USE OF COMBINED NONDESTRUCTIVE TEST METHODS TO PREDICT CONCRETE COMPRESSIVE STRENGTH CAST WITH AGGREGATE OBTAINED FROM SOUTHERN PARTS OF IRAQ

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Abstract

Concrete compressive strength is one of the most important concrete requirements that can be used to decide if the concrete is structurally acceptable or not. In several cases there is a need to estimate the concrete compressive strength on the site during construction or later on during the life of concrete. There are several methods used for this purpose, among the mostly used methods are the Ultra sonic pulse velocity and the Schmidt hammer rebound number. In this work six different fine aggregate and two different coarse aggregate were obtained from different parts of southern Iraq. Using these different aggregate combinations, 120 different concrete mixes with mix proportions of 1:2:4 or 1:1.5:3 and W/C ratios ranging between 0.40 to 0.60 were cast into 152 mm cubes. The compressive strength, ultrasonic pulse velocity, Schmidt hammer's rebound number and concrete density were measured. These results were introduced into nonlinear multiple variable regressions to obtain correlation relationships to predict the concrete compressive strength. Two groups of regressions were formulated, the first used only the Ultrasonic pulse velocity and rebound number in the regressions, and separate regressions were prepared for each single source of aggregate. The results of the predicted strength was in good agreement with the experimentally measured values, the value of the standard errors of these regressions were less than 10% of the lowest concrete strength investigated (20MPa). In the second group of regressions, the data from all concrete mixes with different aggregate sources were combined together to obtain the correlation regressions. These regressions were formulated because in many cases in practice the source of aggregate may not be known exactly. Two subgroups were developed, with different independent variables combinations. The standard error of this group was higher than for the first group, its best value was 16% of the minimum value of concrete strength investigated. This clearly proves the importance of the aggregate source on the predicted concrete compressive strength values.

Key words: Nondestructive test, ultrasound pulse velocity, rebound number, combined NDT test, strength evaluation, concrete compressive strength.

استخدام طرق الفحص الإتلافي المشترك لتقييم مقاومة الانضغاط لخرسانة مصنعة من ركام من المنطقة الجنوبية للعراق

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الخلاصة:

تعتبر مقاومة انضغاط الخرسانة أحد أهم الخواص اللازمة لتحديد مدى قبولية الخرسانة من الناحية الإنشائية و الديمومة. في عدة حالات تظهر حاجة لتقييم مقاومة انضغاط الخرسانة في الموقع سواءً أثناء التنفيذ أو خلال عمر المنشأ بعد الانجاز. تستخدم عدة طرق لاأتلافية لتقييم مقاومة انضغاط الخرسانة و من أكثر هذه الطرق شيوعاً هي سرعة الأمواج فوق الصوتية ورقم ارتداد مطرقة شميت. في هذا البحث تم استخدام ستة أنواع مختلفة من الركام الناعم ونوعين من الركام الخشن من مصادر طبيعية مختلفة من المنطقة الجنوبية من العراق. استخدمت هذه الأنواع المختلفة من الركام في أعداد ١٢٠ خلطة خرسانية مختلفة بنسب خلط وزنية (١:٢:٤) أو (١:١.٥:٣) وبنسب ماء/سمنت تتراوح من ٠.٤ إلى ٠.٦ . استخدمت مكعبات قياسية بأبعاد ١٥٢ مم كنماذج للفحص . تم قياس سرعة الأمواج فوق الصوتية ورقم ارتداد مطرقة شميت وكثافة الخرسانة على هذه النماذج ثم بعد ذلك تم قياس مقاومة أنضغاطها أتلافيا لحين الفشل. استخدامت نتائج هذه الفحوصات في إجراء تحليل لاخطي متعدد المتغيرات لإيجاد علاقات ارتباط لتخمين مقاومة انضغاط الخرسانة بأستخدام الفحوصات اللاأتلافية. تم صياغة مجموعتين من عمليات التحليل، في المجموعة الأولى استخدم سرعة الأمواج فوق الصوتية ورقم ارتداد مطرقة شميت فقط لتحديد مقاومة أنضغاط الخرسانة. أجريت عمليات التحليل لكل نوع من أنواع الركام وكانت القيم المستنبطة لمقاومة انضغاط الخرسانة مقاربة للنتائج العملية وبنسبة خطأ قياسي لاتتجاوز ١٠% من أقل قيمة مسجلة لمقاومة انضغاط الخرسانة. أما في المجموعة الثانية من عمليات التحليل فقد تم أعتماد نتائج كافة الفحوصات و لجميع الخلطات بغض النظر عن نوع الركام والسبب في ذلك أن مصدر الركام في كثير من الاحيان قد يكون مجهولاً عند تقييم خرسانة المنشأ. أعطت نتائج المجموعة الثانية نسبة خطأ أعلى من المجموعة الأولى حيث كانت أفضل قيمها تساوي ١٦% من أقل قيمة مسجلة لمقاومة الانضغاط. هذه النتيجة تثبيت أن تحديد نوع و مصدر الركام المستخدم في الخلطة الخرسانية عامل مهم في عملية تحمين مقاومة انضغاط الخرسانة.

Introduction

It is often necessary to test concrete structures after the concrete has hardened to determine whether the structure is suitable for its designed use. Ideally such testing should be done without damaging the concrete. The tests available for testing hardened concrete range between the completely nondestructive, where there is no damage to the concrete, through those were the concrete surface is slightly damaged, to partially destructive tests, where the concrete surface had to be repaired after testing. The range of properties that can be assessed using nondestructive tests is quite large and includes such fundamental parameter as density, elastic modulus, compressive strength, surface hardness and absorption as well as reinforcement size and location.

Concrete compressive strength is one concrete property that is widely needed to be evaluated during the progress of concrete structures execution. Among the most used nondestructive test methods in assessing concrete compressive strength are the Ultrasonic pulse velocity and the Schmidt hammer rebound number. These two methods are known for more than 50 years [(Carino ,1994) (Bungey and Millard ,1996)]. The first method is used to measure the sound velocity in concrete and concrete compressive strength, while the second method evaluates concrete compressive strength through measuring its surface hardness. These two methods have been known for more than 50 years and gained wide spread use worldwide for their low cost and simple and fast test procedures. Numerous reports and researches have been published on these two methods aiming to obtain mathematical formulations to be used to determine the concrete compressive strength. From previous literature it can be recognized that there is no unique mathematical relationship that can be used worldwide for this purpose. This is because the readings and results of these two methods are largely affected by many factors; among these factors are the elastic properties of aggregate (aggregate source) and their proportion in the concrete, concrete density and moisture content. Thus large number of mathematical relationships was obtained aiming to give good assessment to concrete compressive strength [(IAEA ,2002)(ACI Committtee 228.1R-95)].

In this research work, it was aimed to obtain mathematical relationships that can be used for the assessment of compressive strength of concrete cast using fine and coarse aggregate obtained from different sources in the southern parts of Iraq. Six different fine aggregate and two coarse aggregate sources were investigated. In addition, two nominal concrete mix proportions with different water / cement ratios were also included as a variable in this research. These two nominal mixes are commonly used in the southern part of Iraq.

Experimental Work

Two well known nondestructive test methods were used in this work, these methods are the ultrasonic pulse velocity and the Schmidt hammer. The readings and the accuracy of these two methods are very much affected by the elastic properties and proportions of aggregate in the concrete mix. In order to obtain a clear image on the effects of these factors on the accuracy of predicting concrete compressive strength using combined nondestructive test methods, several types of coarse and fine aggregates, from different sources in southern parts of Iraq were used.

Testing Program

The testing program was planned to obtain information about the effect of mix proportions (aggregate to cement and water to cement ratios) and type of coarse and fine aggregates and concrete density on the results of the UPV and RN methods and on their accuracy in predicting concrete compressive.

Two nominal concrete mixes 1:2:4 and 1:1.5:3 mixes with W/C ratio in the range of 0.40 to 0.60 were investigated. These mixes were chosen to represent those widely used in Iraqi construction projects.

Also two natural types of coarse aggregate and six types of fine aggregate obtained from different sources in southern part of Iraq was used in the preparation of the concrete mixes. The details of the materials used are given below:

Cement (C)

Two types of cement, Ordinary and Sulphate Resisting Portland cements conforming to Iraqi standard IQS 5 [6] was used in this work.

Fine Aggregate (FA)

Six fine aggregate types conforming to Iraqi standard IQS 45 [7] were used. The sources of these aggregate and notation are given in the **Table 1**.

Coarse Aggregate (CA)

Two coarse aggregate types conforming to Iraqi standard IQS 45[7] were used. **Table 1** also shows the source and notation of these aggregate.

Concrete Mixes

As detailed in **Table 2**, hundred and twenty different concrete mixes with aggregate from different sources were investigated; the general characteristics of the mixes are given below:

1. Mix proportions 1:2:4 or 1:1.5:3
2. Nominal water/cement ratio (W/C) from 0.4 to 0.6 (the effective W/C ratio depended finally on the natural moisture condition of the aggregate and ranged between 0.444 to 0.628)

Casting and Curing of Test Specimens

152x152x152 mm concrete cubes were prepared and cast to measure concrete compressive strength; six cubes of each mix were cast in steel moulds then covered for 24 hours by polyethylene sheets for 24 hour. The cubes were then stored in curing tanks for a total period of 28 days. After the 28 days of curing the cube specimens were removed out of water and tested immediately.

Testing of Concrete Cube Specimens

Concrete Density

The densities of the concrete cubes were measured according to ASTM C 138-02 [9]. Each value of density of each mix represents the average of densities of six cubes. Values of concrete densities are given in **Table 3**.

Ultrasonic Pulse Velocity

The ultra sonic pulse velocities of the cast concrete cubes were measured according to ASTM C 597-02 [10]. Two readings on each cube were measured (using the opposite smooth surfaces of the cube). Thus each mix result of ultrasonic pulse velocity represents an average of twelve readings. **Table 3** gives the ultrasonic pulse velocities of all the mixes investigated.

Rebound Number

The rebound number was measured on the cube specimens using Schmidt hammer and according to ASTM C 805-02 [11]. Each cube was fixed in the compression machine, and a pressure of 7 MPa was applied on the cube. Five readings were taken on each two opposite smooth surfaces of the cube, thus a total of 10 readings were taken on each cube. The final reading of rebound number of each mix was therefore the average of 60 readings. **Table 3** shows the values of the rebound numbers of all the concrete mixes investigated.

Concrete Compressive Strength

The compressive strengths of the concrete mixes were determined using a compression machine with ultimate capacity of 3000 kN and according to IQS 248[8]. The compressive strength of each mix was the average of the compressive strength of six cubes. The results of the compressive strengths of all the 120 concrete mixes are given in **Table 3**.

Experimental Results

Table 3 shows the experimentally measured properties of all the 20 concrete mixes investigated with their ranges of actual W/C and aggregate to cement ratios. These results were fed into the Statistica program in different combinations to find the constants of the multiple regressions (a_0, a_1, a_2, a_3, a_4, a_5).

Multiple Non-linear Regressions for Prediction of Concrete Compressive Strength

In practice, it is advantageous to use more than one method of non destructive testing (NDT) at a time in predicting or monitoring concrete strength and quality. Using more than one method is beneficial especially because the variations in properties and composition of concrete (aggregate type and source) largely affect the test results of the NDT. Both the Schmidt hammer and UPV are affected by the mix proportions of the concrete, aggregate elastic properties and also by its moisture condition each in a certain manner [(ASTM C 805-02) (Kaplan,1959)]. These factors may result in an increase or decrease in the value of the estimated concrete strength (error). Such as the case of the presence of moisture in concrete: presence of moisture in concrete increases the UPV, but on the other hand, it decreases the rebound number recorded by the Schmidt hammer (Neville,2005), so when both methods are used together, the error in one method will correct the error in the second method. The presence of moisture in concrete will increase the UPV reading but at the same time will decrease the rebound number, so readings of the UPV and RN will correct each other and the effect of moisture will be eliminated in the estimation of concrete strength. Another factor that largely affects the NDT results are the concrete mix proportions, for the same compressive strength, mixes with higher coarse aggregate will result in an increase in the UPV and rebound number(Bungey and Millard,1996).

There have been numerous attempts from different researchers throughout the world to find mathematical relationships that can predict the concrete compressive strength by using the Ultra Sonic Pulse and the Schmidt Rebound Hammer either separately or combined [(Facacoaru ,1984) to (Tanigawa and etl,1984)]. All these methods used local materials and cannot be applied for concrete cast using aggregate from other different sources. The predicted concrete strength values using the previously developed relationships will show large scatter compared to the experimentally measured values when aggregate from other sources are used in casting concrete.

In order to obtain accurate relationships to predict concrete strength, multiple linear regressions were used. Different forms of relationships with different combinations of independent variables can be obtained to predict the concrete compressive strength. These independent variables are: Ultrasonic pulse velocity, Schmidt rebound number, water/cement ratio, aggregate / cement ratio and concrete density, Depending on the availability of these information on the concrete mix characteristics and aggregate origin (source). The general form of the regression is given below:

$$\mathbf{f_{cu} = a_o \, . \, (UPV)^{a1} \, . \, (RN)^{a2} \, . \, (A/C)^{a3} \, . \, (W/C)^{a4} \, . \, (\rho)^{a5}}$$

Where:

f_{cu} : Concrete compressive strength in MPa.
UPV : Ultrasonic pulse velocity in km/sec.
RN : Rebound number.
W/C : Water to cement ratio by weight.
A/C : Aggregate to cement ratio by weight.
ρ : Concrete density in (kg/m^3).
a_o, a_1 to a_5: regression constants.

The mathematical regressions were divided into two groups. The first group considered each type of aggregate from a particular source in Southern part of Iraq individually, while the second group combined all the data of concrete specimens, regardless to the aggregate source, in an attempt to get more practical and easier to use regressions, and also, because in some cases, the source of aggregate may not be known. This of course will affect the accuracy of the regressions adversely, but the engineer must take this into consideration in his assessment to concrete strength. All regressions considered either Ordinary Portland cement or Sulphate Resisting Portland cement.

Group 1: Regressions for Aggregates from Known (Particular) Sources

Group one was divided into 20 subgroups, ten groups for each of the Ordinary or Sulphate Resisting Portland cements concrete. In each subgroup, three regressions were derived. Each regression included different either the ultrasonic pulse velocity or rebound number separately or combined depending on the availability nondestructive method used in testing the concrete. In each table, the values of regression constants (a_o, a_1, a_2,) are given. These tables also give the standard errors of estimates in the compressive strength (SE) and the multiple variable correlation coefficients (R) of each regression to show its accuracy.

Table 4 gives the regressions constants for each type of aggregate source for concrete mixes cast with Ordinary Portland cement, while **Table 5** gives the constants for concrete mixes cast with Sulphate Resisting Portland cement. Each group included both 1:2:4 and 1:1.5:3 mixes.

From **Tables 4 and 5**, it can be clearly seen that the regressions gave excellent prediction, using UPV test only, the value of standard error was between 0.32 to 3.41 MPa, while when using the Schmidt hammer the this error was between 0.94 to 2.59 MPa. Combining both nondestructive test methods, the maximum standard error value is decreased to 0.27 to 2.03 MPa. The latter value is less than 10% of the lowest concrete compressive strength investigated (20MPa). Introducing the mix proportions in the regression (aggregate/cement, water/cement and density) improved the regression, but to a limited extent. Therefore, using the combined UPV and RN regression (with particular reference to aggregate source) was found to be sufficient and practical to predict the concrete compressive strength.

Group 2: Regressions for Aggregate from Unknown Source

In order to extend the validity of the regressions derived for particular sources of aggregates (**Tables 4 and 5**), other combinations of regressions were derived, in these regressions; the source of aggregate was overlooked. **Table 6 and 7** give regressions constants for predicting concrete strength cast with Ordinary or Sulphate Resisting Portland cements respectively, regardless to the aggregate source.

It is important to highlight here that these regressions must only be used for concrete cast with aggregate from the southern parts of Iraq.

In these two groups of regressions (Ordinary or Sulphate Resisting Portland cements), the maximum value of standard error was 4.05 MPa when using UPV method only, and 4.44 MPa when using Schmidt hammer only, the value of standard error decreases to 3.52 MPa when using the combine UPV and Schmidt hammer test methods. When the mix properties are included, the standard error value was further decreased to 3.36 MPa. The four values of standard errors for these regressions give errors of about 20%, 22%, 19% and 17% respectively. **Figure 1** and **Figure 2** shows the observed versus predicted compressive strength for the first regression of the two groups (Regressions N1 and S1).

It is important to mention here that the age of concrete was not included in the regressions, because it is more preferable to depend only on the result of the UPV and rebound number in addition to the mix proportions if available to represent the condition of concrete hardened properties, in many practical site cases the age of concrete may not be known exactly.

Limitations of The Developed Regressions

In order to obtain a realistic predicted value for the concrete compressive strength, the general ranges of the independent variables introduced in the derivation of these regressions must be taken into consideration. These final ranges are given in **Table 8**.

Conclusions

On the basis of the experimental results obtained in this work, using two different nondestructive test methods for predicting concrete compressive strength, cast with aggregate obtained from different sources in the southern part of Iraq, following conclusions can be withdrawn:

1. Changing the source of aggregate affects the results of the ultra sonic pulse velocity and the rebound number of the Schmidt hammer. There is no generalized formula that can be used

for predicting concrete compressive strength using nondestructive testing. The stiffness of aggregate largely affects the readings of the UPV and RN methods.
2. The combined usage of UPV and RN methods improves the predicted values of concrete compressive strength, several factors that causes variations in the readings of these methods eliminate each other, thus resulting in more accurate predicted values of concrete strength. Further introducing information on concrete mix proportions and density into the mathematical regressions can improve the accuracy of the predicted value.
3. Several regressions were derived for each type of aggregate source used in the concrete mix. These regressions gave excellent accuracies especially when both UPV and RN methods were used together. In most cases, the standard error of the regression was less than 10 % compared with the minimum concrete strength investigated (20 MPa). It was found that there is no need to introduce the mix proportions in this case, since the regressions gave good and acceptable accuracy.
4. The accuracy of the regressions decreased when all the data from the different aggregate sources were used, due to the variation in the elastic properties of the concrete. The standard error maximum values exceeded 20% when using UPV or RN methods separately. This error decreased to less than 19% when using the combined tests together. A further decrease in the standard error was obtained when the mix proportions and concrete density was introduced into the regressions, the maximum value of the standard error became less than 17%.
5. In using the derived regression, the engineer must be aware not to tolerate the limits of the independent variables used in the regression. This may result in nonrealistic predicted values.

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Table 1: Materials sources and notations*

item	Cement type	Fine aggregate source	Coarse aggregate source
1	Ordinary **N**	Najaf1(Wilayat Ali) **A**	Badrah **B**
2	Sulphate resisting **S**	Badrah **B**	Basrah **S**
3		Najaf2(Khamas) **K**	
4		Zubair **Z**	
5		Jabal Sanam **S**	
6		Al Ukhaider **G**	

*NBS: Concrete mix with Ordinary Portland cement, FA from Badrah and CA from Basrah.

Table 2: mix proportion details and notations

Mix notation	Mix proportion	Effective W/C ratio	Mix notation	Mix proportion	Effective W/C ratio	Mix notation	Mix proportion	Effective W/C ratio	Mix notation	Mix proportion	Effective W/C ratio
NBB1	1:2:4	0.557	SKB1	1:2:4	0.628	NAS1	1:2:4	0.600	SZS1	1:2:4	0.600
NBB2	1:2:4	0.507	SKB2	1:2:4	0.578	NAS2	1:2:4	0.550	SZS2	1:2:4	0.550
NBB3	1:2:4	0.457	SKB3	1:2:4	0.528	NAS3	1:2:4	0.500	SZS3	1:2:4	0.500
NBB4	1:1.5:3	0.544	SKB4	1:1.5:3	0.600	NAS4	1:1.5:3	0.578	SZS4	1:1.5:3	0.578
NBB5	1:1.5:3	0.494	SKB5	1:1.5:3	0.550	NAS5	1:1.5:3	0.494	SZS5	1:1.5:3	0.528
NBB6	1:1.5:3	0.444	SKB6	1:1.5:3	0.500	NAS6	1:1.5:3	0.444	SZS6	1:1.5:3	0.478
SBB1	1:2:4	0.600	NZB1	1:2:4	0.557	SAS1	1:2:4	0.557	NSS1	1:2:4	0.600
SBB2	1:2:4	0.550	NZB2	1:2:4	0.507	SAS2	1:2:4	0.507	NSS2	1:2:4	0.550
SBB3	1:2:4	0.500	NZB3	1:2:4	0.457	SAS3	1:2:4	0.457	NSS3	1:2:4	0.500
SBB4	1:1.5:3	0.578	NZB4	1:1.5:3	0.544	SAS4	1:1.5:3	0.544	NSS4	1:1.5:3	0.578
SBB5	1:1.5:3	0.528	NZB5	1:1.5:3	0.494	SAS5	1:1.5:3	0.494	NSS5	1:1.5:3	0.528
SBB6	1:1.5:3	0.478	NZB6	1:1.5:3	0.444	SAS6	1:1.5:3	0.444	NSS6	1:1.5:3	0.473
NAB1	1:2:4	0.500	SZB1	1:2:4	0.600	NKS1	1:2:4	0.600	SSS1	1:2:4	0.557
NAB2	1:2:4	0.450	SZB2	1:2:4	0.550	NKS2	1:2:4	0.550	SSS2	1:2:4	0.550
NAB3	1:2:4	0.400	SZB3	1:2:4	0.500	NKS3	1:2:4	0.500	SSS3	1:2:4	0.457
NAB4	1:1.5:3	0.550	SZB4	1:1.5:3	0.600	NKS4	1:1.5:3	0.578	SSS4	1:1.5:3	0.544
NAB5	1:1.5:3	0.500	SZB5	1:1.5:3	0.550	NKS5	1:1.5:3	0.528	SSS5	1:1.5:3	0.494
NAB6	1:1.5:3	0.450	SZB6	1:1.5:3	0.500	NKS6	1:1.5:3	0.478	SSS6	1:1.5:3	0.444
SAB1	1:2:4	0.600	NSB1	1:2:4	0.557	SKS1	1:2:4	0.557	NGB1	1:2:4	0.600
SAB2	1:2:4	0.550	NSB2	1:2:4	0.550	SKS2	1:2:4	0.507	NGB2	1:2:4	0.550
SAB3	1:2:4	0.500	NSB3	1:2:4	0.500	SKS3	1:2:4	0.457	NGB3	1:2:4	0.500
SAB4	1:1.5:3	0.578	NSB4	1:1.5:3	0.578	SKS4	1:1.5:3	0.544	NGB4	1:1.5:3	0.578
SAB5	1:1.5:3	0.528	NSB5	1:1.5:3	0.528	SKS5	1:1.5:3	0.494	NGB5	1:1.5:3	0.528
SAB6	1:1.5:3	0.478	NSB6	1:1.5:3	0.478	SKS6	1:1.5:3	0.444	NGB6	1:1.5:3	0.478
NKB1	1:2:4	0.628	SSB1	1:2:4	0.600	NZS1	1:2:4	0.600	SGB1	1:2:4	0.600
NKB2	1:2:4	0.578	SSB2	1:2:4	0.550	NZS2	1:2:4	0.550	SGB2	1:2:4	0.550
NKB3	1:2:4	0.528	SSB3	1:2:4	0.500	NZS3	1:2:4	0.500	SGB3	1:2:4	0.528
NKB4	1:1.5:3	0.600	SSB4	1:1.5:3	0.589	NZS4	1:1.5:3	0.578	SGB4	1:1.5:3	0.578
NKB5	1:1.5:3	0.550	SSB5	1:1.5:3	0.539	NZS5	1:1.5:3	0.528	SGB5	1:1.5:3	0.528
NKB6	1:1.5:3	0.500	SSB6	1:1.5:3	0.489	NZS6	1:1.5:3	0.478	SGB6	1:1.5:3	0.478

Table 3: Range of measured properties of the tested concrete mixes

Mix notation	Compressive strength MPa	UPV m/sec	RN	W/C Ratio	Agg/cement ratio	Density kg/m^3
NBB	25.02-45.2	4573-4870	21.2-27.3	0.444-0.557	6 or 4.5	2296-2381
SBB	19.64-41.42	4310-4813	23.7-30.7	0.478-0.60	6 or 4.5	2309-2379
NAB	25.91-34.22	4412-4839	23.4-31.3	0.45-0.55	6 or 4.5	2353-2415
SAB	20.27-31.84	4412-4639	25.3-27.4	0.478-0.60	6 or 4.5	2295-2399
NKB	18.82-33.41	4167-4518	18.8-33.4	0.50-0.628	6 or 4.5	2296-2379
SKB	24.12-33.19	4265-4478	24.1-33.2	0.50-0.628	6 or 4.5	2305-2360
NZB	22.40-31.45	4412-4545	22.4-31.5	0.444-0.557	6 or 4.5	2343-2418
SZB	28.02-43.08	4335-4663	28.0-43.2	0.50-0.60	6 or 4.5	2315-2389
NSB	23.24-35.48	4369-4545	23.2-35.5	0.478-0.557	6 or 4.5	2335-2383
SSB	26.77-35.94	4455-4615	26.8-35.9	0.489-0.60	6 or 4.5	2337-2396
NAS	20.93-42.12	4186-4687	20.4-42.1	0.444-0.60	6 or 4.5	2357-2441
SAS	29.02-42.28	4434-4687	29.0-42.3	0.444-0.557	6 or 4.5	2349-2451
NKS	27.95-32.94	4360-4545	29.3-29.5	0.478-0.60	6 or 4.5	2359-2387
SKS	34.60-50.47	4390-4580	28.2-31.1	0.478-0.60	6 or 4.5	2378-2418
NZS	23.05-32.94	4478-4712	27.1-31.7	0.473-0.60	6 or 4.5	2358-2471
SZS	22.50-33.05	4310-4580	27.9-30.4	0.444-0.557	6 or 4.5	2403-2481
NSS	18.07-30.98	4592-4813	27.8-32.7	0.473-0.60	6 or 4.5	2388-2464
SSS	27.18-35.60	4523-4737	27.2-32.6	0.444-0.557	6 or 4.5	2386-2474
NGB	22.83-27.76	4390-4545	28.2-30.4	0.478-0.60	6 or 4.5	2385-2422
SGB	21.91-26.03	4348-4412	27.0-30.6	0.478-0.60	6 or 4.5	2374-2460

Table 4: Regressions constants of groups cast with Ordinary Portland cement

Reg. No.	**a_0**	**a_1**	**a_2**	**S.E MPa**	**R**	**Reg. No.**	**a_0**	**a_1**	**a_2**	**S.E MPa**	**R**
NAB						NKS					
NAB1	0.445	1.676	0.498	1.39	0.871	NKS1	$3.3x10^{-5}$	2.797	2.826	0.47	0.990
NAB2	0.272	3.053		1.85	0.759	NKS2	$7.8x10^{-5}$	8.511		1.16	0.941
NAB3	2.734		0.735	1.69	0.803	NKS3	$5.9x10^{-5}$		3.908	٠.66	0.981
NBB						NSB					
NBB1	0.1755	-0.553	1.888	1.04	0.991	NSB1	$7.8x10^{-5}$	9.136	-0.34	1.11	0.928
NBB2	$1.92x10^{-6}$	10.722		3.55	0.897	NSB2	$1.39x10^{-4}$	8.028		1.12	0.927
NBB3	0.096		1.809	1.05	0.991	NSB3	0.028		2.103	1.55	0.854
NAS						NSS					
NAS1	$1.87x10^{-4}$	4.49	1.545	1.44	0.978	NSS1	0.0671	1.055	1.278	0.88	0.952
NAS2	$6.64x10^{-5}$	8.614		1.88	0.963	NSS2	0.0330	4.357		1.06	0.931
NAS3	0.0011		3.044	1.91	0.962	NSS3	0.0924		1.659	0.90	0.950
NGB						NZB					
NGB1	0.0012	3.264	1.492	0.43	0.957	NZS1	$9.55x10^{-4}$	5.147	0.786	0.97	0.963
NGB2	0.010	5.216		1.10	0.823	NZS2	$2.48x10^{-4}$	7.762		1.48	0.912
NGB3	0.0189		2.138	0.94	0.873	NZS3	0.1595		1.577	1.91	0.847
NKB						NZS					
NKB1	$1.29x10^{-3}$	7.062	-0.211	0.28	0.998	NZB1	0.01849	7.287	-1.126	2.03	0.715
NKB2	$1.19x10^{-3}$	6.656		0.32	0.997	NZB2	0.08616	3.790		2.19	0.655
NKB3	$2.88x10^{-3}$		2.795	2.55	0.856	NZB3	1.9157		0.794	2.56	0.468

Table 5: Regressions constants of groups cast with Sulphate Resisting Portland cement

Reg. No.	**a_0**	**a_1**	**a_2**	**S.E MPa**	**R**	**Reg. No.**	**a_0**	**a_1**	**a_2**	**S.E MPa**	**R**
SAB						SKS					
SAB1	0.0008	4.346	1.176	1.01	0.965	SKS1	1.55×10^{-4}	4.727	1.557	0.84	0.984
SAB2	0.0022	6.258		1.21	0.949	SKS2	1.94×10^{-7}	12.67		1.82	0.922
SAB3	0.001		3.084	1.62	0.908	SKS3	0.0164		2.283	1.18	0.968
SBB						SSB					
SBB1	1.42×10^{-4}	5.774	1.037	0.98	0.991	SSB1	0.0677	1.008	1.396	1.25	0.935
SBB2	1.806×10^{-5}	9.411		1.47	0.981	SSB2	6.44×10^{-4}	7.145		1.70	0.875
SBB3	7.973×10^{-3}		2.459	1.90	0.968	SSB3	0.164		1.588	1.27	0.933
SAS						SSS					
SAS1	6.11×10^{-3}	4.8	0.405	0.67	0.993	SSS1	0.0128	3.961	0.505	0.63	0.98
SAS2	1.67×10^{-3}	6.554		0.97	0.985	SSS2	6.32×10^{-3}	5.539		0.76	0.971
SAS3	0.4256		1.309	1.83	0.945	SSS3	0.173		1.528	1.13	0.933
SGB						SZS					
SGB1	2.19×10^{-4}	5.013	1.272	0.37	0.99	SZS1	3.30×10^{-5}	2.192	3.060	0.81	0.974
SGB2	1.63×10^{-5}	9.644		1.03	0.926	SZS2	3.16×10^{-3}	6.042		1.39	0.922
SGB3	0.02074		2.130	0.91	0.943	SZS3	8.87×10^{-6}		4.422	0.99	0.961
SKB						SZB					
SKB1	0.0029	5.372	0.333	0.27	0.998	SZB1	9.37×10^{-4}	3.037	1.775	0.78	0.987
SKB2	1.75×10^{-3}	6.440		0.51	0.993	SZB2	4.08×10^{-4}	7.496		2.12	0.905
SKB3	0.152		1.580	2.02	0.885	SZB3	6.42×10^{-3}		2.578	1.34	0.963

Table 6: Regressions for concrete with Ordinary Portland cement and all aggregate types

Ordinary Portland Cement (all groups: 60 points : 360 cubes) All aggregate types								
Regression No.	a_0	a_1	a_2	a_3	a_4	a_5	S.E MPa	R
N1	504.882	3.069	0.755	-0.543	0.085	-3.324	2.73	0.833
N2	0.0857	3.055	0.267	-0.552	-0.053		2.89	0.812
N3	37.621	4.311	0.712			-2.9	2.96	0.801
N4	0.0126	4.34	0.337				3.10	0.778
N5	0.0219	4.715					3.21	0.761
N6	1.432		0.901				4.44	0.440

Table 7: Regressions for concrete with Sulphate Resisting Portland cement and all aggregate types

Sulphate Resisting Portland Cement (all groups: 60 points : 360 cubes) All aggregate types								
Regression No.	a_0	a_1	a_2	a_3	a_4	a_5	S.E MPa	R
S1	69.644	2.256	1.474	-0.524	0.127	-3.058	3.20	0.848
S2	0.0145	2.933	0.906	-0.390	-0.032		3.47	0.818
S3	1.266	2.954	1.594			-2.082	3.36	0.831
S4	0.00315	3.382	1.220				3.52	0.812
S5	0.00247	6.249					4.05	0.741
S6	0.0421		1.969				3.94	0.758

Table 8: General ranges of measured properties of the tested concrete mixes

UPV m/sec	RN	W/C Ratio	Agg/cement ratio	Density kg/m^3
4167-4870	18.8-43.2	0.444-0.628	4.5-6.0	2295-2481

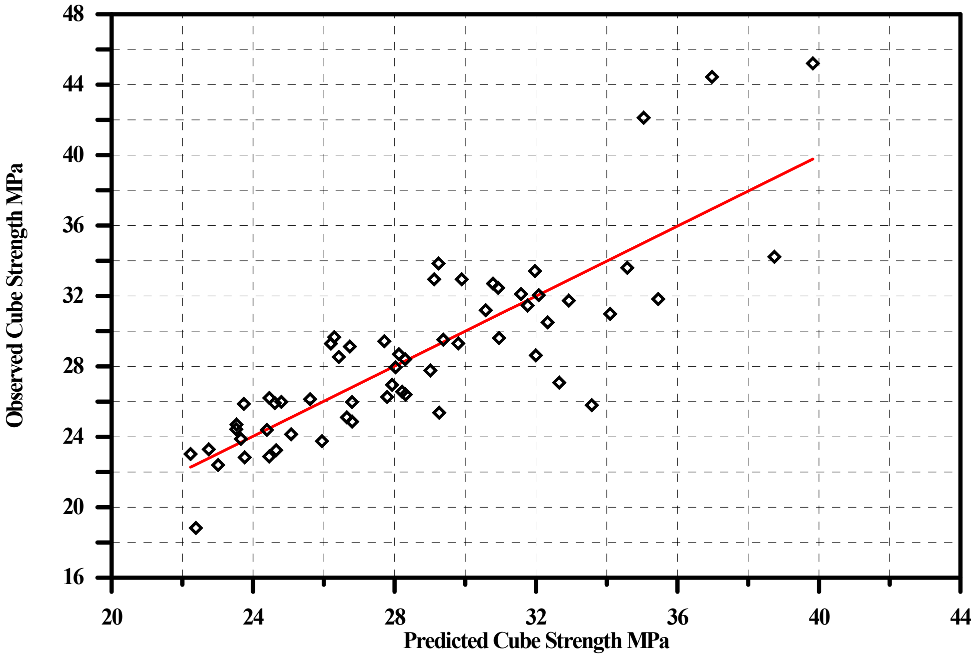

Figure 1: Observed versus predicted compressive strength values of regression N1.

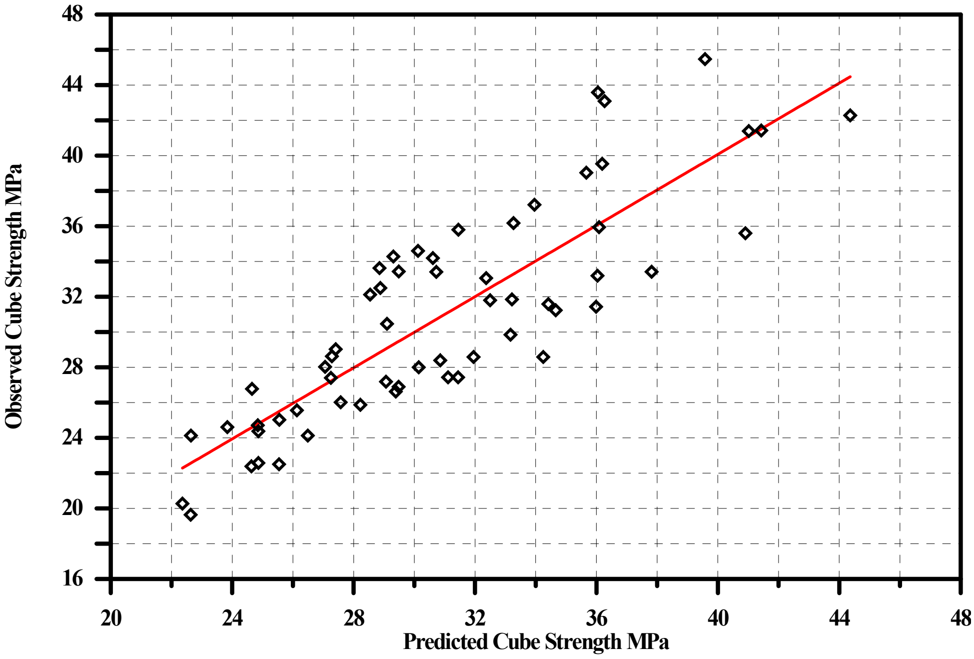

Figure 2: Observed versus predicted compressive strength values of regression S1.