Predicting Mechanical Properties of High Performance Concrete by Using Non-destructive Tests

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Abstract

In this study, high performance concrete mixes were produced by using high range water reducing agent 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, 132 (100×200 mm) cylinders, 132 (100×100×400 mm) prisms, and 66 (150×300 mm) cylinders were casted and cured to the required age of test . All specimens were cured in tap water except 165 cubes, which were submerged in $Cl^{-} + SO_4^{--}$ solution at concentration identical to those present in severe aggressive environment to study the effect of this solution on the compressive strength of high performance concrete mixes. Compressive strength, splitting tensile strength, modulus of rupture, static modulus, rebound number, ultrasonic pulse velocity, dynamic modulus, initial surface absorption, density ,and total absorption tests were investigated for all mixes at 7, 28, 90, and 120 days age. tensile strength, Results of the destructive tests (compressive strength, splitting modulus of rupture, and static modulus) 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 predicting the mechanical properties 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, splitting tensile strength, modulus of rupture, and static modulus by using one or two or three of the above mentioned non–destructive tests. Analysis of variance (ANOVA) and t–test was also used to investigate the adequacy of the statistical models.

Keywords: High Performance Concrete, Mechanical Properties, Non-destructive Tests, Superplasticizer, Silica Fume, High Reactivity Metakaolin.

التنبؤ بالخواص الميكانيكية للخرسانة عالية الأداء بإستخدام الفحوصات اللاإتلافية

الخلاصة

تم في هذه الدراسة انتاج خلطات خرسانية عالية الاداء باستخدام مضاف مقلل للماء بدرجة متفوقة وكذلك باستخدام ابخرة السليكا المكثفة بنسبة □١% او الميتاكاؤولين عالي الفعالية بنسبة □١% كتعويض عــن جــزء مــن وزن الاســمنت ، كمــا و تــم اســتخدام ثــلاث محتويــات مــن الــسمنت

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(٣٥٠، ٤٥٠ و ٥٥٠) كغم/م٣. تم صب و تهيئة ٣٣٠ مكعب بابعاد (١٠٠ملم) ، ١٣٢ اسطوانة بابعاد (١٠٠×٢٠٠ملم) ، ١٣٢ موشور بابعاد (١٠٠×١٠٠×٤٠٠ملم) و٦٦ اسطوانة بابعاد (١٥٠×٣٠٠ملم) و قد عولجت جميعها بالماء لغاية عمر الفحص المطلوب ما عدا ١٦٥ مكعب تم غمرها جزئياً في محلول الكلوريدات و الكبريتات بتراكيز مماثلة لتلك الموجودة في ظروف بيئية قاسية لدراسة تأثير هذا المحلول على مقاومة الانضغاط للخلطات الخرسانية العالية الاداء.
اجريت فحوصات مقاومة الانضغاط ، مقاومة الشد الانفلاقي ، مقاومة الانثناء ، معامل المرونة الاستاتيكي ، رقم الارتداد، سرعة الموجات فوق الصوتية، معامل المرونة الديناميكي ، فحص الامتصاص السطحي الاولي ، الكثافة ، وفحص الامتصاص الكلي باعمار ٧، ٢٨، ٩٠، ١٢٠يوم.
تم تحليل نتائج الفحوصات الإتلافية (مقاومة الانضغاط ، مقاومة الشد الانفلاقي ، مقاومة الانثناء ، ومعامل المرونة الاستاتيكي) و اللاإتلافية (رقم الارتداد، سرعةالموجات فوق الصوتية، معامل المرونة الديناميكي) احصائياً باستخدام برنامج (SPSS Ver.15) لدراسة امكانية التنبؤ بالخواص الميكانيكية لخرسانة عالية الاداء باستخدام الفحوصات اللاإتلافية. التحليل الانحداري البسيط والمتعدد الخطي للنتائج المستحصلة ادى الى النماذج الاحصائية المقترحة لتقييم الخواص الميكانيكية باستخدام فحص واحد او فحصين او ثلاثة من الفحوصات اللاإتلافية. كذلك تم استخدام تحليل التباين (ANOVA) و(t-test) لتحري كفاءة النماذج الاحصائية.

Introduction

The evaluation of mechanical properties of concrete by non-destructive techniques is one of the most challenging tasks in modern civil engineering. Several techniques that meet this demand are currently in use. Research and activities in various non-destructive tests (NDT) have a great potential to be applied to concrete structures. Most materials in building, bridges, dams, tunnels, etc. are made of concrete. This construction requires high quality concrete in terms of strength, and durability. NDT has the ability to determine these parameters of critical construction without damaging them and the test can be carried out on-site.

Considerable amount of work has been conducted to assess or predict the mechanical properties of normal concrete using non-destructive tests. However, very limited amount of work has been undertaken to predict the mechanical properties of high performance concrete using non-destructive tests.

In this investigation silica fume and metakaolin are used as mineral admixture in conjunction with high range water reducing agent to produce high performance concrete. The rebound hammer, ultrasonic pulse velocity, and resonance, which are non-destructive tests are used to predict the mechanical properties of high performance concrete.

The main objective of this study [1] is to investigate the following properties:
1. Suitability and the reliability of the rebound hammer, ultrasonic pulse velocity, and resonance tests for the estimation of concrete strength and elastic properties.
2. Effect of different variables on the rebound hammer, ultrasonic pulse velocity, and resonance tests and these include: **a-**Concrete strength level. **b-**Presence of admixtures (high range water reducing agent as chemical admixture

and silica fume, metakaolin as mineral admixtures).
3. Influence of the external salts (sulfate and chlorides) on the compressive strength and durability properties of the high performance concrete.
4. Suggesting relationships and formulas based on a comprehensive theoretical analysis.

For the purpose of this investigation, compressive strength, rebound hammer, ultrasonic pulse velocity, initial surface absorption, density, and total absorption tests were performed on 165 cubes. Splitting tensile strength test was performed on 132 cylinders. Flexural strength and resonance tests were undertaken on 132 prisms. All these specimens were cured in water up to 120 day. Static modulus of elasticity was performed on 66 large cylinders. They were cured in water for 28 day. To assess the strength of high performance concrete which contained high range water reducing agent and mineral admixtures, namely silica fume and metakaolin and exposed to aggressive solutions, compressive strength, test was performed on 165 cubes that were partially submerged in CL^{-} + SO_4^{--} solution up to 120 day. The types and concentrations of anions and cations used in curing solution were identical to those present in soil and underground water of the southern part of Iraq.

Literature Review

High performance concrete (HPC) may be broadly defined as concrete made from appropriate material combined according to a selected mix design and properly mixed, transported, placed, consolidated, and cured so that the resulting concrete will give excellent performance in the structure in which it will be placed, in the environment to which it will be exposed, and with the loads which it will be subjected for its design life [2]. Several definitions of high performance concrete have been proposed, ACI [3]defines the high performance concrete as the concrete meeting special combinations of performance and uniformity requirements which can't always be achieved routinely using conventional constituents and normal mixing, placed, and curing practices. These requirements may involve enhancements of the following: ***a-*** Ease of placement and compaction without segregation. ***b-*** Enhanced long term mechanical properties. ***c-*** High early age strength. ***d-*** High toughness. ***e-*** Volume stability. ***f-*** Long life in severe environments .

Strategic Highway Research Program (SHRP) [4] requirements for HPC are : ***a-***High performance concrete shall have one of the following strength characteristics, 28 day, compressive strength ≥ 69 MPa. 4 hours, compressive strength ≥ 21 MPa. 24 hours, compressive strength ≥ 34MPa. ***b-*** High performance concrete shall have a durability factor greater than 80% after 300 cycles of freezing and thawing as determined by ASTM C666 Method A. ***c-*** High performance concrete shall have a water/cementitious material ratio less or equal to 0.35.

Prestressed Concrete Institute (PCI) [5] defines the HPC, as a concrete with silica fume having a water/cement ratio of 0.38 or less, compressive strength equal to or greater than 55.2 MPa and permeability 50% lower than that of conventional concretes.

The pulse velocity method has successfully been applied in the laboratory as well as in the field. It may provide a means of estimating the strength of both in situ and precast concrete although there is no physical relation between the strength and pulse velocity. The strength can be estimated from the pulse velocity by a pre–established graphical correlation between the two parameters [6], an example of which is shown in Fig. (1). Lin et al [7] investigated the relationship between the ultrasonic pulse velocity and the compressive strength of concrete. Fifteen concrete mixes were used in this investigation. The w/c ratios ranged from 0.3 to 0.7, cement paste occupied 36% of the total concrete volume, three volume ratios of fine aggregate to total aggregate are 30%, 45%, and 60% for each w/c. High range water reducing agent was added into each group of concrete to control the slump of concrete above 130mm. The compressive strength and ultrasonic pulse velocity measurements were carried out at age of 1, 3, 7, 14, and 28 days. The experimental results show that the relationship between the compressive and ultrasonic pulse velocity is significantly influenced by age and coarse aggregate content. Also in this investigation, five simulation curves of the relationship between the ultrasonic pulse velocity and strength were proposed for concrete with coarse aggregate contents of 700, 800, 900, 1000, and 1100 kg/m^3 as shown in Fig. (2).The expressions for the simulation curves of these five coarse aggregate contents are as follows[7] :

$$f_{c(700)} = 0.00440 \times exp(0.00210 \times v) \quad ..(1)$$

$$f_{c(800)} = 0.00294 \times exp(0.00218 \times v) \quad ..(2)$$

$$f_{c(900)} = 0.00183 \times exp(0.00227 \times v) \quad ..(3)$$

$$f_{c(1000)} = 0.00106 \times exp(0.00237 \times v) \quad ..(4)$$

$$f_{c(1100)} = 0.00550 \times exp(0.00250 \times v) \quad ..(5)$$

where f_c and υ represent the compressive strength (MPa) and the ultrasonic pulse velocity (m/s), respectively. The dynamic modulus of elasticity is affected by the elastic moduli of its constituent materials and their relative proportions**.** According to **Jones** [8], 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 [8].

Material and Mixes

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. The chemical composition and physical properties of the cement used through this work are presented in Tables (1) and (2) respectively. The results indicate that the used cement conforms to the Iraqi specification No. 5/1984 [9].

Fine Aggregate

The fine aggregate used was AL-Ekhaider natural sand of 4.75mm maximum size with grading within zone 3. Table (3) and Fig. (3) illustrate the grading of the fine aggregate. Results indicate that the fine aggregate grading and the sulfate content are within the requirements of the Iraqi specification No. 45/1984 [10]. Table (4) shows some of the physical properties of fine aggregate used.

Coarse Aggregate

The coarse aggregate used was AL-Nabai crushed gravel of 12.5mm size. The grading of coarse aggregate, given in Table (5) and Fig. (4) ,conforms to the Iraqi specification No. 45/1984 [10]. The specific gravity, sulfate content and absorption of coarse aggregate are listed in Table (6).

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 [11]. Table (7) shows the technical description of Glenium 51.

Silica Fume (SF)

Silica fume is a by–product from electric arc furnaces used in the production of silicon and ferrosilicon alloys. The chemical composition of SF is shown in Table (8). The SF, which is used throughout this work, conformed to the chemical and physical requirements of ASTM C1240–03[12], as illustrated in Tables (8) and (9) respectively.

High Reactivity Metakaolin (HRM)

Local kaolin was used in this study, it was ground by the blowing techinque. The burning procedure was based on the work conducted by many researchers[13,14,15], the calcination temperture was 700˚C (the temperture was raised by rate of 2˚C/min). The chemical composition of HRM is shown in Table (10).The HRM, used throughout this work, conformed to the chemical and physical requirements of ASTM C618 class N Pozzolan[15] , as illustrated in Tables (10) and (11) respectively. The strength activity index for the silica fume was determined according to ASTM C1240–03[12]. The strength activity index for the high reactivity metakaolin was determined according to ASTM C311–02 [16].The results and the details of the tested mortars are presented in Tables (12) and (13). The strength activity index (S.A.I) with Portland cement is determined as follows:

S.A.I = (A/B) ×100 where: **A**: average compressive strength of test mix cubes,(MPa). **B** : average compressive strength of control mix cubes,(MPa).

Mixing Water: Tap water was used as mixing water for all concrete mixes.

Concrete Mixes: Design of mixes was performed in according 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 (14).

Preparation of Salts Solution

The underground water analysis report prepared by the National Center for Geological Survey and Mining shows that the chloride ion concentration ranges between (20000–40000) ppm, while the sulfate ion concentration lies between (5000–7000) ppm. The cations concentrations are (10000–20000) ppm for sodium, (1500–2000) ppm for magnesium and (1000–1500) ppm for calcium[17]. The salts used in preparing the solution are pure NaCl, $CaCl_2.H_2O$ and $MgSO_4.H_2O$. Tap water is used as a solvent for these salts. Table (15) illustrates the types and concentrations of salts used in curing solution and the actual anions and cations provide by such salts.

Destructive Tests of Concrete

Compressive Strength Test : The compressive strength of the concrete was measured on 100mm cube in accordance with BS 1881:part 116[18], 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.

Splitting Tensile Strength Test : The splitting tensile strength of the concrete was carried out in accordance with ASTM C496–96[19]. Cylinders of 100×200mm were used and tested at 7, 28, 90, and 120, using a standard testing machine of capacity 2000 kN. The average of three cylinders was taken at each test. The splitting tensile strength is given by the following formula:

$$\mathbf{F_t} = \frac{\mathbf{2\,P}}{p\ \mathbf{d\,L}} \quad \ldots\ldots (6)$$

Where:

F_t = splitting tensile strength (MPa)

P = maximum applied load (N)

d=diameter of the specimen, (mm)

L = length of the specimen,(mm)

Modulus of Rupture Test: This test was done according to ASTM C 78–02[20], it was carried out on 100×100×400mm simply supported prisms with third–point loading, the specimens were tested at 7, 28, 90, and 120 days. The rate of loading was about 1.5 MPa per minute and the modulus of rupture is calculated using the following formula:

$$R = \frac{PL}{bd^2} \quad ......(7)$$

where:
R= modulus of rupture,(MPa)
P=maximum applied load indicated by testing machine,(N) b=average width of specimen, (mm)
d=average depth of specimen, (mm)
L= span length,(mm)

Satic Modulus of Elasticity Test: The elastic modulus was obtained using the uniaxial compression tests, the chord–modulus method was used as recommended by ASTM C469-02 [20]. The test was performed at age of 28 day using cylinders of 150×300 mm. The chord modulus is the slope of the line drawn between two fixed points on the stress–strain diagram. The lower point, established to eliminate the effect of crack on initial portion of the stress–strain curves, is the point where the strain is 0.00005mm, while the upper point is the point where the stress is equal to 40 percent of the ultimate stress. The chord modulus is calculated as follows:

$$E_C = \frac{S_1 - S_2}{e_2 - 0.00005} \quad ....(8)$$

where:
E_c=static modulus of elasticity,(MPa)
S_1= stress corresponding to 40% of ultimate load,(MPa)
S_2= stress corresponding to a longitudinal strain (0.00005), (MPa)
e_2=longitudinal strain produced by stress S_1

Non-destructive Tests of Concrete

Hammer Test: The hammer test was carried out in accordance with ASTM C805–02 [22], 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 [23]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 it cast).

Ultrasoic Pluse Velocity Test: The ultrasoic pluse velocity test was carried out according to ASTM C597–02 [24], 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 exprssion:

$$V = \frac{L}{T} \quad .....(9)$$

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

Resonance Test: It is based on ASTM C215–02 [25] 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:

$$E_d = DM(n')^2 \quad ....(10)$$

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)

Initial Surface Absorption Test (ISA) : Initial surface absorption was performed on 100mm cube according to BS 1881: part 5 [26].The rate of water absorption by the surface zone of concrete was determined during a prescribed period under a head of 200 mm of water. This head was only slightly greater than that which would be caused by driving rain .The rate of initial surface absorption is expressed in milliliters per square meter per second. The sample was dried in a well - ventilated oven at 105±5˚C until constant weight was achieved. When the sample reached constant weight it was placed in a suitable air-tight cooling cabinet where it remained until the temperature in the cabinet fell to a temperature within 2˚C of that of the room .The reservoir would be filled with a water and readings were taken after the following intervals from the start of test; 10 min ,30 min ,1 hr and 2 hr. The specimens were tested for ISA after 28 day of curing in water.

Density and Total Absorption: 100 mm cubes were used to determine the density, and total absorption according to ASTM C642-97[27].The total absorption and density are calculated as follows:-

Total absorption,% =[(B- A)/A]×100 …….. (11)

Bulk density, dry =[A/(C-D)]×ρ = g_1 ...... (12)

where: A = mass of oven-dried sample in air, g

B = mass of surface-dry sample in air after immersion, g

C = mass of surface-dry sample in air after immersion and boiling, g

D = apparent mass of sample in water after immersion and boiling, g

g_1 = bulk density, dry, Mg/m^3

ρ = density of water = 1 Mg/m^3 = 1 g/ cm^3

Results and Statistical Models

SPSS (Ver.15), statistical software has been used to derive statistical models for the relationship between the destructive tests (compressive strength, splitting tensile strength, modulus of rupture, and static modulus), 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 as linear curves. The statistical models were subjected to an adequacy checks at a selected level of significant of 5%.

Statistical Models for Compressive Strength of High Performance Concrete The general statistical models for the relationships between the compressive strength and the non–destructive tests (hammer test, ultrasonic pulse test, and resonance test) at all curing ages of this study are shown in Eqs. 13 through 19. Fig. (5) shows the relationship between compressive strength and the non–destructive test in the form of nomogram.

***F_c=3.106RN - 91.107** ……(13)

***F_c=46.784V - 158.406** ……(14)

***F_c=5.106E_d - 178.588** ……(15)

$*F_c = 2.168\ RN + 16.347\ V - 122.041$ ……(16)

$*F_c = 1.317\ RN + 3.094\ E_d - 148.781$ ……(17)

$*F_c = 9.989\ V + 4.149\ E_d - 180.642$ ……(18)

$*F_c = 1.213\ RN + 6.036\ V + 2.674\ E_d - 152.377$ ……(19)

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 ≥ 4.12 km/sec, and E_d ≥ 35.61 GPa

Statistical Models for Splitting Tensile Strength of High Performance Concrete

The statistical models for the relationships between the splitting tensile strength and the non–destructive tests (hammer test, ultrasonic pulse test, and resonance test) at different curing ages are shown in Eqs. 20 through 26. Fig. (6) shows the relationship between splitting tensile strength and the non–destructive test in the form of nomogram.

$*Ft = 0.141RN - 2.892$ ……(20)

$*Ft = 2.106V - 5.883$ ……(21)

$*Ft = 0.224E_d - 6.532$ ……(22)

$*Ft = 0.101\ RN + 0.681\ V - 4.180$ ……(23)

$*Ft = 0.093\ RN + 0.082\ E_d - 4.429$ ……(24)

$*Ft = 0.771V + 0.151\ E_d - 6.690$ ……(25)

$*Ft = 0.084\ RN + 0.496\ V + 0.048\ E_d - 4.724$ ……(26)

where:

F_t=splitting tensile strength (MPa) RN= rebound number V=ultrasonic pulse velocity (km/sec) E_d=dynamic modulus of elasticity (GPa)

*For RN ≥ 35, V ≥ 4.12 km/sec, and E_d ≥ 35.61 GPa

Statistical Models for Modulus of Rupture of High Performance Concrete

The statistical models for the relationships between the modulus of rupture and non–destructive tests (hammer test, ultrasonic pulse test, and resonance test) at different curing ages are shown in Eqs. 27 through 33. Fig. (7) shows the relationship between compressive strength and the non–destructive test in the form of nomogram.

$*MR = 0.170RN - 0.535$ ……(27)

$*MR = 2.794V - 5.320$ ……(28)

$*MR = 0.255E_d - 4.121$ ……(29)

$*MR = 0.051RN + 2.080V - 4.467$ ……(30)

$*MR = 0.198\ RN – 0.048\ E_d + 0.363$ ……(31)

$*MR = 3.566\ V – 0.087\ E_d - 4.854$ ……(32)

$*MR = 0.145\ RN + 3.094\ V – 2.63\ E_d - 1.480$ ……(33)

where:

MR = modulus of rupture (MPa)
RN = rebound number
V=ultrasonic pulse velocity (km/sec)
E_d = dynamic modulus of elasticity (GPa)

*For RN ≥ 35, V ≥ 4.12 km/sec, and E_d ≥ 35.61 GPa

Statistical Models for Static Modulus of High Performance Concrete

The statistical models for the relationships between the static modulus and the non–destructive tests (hammer test, ultrasonic pulse test, and resonance test) at 28 day of curing are shown in Eqs. 34 through 40. Fig. (8) shows the relationship between static modulus and the non–destructive test in the form of nomogram.

$*E_c=0.743RN + 3.597$ ……(34)

$*E_c=17.691V - 42.033$ ……(35)

$*E_c=1.11E_d - 11.781$ ……(36)

$*E_c = 0.180\ RN + 14.122\ V - 34.328$ ……(37)

$*E_c = 1.045\ RN – 0.646\ E_d + 18.807$ ……(38)

$*E_c = 16.999\ V + 0.082\ E_d - 42.657$ ……(39)

$*E_c = 0.340\ RN + 13.072\ V – 0.251\ E_d - 25.588$ ……(40)

where:

E_c = modulus of rupture (MPa)
RN = rebound number
V = ultrasonic pulse velocity (km/sec)
E_d = dynamic modulus of easticity (GPa)

*For RN ≥ 35, V ≥ 4.12 km/sec, and E_d ≥ 35.61 GPa

Recommended Equations for Predicting the Mechanical Properties of High Performance Concrete :

a) For predicting the compressive strength of high–performance concrete ranged from 21MPa to 93Mpa the following equations are recommended:
$*F_c= 1.317\ RN + 3.094\ E_d – 148.781$

$*F_c=2.168\ RN + 16.347\ V – 122.041$

b) For predicting the splitting tensile strength of high–performance concrete ranged from 2.0MPa to 5.6MPa the following equation is recommended:
$*F_t = 0.141\ RN – 2.892$

c) For predicting the modulus of rupture of high–performance concrete ranged from 4.5MPa to 9.0Mpa the following equations is recommended:
$*MR= 0.145\ RN + 3.094V – 2.63\ E_d – 1.480$

$*MR = 0.051\ RN + 2.080\ V$

d) For predicting the static modulus of high–performance concrete ranged from 24.5GPa to 47GPa the following equations are recommended:
$*E_c = 17.691\ V – 42.033$

$*E_c = 0.743\ RN + 3.597$

*For RN ≥ 35, V ≥ 4.12 km/sec, and E_d ≥ 35.61 GPa

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Table (1) Chemical composition and main compounds of cement used throughout this work*

Oxide composition	Abbreviation	Content (%)	Limit of Iraqi Specification NO.5/1984
Lime	CaO	62.21	-
Silica	SiO_2	20.18	-
Alumina	Al_2O_3	5.00	-
Iron Oxide	Fe_2O_3	3.60	-
Magnesia	MgO	2.31	≤5.0%
Sulfate	SO_3	1.44	≤2.8%
Loss on Ignition	L. O. I.	3.29	≤4.0%
Insoluble residue	I. R.	1.11	≤1.5%
Lime saturation factor	L. S. F.	0.86	0.66-1.02
Main Compounds (Bogue’s equations)			
Tricalcium Silicate	C_3S	56.97	-
Dicalcium Silicate	C_2S	15.183	-
Tricalcium Aluminate	C_3A	7.166	-
Tetracalcium alumino-Ferrite	C_4AF	10.94	-

Table (2) Physical properties of the cement used throughout this work*

Physical properties	Test results	Limits of Iraqi Specification NO.5/1984
Specific surface area (Blaine method), m^2/kg	483	≥ 230
Soundness (Auto clave), %	0.25	≤ 0.8
Setting time (Vicat's apparatus)		
Initial setting time, hrs: min.	2:50	≥ 45 min
Final setting time, hrs: min.	4:30	≤ 10 hrs
Compressive strength		
3days, N/mm^2	35.6	≥ 15
7days, N/mm^2	40.7	≥ 23

Table (3) Grading of fine aggregate used throughout this work

Sieve size (mm)	Cumulative passing %	Limits of Iraqi specification No.45/1984, zone 3
4.75	92.6	90-100
2.36	87.3	85-100
1.18	77.9	75-100
0.60	63.1	60-79
0.30	28.5	12-40
0.15	7.4	0-10
Fineness modulus = 2.43		

Table (4) Physical properties of fine aggregate used throughout this work *

Physical properties	Test results	Limits of Iraqi specification No. 45/1984
Specific gravity	2.60	-
Sulfate content %	0.2	≤0.5%
Absorption %	0.70	-

*Chemical and physical tests were made by the National Center for Construction Laboratories and Researches (NCCLR).

Table (5) Grading of coarse aggregate used throughout this work

Sieve size (mm)	Cumulative passing %	Limits of Iraqi specification No. 45/1984
14	100	90-100
10	65	50-85
5	6	0-10
2.36	0	0-5

Table(6)Physical properties of coarse aggregate used throughout this work *

Physical properties	Test results	Limits of Iraqi specification No.45/1984
Specific gravity	2.63	-
Sulfate content %	0.08	≤ 0.1%
Absorption %	0.52	-

***Physical tests on coarse aggregate were performed by (NCCLR)**

Table (7) Technical description of the Glenium 51

Technical description	Properties
Appearance	Viscous liquid
Color	Light brown
Specific gravity	1.1 at 20°C
Chloride content	Less than 0.001%
pH- value	6.6
Storage life	Up to 1 year in unopened containers.

Table (8) Chemical analysis of Silica Fume*

Oxides	content(%)	Requirements of calss pozzolan ASTM C1240-03
SiO_2	95.95	≥ 85
Al_2O_3	0.02	
Fe_2O_3	1.10	
Na_2O	0.00	–
CaO	1.21	–
MgO	0.10	–
SO_3	0.22	≤ 4
L.O.I	2.50	≤ 6

*Test was carried out at by the National Center for Geological Survey and Mines

Table (9) Physical properties of silica fume

Physical properties	Requirements of calss pozzolan ASTM C1240-03	SF
Specific surface area, min, (m^2/g)	15	20
Strength Activity Index with Portland cement at 7days, min. (%) of control	105	196
Percent retained on 45µm (No.325), max, %	10	7

Table (10) Chemical analysis of High Reactivity Metakaolin*

Oxide	content(%)	Reqiurements of class N pozzolan ASTM C 618-03
SiO_2	51.32	≥ 70
Al_2O_3	32.90	
Fe_2O_3	1.10	
Na_2O	0.23	–
K_2O	0.43	–
CaO	1.70	–
MgO	0.10	–
SO_3	0.18	≤ 4
L.O.I	6.47	≤ 10

*Test was carried out at by the National Center for Geological Survey and Mines

Table (11) Physical properties of HRM

Physical properties	Reqiurements of class N pozzolan ASTM C 618-03	HRM
Specific surface area (m^2/g)	-	19
Strenght activity Index with Portland cement at 7days, min. % of control	75	129
Flow table, max. percent	115	110
Specific gravity , max . variation from average , %	5	3.11

Table (12) Strength activity index and w/c for tested mortar

Index	Mineral type	SP by wt. of cement	w/c to give flow 110± 5mm	Compressive strength at 28 day	S.A.I
Control mix	–	–	0.484	41.6	–
Test mix	SF	0.103	0.484	77.8	187

Table (13) Strength activity index and w/c or w/cm ratios for tested mortar

Index	Mineral type	w/c or w/cm ratio	Compressive strength at 28 day	S.A.I
Control mix	–	0.484	41.6	–
Test mix	HRM	0.495	53.7	129

Table (14) Details of the mixes used through this investigation

Index	Mix				SP % by wt. of cement	SF kg/m^3	HRM kg/m^3	w/c or w/cm to give slump 100 ± 5 mm	Water reduction (%)
	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Water kg/m^3					
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

Table (15) Types and concentration of salts and ions used in curing solution

Type of salt	Concentration		Salt content % by wt. of curing solution	$CL^{-}+SO_4^{--}$ solution			
	ppm	gm/L		Anions		Cations	
				Type	Concentration ppm	Type	Concentration ppm
NaCl	50839.50	50.84	5.1	CL^{-}	33495.8	Na^{++}	20000
$CaCl_2.2H_2O$	5501.42	5.50	0.55			Ca^{++}	1500
$MgSO_4.7H_2O$	17734.66	17.74	1.77	SO_4^{--}	6912.0	Mg^{++}	1750

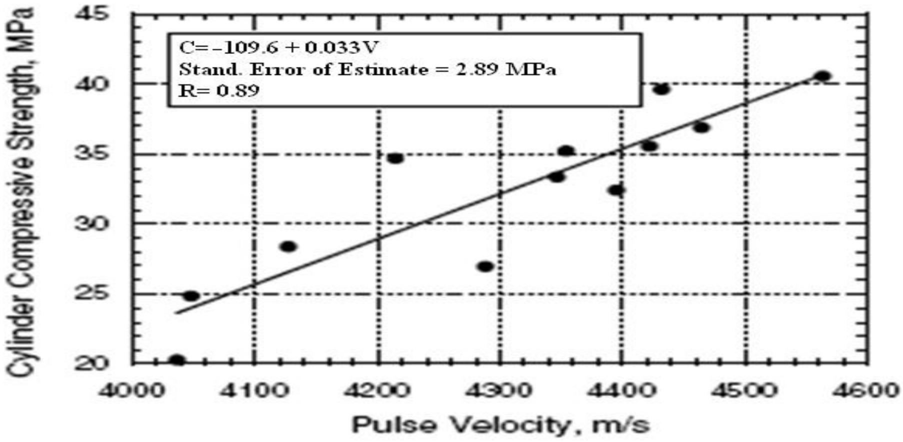


Figure (1)Example strength vs. pulse velocity relationship for estimation the strength of concrete [6]

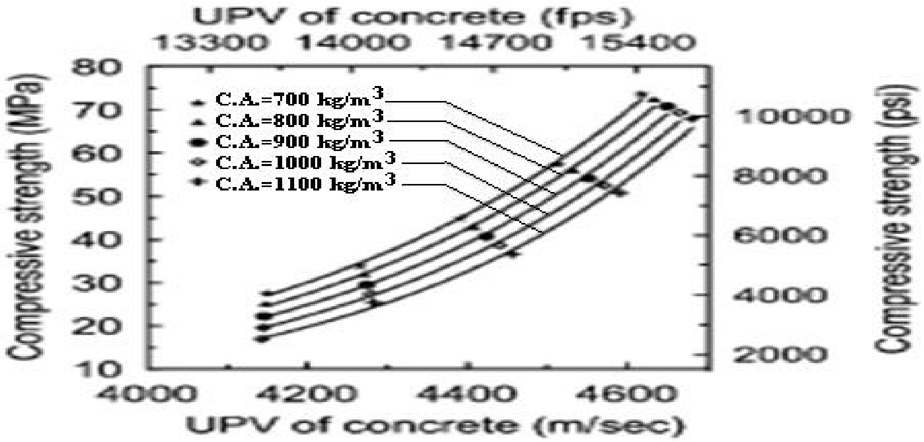


Figure (2) Simulated UPV-strength curves of concrete with five kinds of coarse aggregate contents [7].

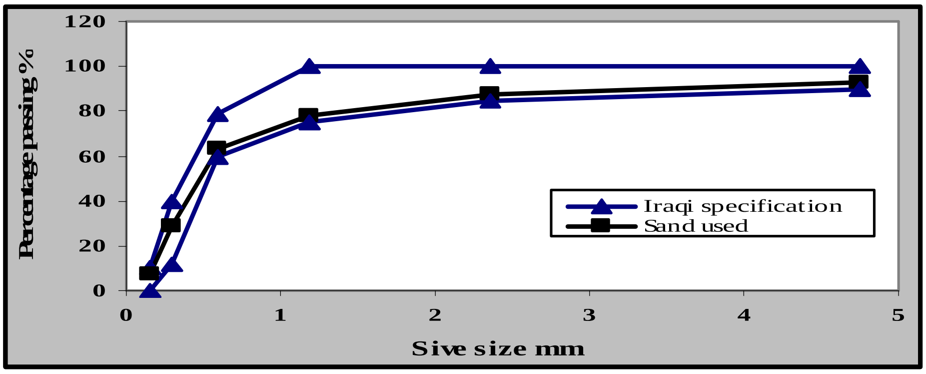


Figure (3) Grading curve for fine aggregate

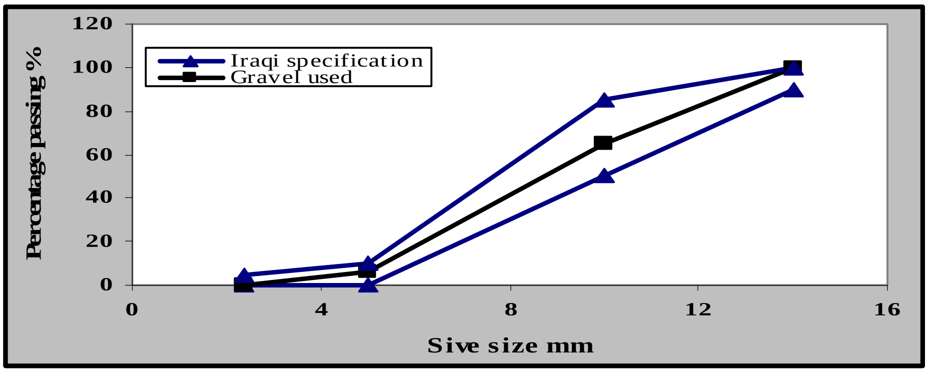


Fig. (4) Grading curve for coarse aggregate

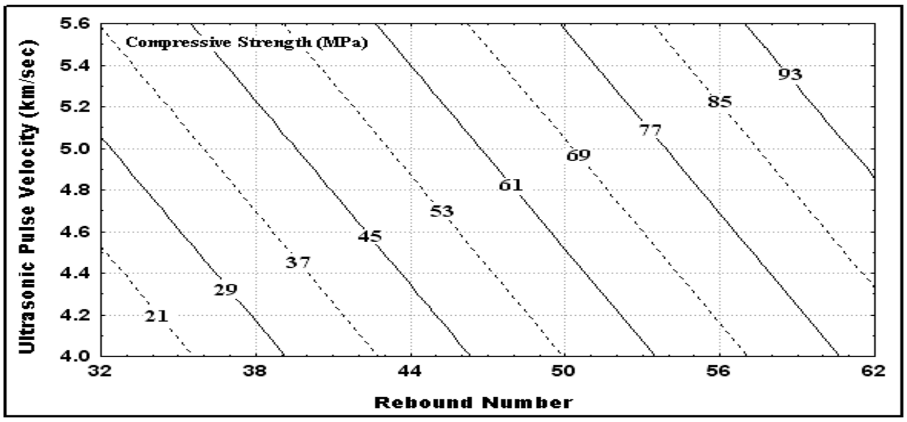
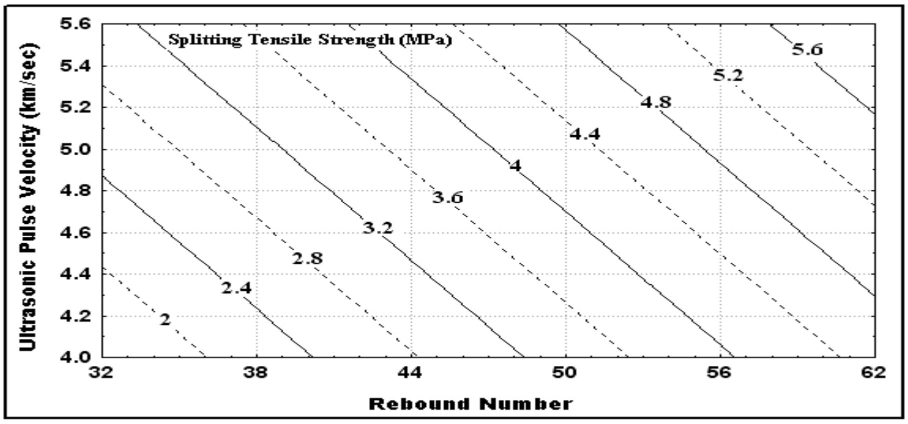


Figure (5) Nomogram for the relationship between compressive strength, rebound number, and ultrasonic pulse velocity



Figure(6) Nomogram for the relationship between splitting tensile strength,rebound number, and ultrasonic pulse velocity

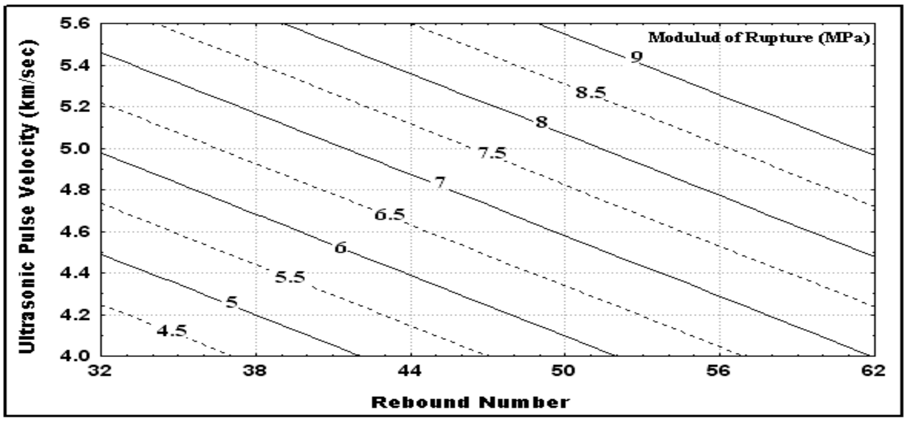


Figure (7) Nomogram for the relationship between modulus of rupture, rebound number, and ultrasonic pulse velocity

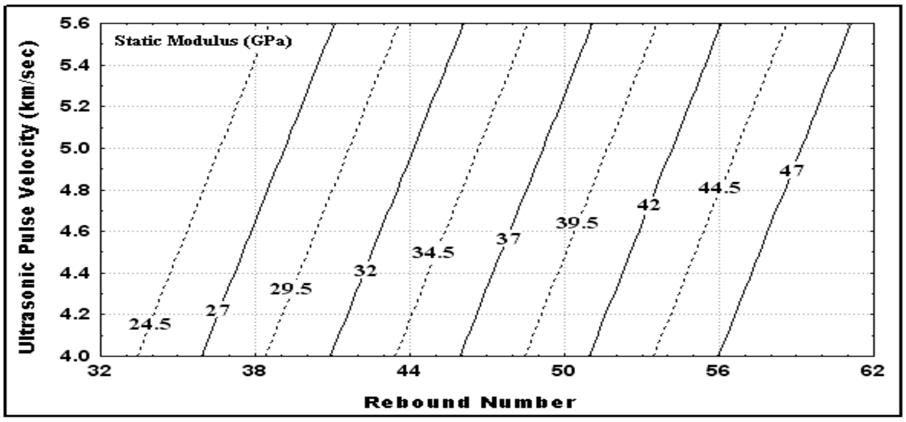


Figure (8) Nomogram for the relationship between static modulus, rebound number, and ultrasonic pulse velocity