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Utility of Non Destructive Tests to Assess the Compressive Strength of High Performance Concrete

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Abstract

In this study, high performance concrete mixes were produced by using high range water reducing agent(Glenium 51) and also by using 10% silica fume or 10% high reactivity metakaolin as a partial replacement by weight of cement. Three cement contents (350, 450, and 550) kg/m^3 were used through this study. A total of 330 (100 mm) cubes, 66 (150×300 mm) cylinders, and 132 (100×100×400 mm) prisms were cast and cured to the required age of test. Compressive strength, rebound number, ultrasonic pulse velocity and dynamic modulus of elasticity were investigated for all mixes at 7, 28, 90, and 120 days age. Results of the destructive test of compressive strength and non–destructive tests (hammer, ultrasonic pulse velocity, and dynamic modulus) are statistically analyzed by using SPSS Ver.15 software to study the possibility of assessing the compressive strength of high performance concrete by using non–destructive tests. Simple and multiple linear regression analysis of the obtained results leads to the proposed statistical models for evaluating the compressive strength by using one or two or three of the above non–destructive tests. Analysis of variance (ANOVA) and t–test was also used to investigate the adequacy of the statistical models. The statistical models were subjected to adequacy checks at a selected level of significance of 5%.

1-Introduction

The shortcoming and limitation of conventional strength tests as a measure of the quality of concrete led to the development of non–destructive methods for testing structural concrete in situ. The main objective of non–destructive methods as applied to concrete, is to provide a reliable estimate of the quality of concrete in a structure without relying solely on results from test specimens which are not necessarily representative of the structural concrete, due to differences in compaction or curing conditions between the test specimens and the corresponding concrete in a structure. The non–destructive tests can be classified broadly into surface hardness, vibration methods, radioactive methods, electrical methods, magnetic methods, and the combined method[1]. The nondestructive testing of in situ concrete was introduced to supply the engineers with information on one or more of the following properties of the structural concrete such as: strength properties, durability, density, moisture content, elastic properties, detection of defects which include surface cracks and large voids, position and condition of the reinforcement, concrete cover over the reinforcement, thickness, and cement content [2]. The main advantages of the non-destructive tests are that repetitive tests could be carried out on the same specimen, and also the structure is not functionally affected by the test, although for some tests such as the pull-out, Windsor probe and core tests, some repairs may be necessary.

2-Objectives

The main objective of this study[3] is to investigate the following properties:

2-1 Suitability and reliability of the rebound hammer, ultrasonic pulse velocity, and resonance tests for the estimation of concrete strength.

2-2 Effect of concrete strength level on the measurements of rebound hammer, ultrasonic pulse velocity, and resonance tests.

2-3 Suggesting relationships and formulas based on a comprehensive statistical analysis.

3-Literature Review

The nondestructive tests (NDT) had achieved an important place in the control of quality of concrete and the evaluation of existing concrete structures with regard to their strength and durability. In certain instances, for example when investigating width and depth of cracks in concrete, NDT methods are the only ones that can provide a reasonable answer[4].According to Malhotra[5] and Kolek[6] there is a general correlation between compressive strength of concrete and the hammer rebound number. The most satisfactory way of establishing this correlation is to measure both the rebound number and the compressive strength on the same concrete cube. For a given concrete mixture, the rebound number is affected by factors such as moisture content of concrete, type of form material, and type of coarse aggregate. These factors should correspond as closely as possible to the in–place concrete and need to be considered in preparing the strength relationship and interpreting test results. The relation between compressive strength and pulse velocity is not unique, and is affected by many factors such as, aggregate size, type, and content; cement type and content; and moisture content. The effect of such factors has been studied by many researchers[7,8,9,10]. Phoon et al[11] have recently proposed a probabilistic model to predict compressive strength from ultrasonic pulse velocity, by using the model together with field data, a consistent statistical quality assurance criterion may be established. Lin et al[12] investigated the relationship between the ultrasonic pulse velocity and the compressive strength of concrete. The experimental results show that the relationship between the compressive and ultrasonic pulse velocity is significantly influenced by age and coarse aggregate content.

The resonant frequency of vibration of a concrete specimen or structure directly relates to its dynamic modulus of elasticity and, hence, its mechanical integrity. The method of determining the dynamic elastic moduli of solid bodies using their resonant frequencies has been in use for the past 66 years. However, until up to the last few years, resonant frequency methods had been used almost exclusively in laboratory studies[13]. The dynamic modulus of elasticity is affected by the elastic moduli of its constituent materials and their relative proportions**.** According to Jones[14], for a given composition of cement paste, that is, the same water/cement ratio, the elastic modulus of hardened concrete increases with an increase in the percentage of total aggregate. It has also been reported that an increase in the amount of mixing water or in the volume of entrapped air reduces the dynamic modulus of elasticity[14].

4- Materials And Mixes

4-1 Cement

Ordinary Portland cement produced at Saudi cement factory, commercially known (AL-Sharqia), was used in this work. It was stored in airtight plastic containers to avoid exposure to atmospheric conditions , and it conforms to the Iraqi specification No. 5/1984[15].

4-2 Fine Aggregate

The fine aggregate was AL-Ekhaider natural sand of 4.75mm maximum size with grading limited zone 3.The fine aggregate grading and the sulfate content (0.20%) were within the requirements of the Iraqi specification No. 45/1984[16].

4-3 Coarse Aggregate

The coarse aggregate was AL-Nabai crushed gravel of 12.5mm size. The grading of coarse aggregate and the sulfate content (0.08%) were within the requirements of the Iraqi specification No. 45/1984[16].

4-4 Superplasticizer (SP)

A modified polycarboxylic ether condensate commercially known as Glenium 51 was used as a superplasticizer to produce high performance concrete by reducing the w/c ratio. This superplasticizer is classified as Type F according to ASTM C494–99a [17].

4-5 Silica Fume (SF)

Silica fume is a by–product from electric arc furnaces used in the production of silicon and ferrosilicon alloys. The SF, which is used throughout this work, conformed to the chemical and physical requirements of ASTM C1240–03[18] , with:

*specific surface area (20 m^2/g). *strength activity index with Portland cement at 7days of control(196%). *percent retained on 45μm (7%).

4-6 High Reactivity Metakaolin (HRM)

Local kaolin was used in this study; it was ground by the blowing technique. The burning procedure was based on the work conducted by many researchers[19,20,21], the calcinations temperature was 700˚C (the temperature was raised by a rate of 2˚C/min). The HRM, which was used throughout this work, conformed to the chemical and physical requirements of ASTM C618 class N Pozzolan[22], with:

* specific surface area (19 m^2/g). *strength activity index with Portland cement at 7days of

control(129%). *flow table (110%). *specific gravity variation from average (3.11 %).

4-7 Concrete Mixes:

Design of mixes was performed in accordance with Building Research Establishment Method. The concrete mixes are divided into three groups as follows:

Group1:– includes reference, SP, HRM–SP and, SF–SP concretes. The reference mix was designed to have a 28 day compressive strength of 25 MPa. Cement content was 350 kg/m^3 and the w/c ratio was 0.56 to give a slump of 100±5mm. The high performance mixes were produced by using superplasticizer and mineral admixtures (silica fume and metakaolin) as partial replacement by weight of cement of 10%.

Group2:– includes reference, SP, and HRM–SP, and SF–SP concretes. The reference mix was designed to have a 28 day compressive strength of 35 MPa. Cement content was 450 kg/m^3 and the w/c ratio was 0.44 to give a slump of 100±5mm. The high performance mixes were produced by using superplasticizer and mineral admixtures (silica fume and metakaolin) as partial replacement by weight of cement of 10%.

Group3:–includes reference, SP, and HRM–SP concretes. The reference mix was designed to have a 28 day compressive strength of 45 MPa. The cement content was 550 kg/m^3 and the w/c ratio was 0.39 to give a slump of 100±5mm. The high performance mixes were produced using superplasticizer and mineral admixtures (silica fume and metakaolin) as partial replacement by weight of cement of 10%. All high performance concrete mixes have a constant w/c ratio of 0.23 and the dosage of the high range water reducing agent was adjusted for each mix to maintain equal workabilities to the reference mixes. Details of the mixes used throughout this investigation are given in Table 1.

4-8 Destructive Tests of Concrete

4-8-1 Compressive Strength Test :

The compressive strength of the concrete was measured on 100mm cubes in accordance with BS 1881:part 116[23], by using a standard testing machine with a capacity of 3000 kN, at a loading rate of 15MPa per minute. The average of three specimens was recorded for each testing age. This test was performed at 7, 28, 90, and 120 days.

4-9 Non-destructive Tests of Concrete

4-9-1 Hammer Test:

The hammer test was carried out in accordance with ASTM C805–02[24], using 100mm cubes. The concrete cubes were held in a compression testing machine under a fixed stress not less than 7 MPa as recommended by BS 1881: part 202[25] for cubes tested with a type N hammer, to restrain the specimen. Ten readings for rebound number were taken on two faces of the cube (five readings for each vertical face of the cube as cast).

4-9-2 Ultrasoic Pluse Velocity Test:

The ultrasoic pluse velocity test was carried out according to ASTM C597–02[26], using 100mm cubes. Pulses of longitudinal stress waves are generated by an electro–acoustical transducer that is held in contact with one surface of the concrete under test. The pulse veloctiy is given by the following expression:

$$V = \frac{L}{T} \qquad (1)$$

where:
V=pulse veloctiy,(km/s)
L = distance between the center of transducers faces,(mm)
T = transit time,(μs)

4-9-3 Resonance Test:

It is based on ASTM C215–02[27] using the force resonance method, the fundamental longitudinal resonance frequencies of the concrete mixes were determined using 100×100×400mm prism specimens for the purpose of calculating dynamic modulus of elasticity. The following formula is used to calculate E_d:

$$E_d = DM(n')^2 \qquad (2)$$

where:
E_d=dynamic modulus of elasticity,(Pa)
D= 4 (L/bt), $N.s^2/(kg/m^2)$
L=length of the specimen,(m)
b,t=dimensions of corss section of prism,(m)
M= mass of specimen,(kg)
N′=fundamental longitudinal frequency,(Hz)

Table 1. Details of the mixes used through this investigation

Index	Mix				SP % by wt. of cement	SF kg/m³	HRM kg/m³	w/c or w/cm to give slump 100 ± 5 mm	Water reduction (%)
	Cement kg/m³	Sand kg/m³	Gravel kg/m³	Water kg/m³					
R1	350	725	1050	195	–	–	–	0.56	–
SP1	350	725	1050	80.50	5	–	–	0.23	62.29
HRM -SP1	315	725	1050	80.50	5.5	–	35	0.23	62.29
SF-SP 1	315	725	1050	80.50	5.5	35	–	0.23	62.29
R2	450	675	1000	200	–	–	–	0.44	–
SP 2	450	675	1000	103.50	4	–	–	0.23	48.19
HRM -SP 2	405	675	1000	103.50	4.5	–	45	0.23	48.19
SF-SP 2	405	675	1000	103.50	4.5	45	–	0.23	48.19
R3	550	615	950	215	–	–	–	0.39	–
SP 3	550	615	950	126.50	3	–	–	0.23	41.17
HRM-SP3	495	615	950	126.50	3.5	–	55	0.23	41.17

5-Results and Statistical Models

SPSS (Ver.15), statistical software has been used to derive statistical models for the relationship between the destructive test (compressive strength), and the non–destructive tests (rebound number, ultrasonic pulse velocity, and dynamic modulus) using simple and multiple linear regression analysis for this study. After many trials in SPSS software the best fit for those correlations was found to be linear curves. The statistical models were subjected to an adequacy checks at a selected level of significant of 5%. The results of the observed versus predicted data are presented in Figs.1 through 7. Figs.8, 9, and 10 show the relationship between compressive strength and the non–destructive test in the form of nomogram.

6-Conclusions

The recommended equations for predicting compressive strength of high performance concrete and the non–destructive tests (hammer test, ultrasonic pulse test, and resonance test) at all curing ages of this study are shown in Eqs. (3) through (9).

***$F_c=3.106RN-91.107$ (3)**

***$F_c=46.784V-158.406$ (4)**

***$F_c=5.106E_d-178.588$ (5)**

***$F_c=2.168RN+16.347V-122.041$ (6)**

***$F_c=1.317RN+3.094E_d-148.781$ (7)**

***$F_c=9.989V+4.149E_d-180.642$ (8)**

***$F_c=1.213RN+6.036V+2.674E-152.377$ (9)**

where:

F_c=compressive strength (MPa)

RN = rebound number

V=ultrasonic pulse velocity (km/sec)

E_d=dynamic modulus of elasticity (Gpa)

***For RN ≥ 35, V ≥ 4 km/sec, and E_d ≥ 35 GPa .**

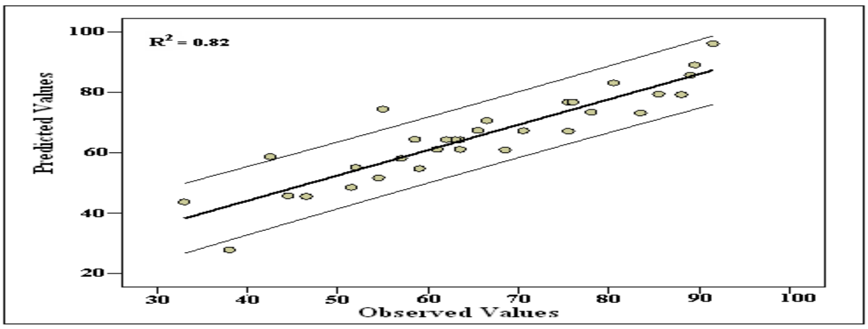

Fig.1 Predicted vs. observed values for the Eq.3 , (MPa)

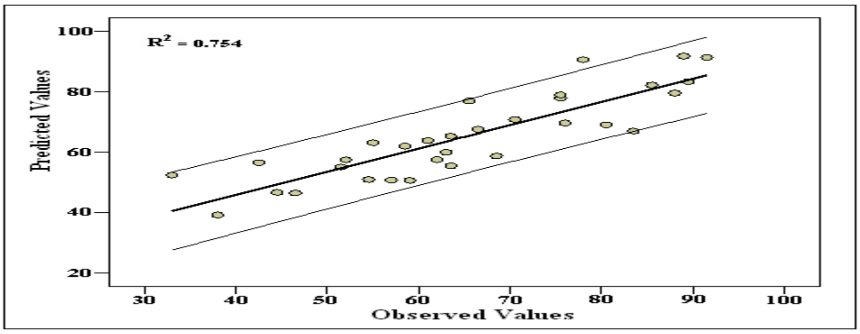

Fig. 2 Predicted vs. observed values for the Eq.4 , (MPa)

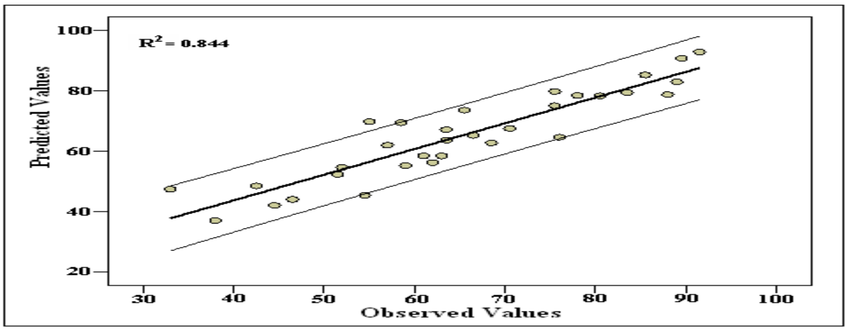

Fig. 3 Predicted vs. observed values for the Eq.5, (MPa)

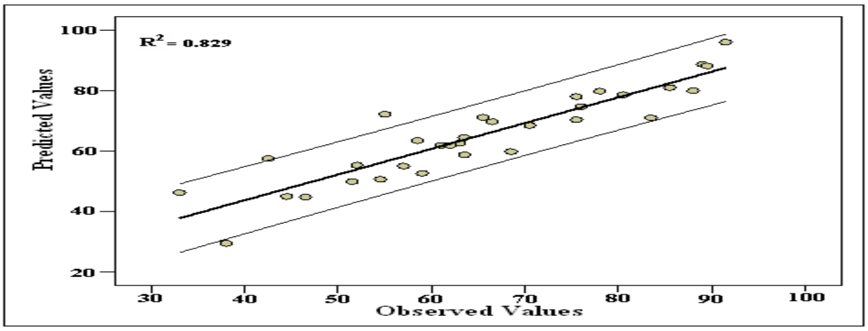

Fig.4 Predicted vs. observed values for the Eq.6 , (MPa)

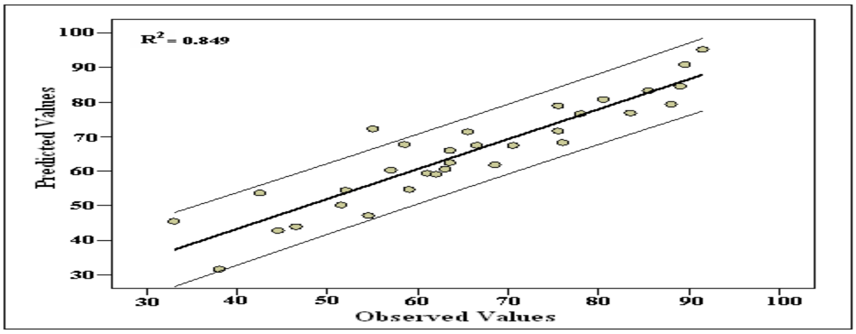

Fig.5 Predicted vs. Observed values for the Eq.7 , (MPa)

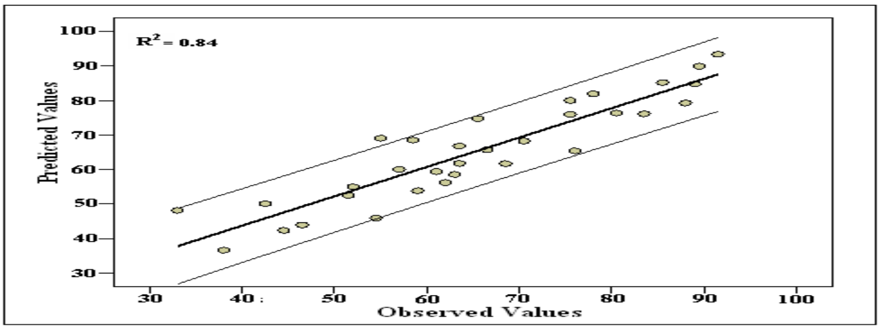

Fig.6 Predicted vs. observed values for the Eq.8 , (MPa)

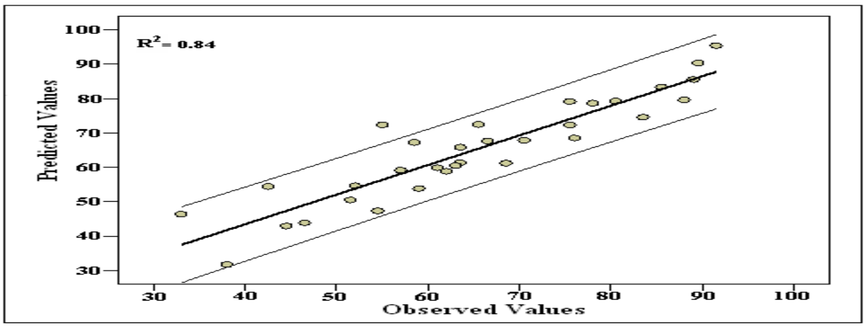

Fig.7 Predicted vs. observed values for the Eq.9 , (MPa)

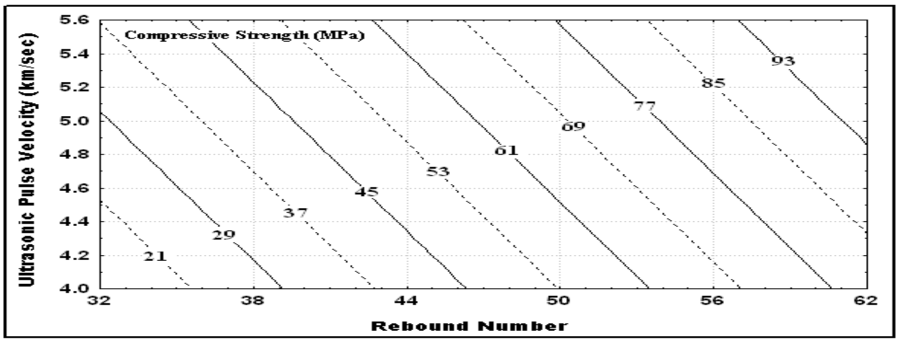

Fig.8 Nomogram for the relationship between compressive strength, rebound number, and ultrasonic pulse velocity

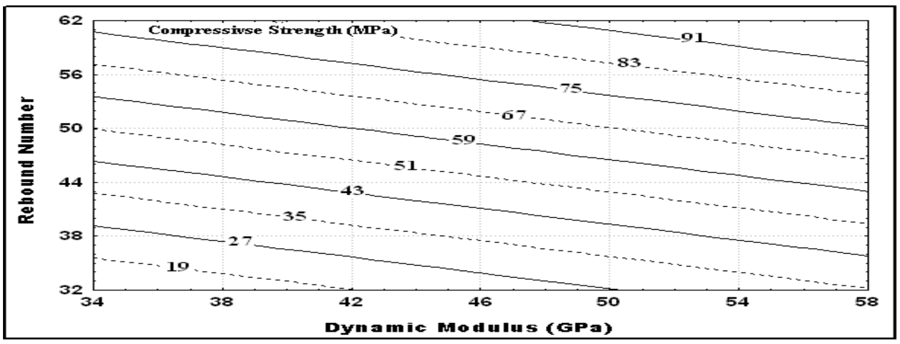

Fig.9 Nomogram for the relationship between compressive strength, rebound number, and dynamic modulus

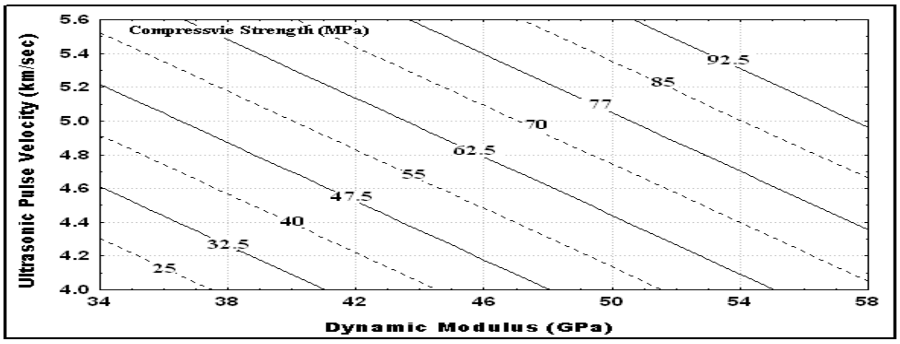

Fig.10 Nomogram for the relationship between compressive strength, ultrasonic pulse velocity, and dynamic modulus

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إمكانية تقييم مقاومة الانضغاط للخرسانة عالية الاداء باستخدام الفحوصات اللاإتلافية

الخلاصة

تم في هذه الدراسة انتاج خلطات خرسانية عالية الاداء باستخدام مضاف مقلل للماء بدرجة متفوقة وكذلك باستخدام ابخرة السليكا المكثفة بنسبة ١٠% او الميتاكاؤولين عالي الفعالية بنسبة ١٠% كتعويض عن جزء من وزن السمنت ، كما و تم استخدام ثلاث محتويات من السمنت (٣٥٠،٤٥٠ و٥٥٠) كغم/م٣. تم صب و تهيئة ٣٣٠ مكعب بابعاد (١٠٠ملم) ، ١٣٢ موشور بابعاد (١٠٠×١٠٠×٤٠٠ملم) و٦٦ اسطوانة بابعاد (١٥٠×٣٠٠ملم) و قد عولجت جميعها بالماء لغاية عمر الفحص المطلوب.اجريت فحوصات مقاومة الانضغاط ، رقم الارتداد، سرعة الموجات فوق الصوتية، معامل المرونة الديناميكي باعمار ٧،٢٨،٩٠،١٢٠يوم. تم تحليل نتائج الفحص الإتلافي (مقاومة الانضغاط) والفحوصات اللاإتلافية (رقم الارتداد ،سرعة الموجات فوق الصوتية ، معامل المرونة الديناميكي) احصائياً باستخدام برنامج SPSS Ver.15 لدراسة امكانية تقييم مقاومة الانضغاط للخرسانة عالية الاداء باستخدام الفحوصات اللاإتلافية. التحليل الانحداري البسيط والمتعدد الخطي للنتائج المستحصلة ادى الى النماذج الاحصائية المقترحة لتقييم مقاومة الانضغاط باستخدام فحص واحد او فحصين او ثلاثة من الفحوصات اللاإتلافية. كذلك تم استخدام تحليل التباين **(**ANOVA) و**(**t–test**)** لتحري كفاءة النماذج الاحصائية.