is specified as clean. The cubes made with water that is tested should have 7- and 28-day compressive strengths equal to or at least 90 percent of the strength of reference specimens made with clean water; the quality of mixing water should not affect the setting time of cement to an unacceptable degree.

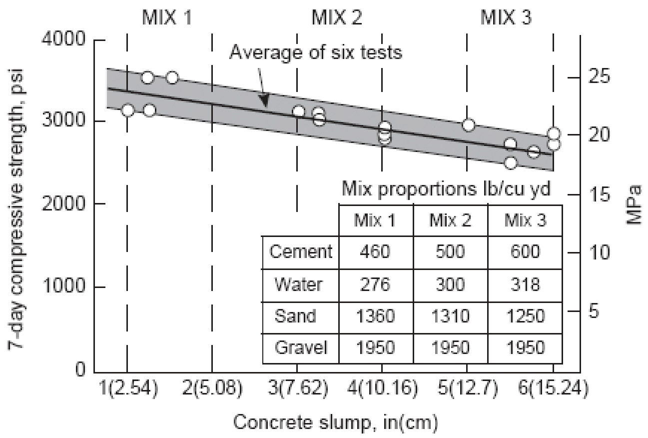

Fig. 4. Influence of the concrete slump on compressive strength

Seawater, which contains about 35,000 ppm dissolved salts, is not harmful to the strength of plain concrete. However, with reinforced and prestressed concrete it increases the risk of steel corrosion; therefore, the use of seawater as concrete-mixing water should be avoided under these circumstances. The presence of excessive amounts of algae, oil, salt, or sugar in the mixing water should be considered a high risk factors..

2.6. Admixtures

The adverse influence of air-entraining admixtures on concrete strength is important. The water-reducing admixtures due to the water content decrease, at a given consistency, can enhance both the early and the ultimate strength of concrete. At a given water-cement ratio, the presence of water-reducing admixtures generally has a positive influence on the rates of cement hydration and early strength development. Admixtures characterized with ability to accelerate or decrease cement hydration obviously would have a great influence on the rate of strength gain; however, the ultimate strengths may not be significantly affected. It is noticed that there is the tendency toward a higher ultimate strength of concrete while having the rate of strength gain at early ages been retarded.

Lately for ecological reasons and for cost control, the use of pozzolanic and cementitious by-products as mineral admixtures in concrete is gradually increasing. Mineral admixtures, when used as a partial replacement for Portland cement, usually have a retarding effect on the strength at early ages. However, the ability of a mineral admixture to react at normal temperatures with calcium hydroxide that is constituent of hydrated Portland cement paste and to form additional calcium silicate hydrate can lead to significant reduction in porosity of both the matrix and the interfacial transition zone. Considerable improvements in the ultimate strength and water-tightness of concrete can be obtained when having mineral admixtures incorporated. It is important to emphasize that mineral admixtures are especially effective in increasing the tensile strength of concrete.

2.7. Curing conditions

Curing of concrete is the technical process which involves a combination of conditions that promote the cement hydration: time, temperature, and humidity conditions immediately after the placement of a concrete mixture into formwork [7].

At a given water-cement ratio, the porosity of a hydrated cement paste is determined by the degree of cement hydration. When exposed to normal temperature some of the constituent compounds of Portland cement begin its hydration as soon as water is added. The hydration reactions slow down considerably when the products of hydration coat the anhydrous cement grains. This is explained by the fact that hydration can be performed satisfactorily only under conditions of saturation; it almost stops when the vapor pressure of water in capillaries falls below 80 percent of the saturation humidity. Time and humidity are important factors in the hydration process controlled by water diffusion.

Temperature has an accelerating effect on the hydration reactions, as these reactions are type of chemical reactions. It should be noted that the time-strength relations in concrete technology generally assume moist-curing conditions and normal temperatures. At a given water-cement ratio, if the longer moist curing period is applied, the higher strength is obtained, assuming that the hydration of anhydrous cement particles is still going on. In thin concrete elements, if water is evaporated from the capillaries, air-curing conditions prevail, and strength will not increase with time. The evaluation of compressive strength with time is very important to structural engineers. ACI Committee's 209 recommendation is related to the moist-cured concrete made with normal portland cement (ASTM Type I) for concrete specimens cured at 20°C; while the CEB-FIP Models Code (1990), is described in next paragraph.

The influence of temperature on strength depends on the time-temperature history *of casting and curing* and it can be described as [8]:

- concrete cast and cure at the same temperature
- concrete cast at different temperatures but cure at a normal temperature
- concrete cast at a normal temperature but cure at different temperatures.

It is hard to claim that any strength developed at the below-freezing curing temperature. The hydration reactions of Portland cement compounds are slow and adequate temperature levels must be maintained for a sufficient time in order to provide the activation energy that is needed for chemical reaction's launch. This enables the strength development process that follows process of incorporating hydration products in voids .

3. ESTIMATED COMPRESSIVE STRENGTH FROM EC2, ACI 209 AND SRPS U.M1.048

The compressive strength of concrete at an age t depends on the type of cement, temperature and curing conditions. For a mean temperature of 20°C and curing in accordance with EN 12390 the compressive strength of concrete at various ages fcm(t) may be estimated from expressions:

$$f_{cm}(t) = \beta_{cc}(t) \cdot f_{cm} \tag{2}$$

with

$$\beta_{cc}(t) = e^{s \cdot (1 - \frac{28}{t})^{0.5}} \tag{3}$$

where:
$f_{cm}(t)$ is the mean concrete compressive strength at an age of t days
f_{cm} is the mean compressive strength at 28 days according to Table 3.1
$\beta_{cc}(t)$ is a coefficient which depends on the age of the concrete t
t is the age of the concrete in days
s is a coefficient which depends on the type of cement:
= 0,20 for rapid hardening high strength cements (R) (CEM 42,5R, CEM 52,5)
= 0,25 for normal and rapid hardening cements (N) (CEM 32,5R, CEM 42,5)
= 0,38 for slow hardening cements (S) (CEM 32,5)

According ACI 209, a study of concrete strength versus time indicates an appropriate general equation in the form (4) for predicting compressive strength at any time.

$$(f_c^{'})t = \frac{t}{a + \beta \cdot t} \cdot (f_c^{'})_{28} \tag{4}$$

where a in days and b are constants, $(f_c')28$ is 28-day compressive strength and t in days is the age of concrete. The evaluation of compressive strength with time is of great concern to structural engineers. ACI Committee 209 recommends the following relationship for moist-cured concrete made with normal Portland cement (ASTM Type I):

$$(f_c^{'})t = \frac{t}{4 + 0.85 \cdot t} \cdot (f_c^{'})_{28} \tag{5}$$

and for moist-cured concrete made with normal Portland cement (ASTM Type III):

$$(f_c^{'})t = \frac{t}{2.3 + 0{,}92 \cdot t} \cdot (f_c^{'})_{28} \tag{6}$$

According SRPS U.M1.048, compressive strength obtained by testing at an age t calculate on the value of compressive strength at an age t in Eq. (7).

$$(f_c^{'})t = \frac{1}{r_c} \cdot (f_c^{'})_{28} \tag{7}$$

where r_c is coefficient given in Table 1

Table 1. Coefficients for the compressive strength estimation [10]

Number of months	1	2	3	6	9	12 and more
Coefficient r_c	1	0.91	0.87	0.81	0.78	0.75

4. Experimental Work

This study has been conducted at Institute IMS, Belgrade. The main characteristics of materials and procedures used for the purpose of this research are as explained below:

4.1. Materials

Locally available river aggregate known as "Moravac" was used when making normal concrete. Recycled brick aggregate was used to make mix proportion RC1-RC4 . CEM I 42.5R, CEM II/A-M(S-L) 42.5R and CEM II/A-S 42.5N cement were used in this study. Several different chemical admixtures were also used.

Water from city supply was used as mixing water.

4.2. Mix proportion

Nine types of normal concrete and four types of recycled aggregate with different amount of cement and water-cement ratio were designed. The proportion of constituent materials is obtained from randomly adopted amount of cement and water cement ratio by Monte Carlo simulation. Necessary corrections were made in order to get consistency of fresh concrete to embed into moulds.

The details of various mix proportions are given in Table 2 (normal concrete) and Table 3. (recycled aggregate concrete).

Two kinds of recycled brick aggregate were made with 100% recycled brick aggregate (RC1 and RC2) and two with combination of natural river sand and recycled brick (RC3 and RC4). Table 3. shows which materials were used in recycled concrete design.

Table 2. Mix proportion of normal concrete

No	Cement	[kg/m^3]	Dmax	Water [kg/m^3]	Admix. [kg/m^3]	Consistency	Density [kg/m^3]
NC1	PC 20 S 42.5N – "TITAN"	300	32mm	140	3.4	2	2430
NC2	PC 42.5R BFC	300	32mm	160	0.0	2	2395
NC3	PC 20S 42.5N Titan	340	32mm	155	2.4	22	2430
NC4	PC 20M (S-L) 42.5R BFC	380	32mm	200	1.5	19	2477
NC5	PC 20S 42.5N Titan	410	32mm	150	2.9	20	2435
NC6	PC 20M (S-L) 42.5R BFC	420	16mm	175	3.4	22	2475
NC7	PC 20S 42.5N Titan	465	32mm	150	3.3	21	2445
NC8	PC 20 S 42.5N – "TITAN"	480	16mm	190	2.4	19	2415
NC9	PC 20S 42.5N Titan	480	16mm	160	4.3	20	2420

Table 3. Mix proportion of recycled aggregate concrete

No	Cement	[kg/m^3]	Dmax	Water [kg/m^3]	Admix. [kg/m^3]	Consistency	Density [kg/m^3]
RC1	PC 42.5R BFC	350	32mm	300	–	5	1944
RC2	PC 42.5R BFC	250	32mm	280	–	5	1972
RC3	PC 42.5R BFC	350	32mm	250	–	5	2135
RC4	PC 42.5R BFC	250	32mm	210	–	5	2105

4.3. Curing

Two types of curing were adopted (one for normal concrete and one for recycled aggregate concrete). These are water curing regimes (after demoulding, at 24h after mixing, the specimens were marked and stored inside the water tank suited in air conditioned room, temperature was maintained at 20±2°C for normal concrete and at 24h after mixing concrete, specimens were stored in water for six days and after that they were stored in air conditioned room.

4.4. Estimated compressive strength

Equations (2,4,7) are mathematical formulation designed to approximately describe the compressive strength of the Portland cement concrete over a certain restricted range of variables primarily.

Table 4. Measured compressive strength and estimated compressive strength (normal concrete)

No	f_3	f_7	f_{28}	f_{56}	f_{90}	f_{56}-EN*	f_{90}-EN*	f_{56}-SRPS**	f_{90}-SRPS**
NC1	31.9	41.4	45.6	51.4	53.9	55.2	56.5	52.6	55.1
NC2	30.1	38.5	46.2	47.4	48.7	56.3	57.7	53.7	56.2
NC3	22.2	30.7	39.4	48.6	54.8	64.1	66.1	59.0	61.7
NC4	–	40.4	47.9	54.3	64.4	54.4	56.1	50.1	52.4
NC5	34.9	48.8	55.5	62.2	65.8	53.2	54.5	50.8	53.1
NC6	–	39.4	48.9	60.3	75.6	47.0	48.5	43.3	45.3
NC7	41.2	58.8	67.0	70.2	74.6	66.2	68.3	61.0	63.8
NC8	38.4	47.6	53.7	57.4	66.1	80.0	82.4	73.6	77.0
NC9	31.5	50.2	63.4	68.7	71.9	75.7	78.0	69.7	72.9

* estimated compressive strength [9]
** estimated compressive strength [10]

Table 5. Measured compressive strength and estimated compressive strength (recycled concrete)

No	f_7	f_{28}	f_{90}	f_{180}	f_{90}-EN*	F_{180}-EN*	f_{90}-SRPS**	F_{180}-SRPS**	f_{90}-ACI***	F_{180}-ACI***
RC1	18.5	28.4	30.5	31.7	33.5	34.1	32.6	35.1	32.3	32.7
RC2	12.1	19.0	19.4	24.0	22.4	22.8	21.8	23.5	20.5	20.8
RC3	20.0	24.5	31.6	32.7	28.9	29.4	28.2	30.2	33.4	33.9
RC4	17.5	21.6	24.4	27.5	25.5	26.0	24.8	26.7	25.8	26.2

* estimated compressive strength [9]
** estimated compressive strength to [10]
*** estimated compressive strength to [11]

4. Discussion Experimental Data

The properties of freshly mixed concrete were determined with respect to slump and unit weight for each type of concrete.

Compressive strength at test specimens was determined at 3, 7, 28, 56 and 90 days after casting under the curing temperature of 20 °C for different type of concrete. The results for compressive strength test are given in Tables 4,5. Determination or estimation of the strength could by attained by EN, SRPS and ACI model capable of predicting strength of concrete at different age.

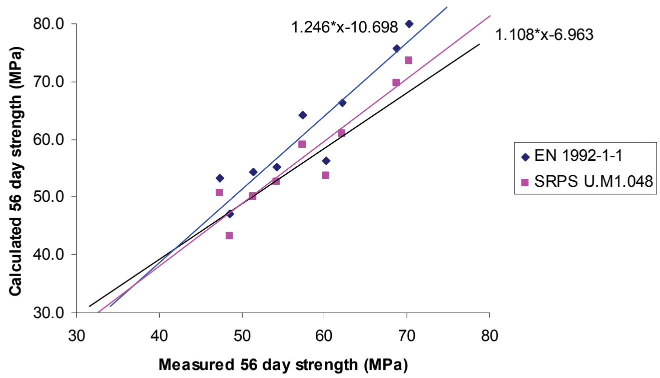

Fig. 5. Overview of the relationship between measured and calculated strength at 56 days for normal concrete

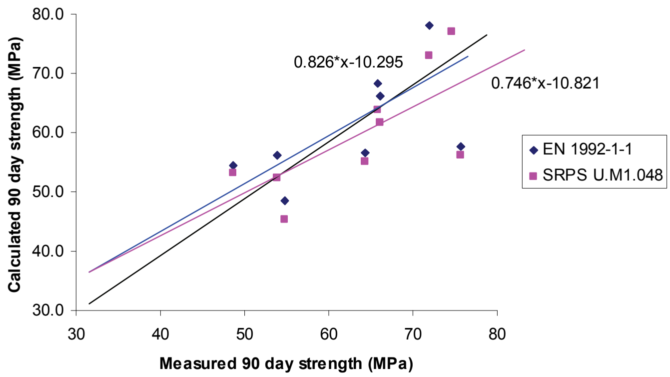

Fig. 6. Overview of the relationship between measured and calculated strength at 90 days for normal concrete

Equations (2,4,7) are mathematical formulations designed to approximately describe the compressive strength of the Portland cement concrete over a certain restricted range of variables involved. This equation provides a clear indication of the range of compressive strength obtainable by simply varying the type of cement. However, the formulation variables such as water to cement ratio and admixture types employed and the environmental variables such temperature and relative humidity as well as cure conditions will generally result in a change standard deviation.

The basic concept of this model is that, it produces a reliable relationship between strength of concrete and its own characteristics (the proposed model uses several parameters that rely on types of cement and cement mineralogy which is considered to have significant effect on compressive strength development).

Figures 5,6 show the relationship between measured compressive strength (x) and computed compressive strength at different ages (56 and 90 days for normal concrete)

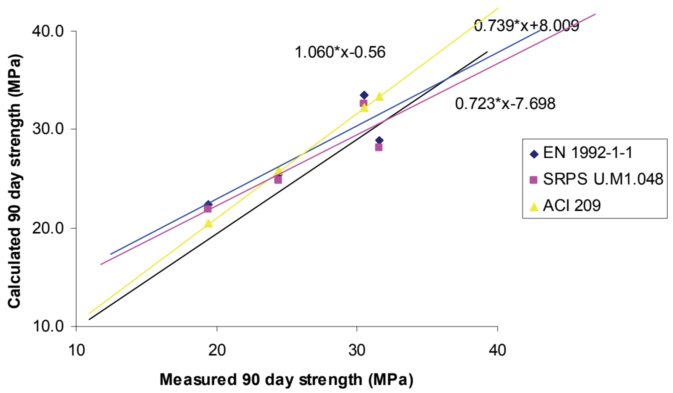

Fig. 7. Overview of the relationship between measured and calculated strength at 90 days for recycled concrete

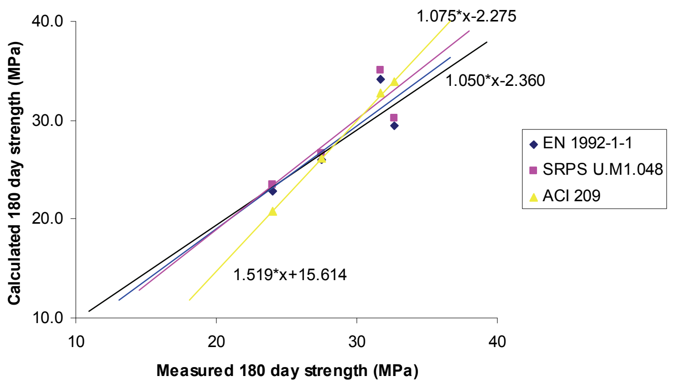

Fig. 8. Overview of the relationship between measured and calculated strength at 180 days for recycled concrete

Figures 7,8 show the relationship between measured compressive strength (x) and computed compressive strength at different ages (90 and 180 days for recycled aggregate concrete).

This relationship is represented by linear regression line for each mix proportion.

Also, the proposed model proved its validity to be used for estimating compressive strength with different mix proportion.

5. CONCLUSION

Previously performed accurate estimations of concrete strength are valuable to the concrete and construction industry. The presence of such model would possibly provide the hard balance and equality between controlling the quality (quality control process) and economics (saving time and and cost control), this model could be used in construction to estimate necessary adjustments on mix proportion used, to avoid the situation where concrete does not reach the required design strength or when concrete is unnecessarily strong.

This methodology allows a fast and accurate prediction of values for compressive strength. Common method for estimation of strength require extensive use of curing of mortar cubes at constant temperatures or the use of databases containing a large number of compressive values made at many ages and cured at different temperatures. Furthermore all of these methods requires many hours of lab and field time for testing, collecting and data analyzing.

Furthermore, the existing variables in the model yielded good reasonable results. Also, it is not preferred to load the prediction model with large number of variables. The model with lower number of variables and with the highest possible accuracy is the mostly appreciated when assuring the rapid and easy use of the model.

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PROCENA ČVRSTOĆE PRI PRITISKU BETONA SA PRIRODNIM I RECIKLIRANIM AGREGATOM

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Procena čvrstoće pri pritisku se postavlja kao važan zadatak proizvođačima betona, naročito pri projektovanju betonskih mešavina i obezbeđenju zahtevanog kvaliteta proizvedenog betona. U radu je prikazano poređenje eksperimentalnih rezultata čvrstoće pri pritisku betona sa prirodnim i recikliranim agregatom sa rezultatima dobijenim na osnovu jednačina prikazanih u tehničkoj regulativi. Prikazan je koeficijent determinacije eksperimentalnih podataka i rezultata dobijenih na osnovu preračuna prema jednačinama datim u EN 1992-1-1, ACI 209 i tabeli za preračun datoj u SRPS U.M1.048. Prikaz zavisnosti čvrstoće pri pritisku betona na osnovu jednačina datih u radu se odnosi na određivanje zavisnosti u odnosu na vrstu upotrebljenog cementa i starosti betona negovanog na konstantnoj temperaturi.

Ključne reči: *čvrstoća pri pritisku, procenjena čvrstoća, reciklirani agregat.*