Prediction of Mechanical Properties of High Strength Concrete

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Abstract:

This research target to study some mechanical properties of high strength concrete (e.g.; compressive strength and splitting tensile strength), For investigating the properties of fresh and hardened concrete, eighteen trial mixes were made, some of them without admixture and the other with admixture. Slump test was carried out on fresh concrete, while compressive strength, splitting tensile strength were carry out on hardened concrete for different mix proportions. Equations were proposed to predict compressive and splitting tensile strength based on parameters affecting them such as (water to cement ratio , aggregate to cement ratio , gel to cement ratio ,maximum size of coarse aggregate ,…, etc.).Also equations were proposed to predict the relation between compressive strength and splitting tensile strength. These proposed equations show good agreement when compare with proposed equation given by codes of practice.

Introduction:

High performance concrete (HPC) is define as any concrete which satisfies certain criteria proposed to overcome limitations of conventional concrete, so high strength concrete (HSC) is one type of HPC [١]. ACI committee ٣٦٣[٢] defined high strength concrete (HSC) as a concrete having cylinder compressive strength exceeding ٤١ MPa and it is exclude concrete made using exotic materials or exotic techniques. High strength concrete manufactured by one of the following methods:

١. **Water reducing agent**: Low water- cement ratio can be obtained for the same workability by providing water-reducing admixtures as (Plasticizers, fly ash… etc.)[٣].

٢**. Quality control for the selection and proportioning of the materials**: Quality control can be attained by several ways; first from the selection of the blends of cement; type and size of aggregate, second high cement content[٤], also HSC can be obtained by cleaning the aggregates from dust, thus reducing clay percentage.

٣. **Re-vibration:** Re-vibration is a one technique to increasing compressive strength [٥,٦].

Benefits of research:

High strength concrete is already being used for high –rise buildings, long span bridges and offshore structures in many parts of the World [٧]. So the results obtained in this research useful for increasing safety of design with given by codes of practice, which have basing on normal strength concrete (NSC).

Materials:

Materials used to producing HSC are; Cement, fine aggregate, coarse aggregate, water and water reducing admixture such as silica fume, class C-fly ash and class F-fly ash and so on.

١. Cement:

Strength development of concrete depended on the cement characteristics & cement content; for example the exact effect of a water-reducing agent on water requirement will depend on the cement characteristics [٧]. The choice of Portland cement (P.C.) for high strength concrete is important, so for this purpose the cement used in HSC must have the following properties [٧]: -

١-The tricalcium silicate content varies by more than ٤ %.

٢-The ignition loss must be not more than ٠,٥ %.

٣-The fineness varies by more than ٣٧٥cm^٢/gr (by Blaine method).

٤-Sulfate ($SO_٣$) levels should be maintained at optimum with variations

Limited to ± ٠,٢٠ %. The effect of cement characteristics on the water demand in batches of HSC more than normal strength concrete (NSC), since higher cement content required for obtaining (HSC).

٢. Fine aggregate:

The required fine aggregates suitable to use for producing (HSC) and must have the following properties [٢, ٨]: -

١- Rounded particle shape.

٢- Smooth texture.

٣- The fineness modulus between [٢,٥-٣,٠], to obtain best workability and compressive strength.

٤- Grading must be within specifications as listed in table below.

٥- Clay contaminants should be avoided

٣. Course aggregate:

For optimum compressive strength with high cement content and low water cement ratio, the maximum size of coarse aggregate should be kept to a minimum of about ٩,٥٢mm or ١٢,٧mm [٧]. The following recommendations required for obtaining high strength Concrete:

١. Smaller size of coarse aggregate required for obtaining higher strength concrete [٧].

٢. Increasing surface area of the individual aggregate thus increases the strength [٧].

٣. Particles appeared to be clean, hard, strong and mineralogical uniform.

٤. Grading must satisfy the standard recommendation of ASTM.

٤. Mixing water:

Mixing water used in concrete shall be clean and free from injurious amounts of oils, acids, alkalis, salts & organic materials; mixing water contributed in the form of free moisture on aggregates, shall not contain deleterious amount of chloride ion [٩].

٥. Admixture:

Admixture is a material other than water, aggregate or hydraulic cement used as a constituent of concrete and added to concrete before or during mixing to modify its property [٩]. Admixture materials are widely used in the production of (HSC), and generally increase in compressive strength, control the rate of hardening, accelerate strength again, and enhance workability and durability.

Mechanical properties of HSC:

The mechanical properties are embracing all of [compressive strength, splitting tensile strength, modulus of elasticity, modulus of rupture, stress-strain curve and Poisson's ratio]. Different investigation studied [٥،٦،١٠] the effect of (temperature, mixing methods, vibrating methods, transportation of fresh concrete, several types of admixture, curing methods, …etc.) on the mechanical properties.

١. Compressive Strength: Compressive strength of HSC affected by several factors, such as type and amount of cement, maximum size and surface texture of coarse aggregate, methods and period of curing, rate of loading, temperature… etc.

٢. Tensile Strength: Direct tension testing of concrete requires specialized equipment, procedures and consideration of boundary condition either third point flexural test (i.e., direct test) [٢١] or the splitting tension test (indirect test) [١٢] is used to estimate concrete tensile strength.

Splitting tensile strength: The approximate equations used to predict splitting tensile strength (f_{ct}) as listed in table (١).

Table (١) some predicting equations for splitting tensile strength

Publication	Predict equations
Materials[١١]	$f_{ct} \cong ٠.٥٦\sqrt{fc'}$ …(١)
Review of concrete and steel properties[١٢]	$f_{ct} \cong ٠.٥٠\sqrt{fc'}$ …(٢)
Properties of hardened concrete[١٣]	$f_{ct} \cong ٠.٤٤٥\sqrt{fc'}$ …(٣)
ACI-٣٦٣R[٢]	$f_{ct} \cong ٠.٥٩\sqrt{fc'}$ $٢١ < fc' < ٨٣MPa$ …(-٤)

Experimental program

The main purpose behind the experimental program is to clarify further role of high strength concrete (HSC) on the mechanical properties of concrete. High strength concrete production requires high quality materials, and usually chemical admixtures are employed to obtain a low water -to - cement ratio and fine workability. The following items are brief description for the materials used in the high strength concrete:

١. Cement:

The choice of (P.C.) for producing (HSC) is very important [٢, ٥،١٤] and recommended to using type I or type III for making HSC. Thus, Turkian [type I] of P.C was used, having the chemical composition and physical properties confirm with ASTM C-١٥٠.

٢. Fine Aggregate:

Darbandikhan (Sulimania Governorate) sand used in the project, table (٢) shows the grading and some physical properties of the fine aggregate. The sand conforms to the limits given by the ASTM. This sand is suitable for making HSC, since fineness modulus between (٢,٥) and (٣,٠) as indicated by [٣].

٣. Course aggregate:

Table (٣) shows the grading of natural gravel from Darbandikhan region (Sulimania Governorates) was used in the project. The gravel conforms to the limits given by ASTM.

٤. Admixture:

The chemical admixture applies in this study to reduce w/c ratio and improving workability and its properties are listed in table (٤). The maximum dosage of (٠,٢٥٪) selected in weight of cement based on the compressive strength at age of ٢٨-days.

Table (٢) Grading of fine aggregate

Sieve size-mm	% passing
٩,٥٢	١٠٠
٤,٧٥	١٠٠
٢,٣٦	٨٠
١,١٨	٦٨,٥
٠.٦٠٠	٥٦
٠.٣٠٠	٢٩,٥
٠.١٥٠	٨,٥
Fineness modulus	٢,٥٧٥
Bulk specific gravity (SSD)	٢,٥٣٨

Table (٣) Grading of Coarse aggregate

Sieve size (mm)	% passing
١٢,٥	١٠٠
٩,٥٢	١٠٠
٤,٧٦	١٥,٤٨
٢,٣٦	٢,٥
١,١٨	٠,٠٤
Bulk specific gravity Based on S.S.D.	٢.٦٩٣٦

Table (٤) Properties of the admixture (Galanium)

Property	
PH at ٢٨,٤C^{o}	٤,٢٥
Specific gravity	١,٠٥٧٧

٥. Mixing water: -

Ordinary drinking water was used for washing sand, gravel and mixing of concrete mixtures. It was clean from injurious amounts of oils and organic materials.

Mixing detail:

Mix properties of concrete are substantially affected by several factors such as fine aggregate properties [percent of clay in sand, absorption per-cent and fineness modulus of sand …etc].Also surface condition of coarse aggregate, percent of clay and vibration time , ….etc.

Mix proportion:

Mix proportion for production of high strength concrete (HSC) is required more quality control than normal strength concrete (NSC), usually chemical admixtures are essential for obtaining low w/c ratios. Many trial mixes are often required to generate the data necessary to identify optimum mixture proportions. In this study the initial proportions were based on those attained by Aziz [٦] & Ziad [١٥].The following steps were followed: -

A .The fine and coarse aggregate were sieved, washed to remove the dust and air dried.

B. Slump tests were made on different mixes having different amounts of cement content in first series ranged between (٤٩٢,٥ to ٦١١,٥ Kg/m^{٣}) without admixture and the second series having different amount of cement ranged between (٥٤١,٥ to ٥٨٣Kg/m^{٣}) with admixture. The optimum dosage of admixture was ٠,٣٥٪ of the weight of cement , and the different ratio of sand to the total aggregate (٠,٣ to ٠,٤) were used in these mixes in order to find the w/c ratio that gives the different slump between (٥-١٠٠ mm).

C. Eighteen trial mixes were made as listed in table (٥), the cement to aggregate ratio ranged from (٠,٢٧٥) to (٠,٢٨٥). The following equation can be solved for the total aggregate weight, knowing the weights of cement, water and the bulk specific gravity of the materials:

$$\left(\frac{W_w}{\gamma_w}\right)+\left(\frac{W_c}{\gamma_c}\right)+\left(\frac{W_s}{\gamma_s}\right)+\left(\frac{W_g}{\gamma_g}\right)=١ \qquad \ldots (٥)$$

Where: -

Ww, Wc, Ws&Wg are weights of water, cement, sand and gravel respectively.

γ_w,γ_c, γ_s & γ_g : are the bulk specific gravity of water, cement, sand and gravel respectively.

D. For each concrete mix in between six cylinders were cast which have dimensions of (١٥٠×٣٠٠ mm); three of them tested at age of ٧ days and the other at age of ٢٨ days as shown in table (٥).The cylinders were cured by immersing in tap water, which is saturated by lime, and dried in the laboratory temperature and humidity until one day before testing.

E. Some of mixing process for the trial mixes done by means of hand (Manually).

Mixing method:

The mixing procedure is important for obtaining the fine workability. A (٠,٠٨ m^٣) tilting mixer was used and the following sequence was adopted during mixing. The interior surface of the mixer was cleaned and moistened before placing the materials; initially the coarse aggregate and fine aggregate were poured in the mixer, followed by ٢٥٪ of the mixing water with admixture to wet them. Then add the cement, followed by ٧٥٪ of the remained water with admixture .The mixing operation ranged between ٤ to ٥ minutes to get uniform mix.

Testing:

Many tests applied on the fresh and hardened concrete. Slump test was done on the fresh concrete while tests for compressive strength, splitting tensile strength, modulus of elasticity and Poisson's ratio were carried out on the hardened concrete.

١. Workability of the fresh concrete: -

Slump test was made on each mix according to ASTM C١٤٣ [١٦] standard before casting. In the present investigation, the water cement ratio was changed to get low slump [٢٥ to ٩٠] mm listed in table (١٠).

٢. Compressive strength:

The tests followed ASTM C٣٩ [١٧], standard steel cylinders (١٥٠ mm diameter by ٣٠٠mm height) were used. In each mixes, three cylinders were cast into two layers after molds were lightly oiled. The specimens cured by immersing in saturated lime water for about ٢٨-days then left at air moisture at a room temperature ranged (٢٠-٢٩C^{o}) at the same age. The concrete cylinders were tested at age of ١٢٠-days. The average compressive strength of three specimens recorded and listed in table
(٥).

٣. Splitting tensile strength of concrete: -

The splitting tensile strength of concrete specimens was carried out according to ASTM C٤٩٦ [١٢]. The average splitting strength of three cylinder-specimens recorded and listed in table (٥).

Table (٥) Trial mixes properties

No.	Mix prop. C:S:G	Slump-(mm)	W/C-ratio	A/C-ratio	fct-MPa	fc'-at ٧-days-MPa	fc'-at ٢٨-days-MPa
١	١:١.٠٣:١.٥٨	٦٥	٠.٣٦	٢.٦١	٢.٩٩	١٨.٠٥*	٢٥.٧
٢	١:١.١٥:١.٨٥	١٤٠	٠.٣٨	٣.٠٠	٣.٤٧	٢٤.٣٥*	٣٤.٦
٣	١:٠.٧٨:١.٨٢	٩٠	٠.٣٤	٢.٦٠	٢.٨٢	١٦.٠٧*	٢٢.٨
٤	١:٠.٩١:١.٦٩	٦٥	٠.٣٤	٢.٦٠	٣.٠٨	١٩.٢١*	٢٧.٣
٥	١:١.٠٤:١.٥٦	١٠٠	٠.٣٤	٢.٦٠	٣.٠٨	١٩.٢١*	٢٧.٣
٦	١:١.٢٤:١.٨٦	٥	٠.٢٩	٣.١٠	٤.١٨	٣٥.٣٥*	٥٠.٢
٧	١:١.٢٣:١.٨٧	٥	٠.٣٣	٣.١٠	٤.١٣	٣٤.٤٥*	٤٩.٠
٨	١:٠.٩١:١.٦٩	٥	٠.٢٨	٢.٦٠	٢.٩٣	١٧.٣٧*	٢٤.٧
٩	١:١.٤٣:٢.١٧	٥	٠.٣٥	٣.٦٠	٣.٨٦	٣٠.٠٥*	٤٢.٧
١٠	١:١.٠٩:٢.٥٤	٥	٠.٣٨	٣.٦٣	٣.٦٢	٢٦.٤٧*	٣٧.٦
١١	١:١.٢١:٢	٥	٠.٣٤٥	٣.٢١	٤.٢٧	٣٦.٨٥*	٥٢.٤
١٢	١:١.٩٤:١.٨٥٦	٨٥	٠.٣٣	٣.٠٥	٤.٢٩	٣٧.١١**,"	٥٢.٨
١٣	١:١.١٨:١.٩٥	٧٥	٠.٣٦	٣.١٣	٤.١٥	٣٤.٧٥**,"	٤٩.٤
١٤	١:١.٩١:٢.٩٨	٣٥	٠.٣٦٥	٤.٨٩	٤.٠٦	٣٣.٣٢**,"	٤٧.٤
١٥	١:١.٢١:٢	٥	٠.٣٤٥	٣.٢١	٤.٠١	٣٢.٤٧+,**	٤٦.٢
١٦	١:١.٢١:٢	٥	٠.٣٤٥	٣.٢١	٤.٠٨	٣٣.٦٥++,**	٤٧.٨
١٧	١:١.٢١:٢	٥	٠.٣٥	٣.٢١	٣.٨١	٢٩.٣+++,**	٤١.٦
١٨	١:١.١٧٥:٢	٥٠	٠.٣٢	٣.١٧٥	٤.٠٤	٣٣.٠٥++++	٤٧.٠

+: Admixture/Cement=٠,٠٠٣ ++++: Admixture/Cement=٠,٠٠٢٥ W/C: water cement ratio

++: Admixture/Cement=٠,٠٠٤ *: Type III of P.C. **: Type I of P.C. A/C: aggregate -cement ratio

+++: Admixture/Cement=٠,٠٠٥ C: S: G = cement: sand: gravel ": produced by mixer

Statistical analysis:

An attempt has been made to apply the statistical regression analysis to the data obtained from the experimental work and other previous literature and equations were proposed to predict the mechanical properties for high strength concrete.

Regression analysis:

Regression analysis is an important statistical method. It should be proceeded to determine whether the relationship is linear or nonlinear, direct or indirect and if there are any extreme events that will control the relationship.

Stepwise regression:

The stepwise regression is so commonly used, which can be done either forward or backward. Forward stepwise regression programs are designed to select the one variable at each stage which has the largest correlation coefficient and hence makes the largest contribution to $R^{٢}$. Backward stepwise regression procedures work in the opposite situation.

Based on the data attained from this work and the other previous literatures, Non-linear stepwise regression analysis was developed to predict equations such as for concrete properties. The general equation is formed as: -

$$Y= a\,(X)^{b} \qquad \ldots(٦)$$

Where;

Y: predicted value (such as concrete compressive strength, shear strength…etc).

X: independent variables (such as water cement ratio, cement content, …etc).

a and b are regression parameters.

Prediction equations of high strength concrete properties:

١. Compressive strength:

The compressive strength of high strength concrete is a function of many variables such as water to cement ratio, aggregate to cement ratio, gel of cement to total aggregate ratio,…etc. The best representation of compressive strength may be written as follows:

$$fc' = f\,(X_{١}, X_{٢}, ..., X_{٧}) \qquad \ldots (٧)$$

Where:

fc' : Compressive strength of concrete, N/mm^{٢}.

$X_{١}$: water cement ratio.

$X_{٢}$: Aggregate to cement ratio.

$X_{٣}$: Course aggregate to fine aggregate ratio.

$X_{٤}$: Coarse aggregate to mortar ratio.

$X_{٥}$: Gel of cement to total aggregate ratio.

$X_{٦}$: Sand to total aggregate ratio.

$X_{٧}$: Gravel to total aggregate ratio.

The basic format for predicting the compressive strength can be written as follows:

$$fc' = a(X)^{b} \qquad \ldots (٨)$$

The constants (a and b) were calculated as described earlier using data from this work and other literature data, then several equations for predicting compressive strength of high strength concrete based on the variables ($X_{١}$ to $X_{٧}$).

To test these equations the relative compressive strength (exp./predicted) were found using each of those equations ,based on the such as standard derivation S.D., standard error S.E ,coefficient of variation C.O.V, and correlation coefficient $R^{٢}$ were calculated for these equations and the most efficient equation selected. It is obvious that equation (٩) has the higher value of correlation coefficient ($R^{٢}$) and at same time smallest value of C.O.V. and S.E; which is the best simple equation for predicting compressive strength and can be written as follows:

$$fc' = \frac{٤٣.١٧٦٣٨}{\left(\frac{w}{c}\right)^{٠.١٨٤١٢}} \qquad \ldots (٩)$$

Where:

w/c: water to cement ratio

But the more general equation for same the purpose is:

$$fc' = \frac{٥٠.٤٢٩٥}{\left(\frac{W}{c} * \frac{A}{c} * \frac{G}{S} * \frac{G}{M} * \frac{Gel}{A} * \frac{S}{A} * \frac{G}{A}\right)^{٠.٠١١٧٧١}} \qquad \ldots (١٠)$$

٢. Splitting tensile strength:

Splitting tensile strength of HSC affected by many variables such as aggregate to cement ratio, water to cement ratio, maximum size of aggregate... etc, as shown in the following form:

$$fct = f(X_{١}, X_{٢}, ..., X_{٩}) \qquad \ldots (١١)$$

Where:

fct : Splitting tensile strength of high strength concrete-N/mm^{٢}

$X_{١}$: water to cement ratio

$X_{٢}$: Aggregate to cement ratio

$X_{٣}$: Maximum size of aggregate-mm

$X_{٤}$: Sand to total aggregate ratio

$X_{٥}$: Gravel to total aggregate ratio

$X_{٦}$: Gel of cement to total aggregate ratio

$X_{٧}$: Coarse aggregate to mortar ratio

$X_{٨}$: Course aggregate to fine aggregate ratio

$X_{٩}$: Cylinder compressive strength, MPa.

The same basic formula $Y=a.(X)^{b}$ as used for evaluating splitting tensile strength of HSC. The constants (a and b) were calculated as described earlier using data from this work and data from other literatures. Several equations were predicted based on the above variables. It is apparent that the best equation is Eq. (١٢) has the higher value of correlation coefficient ($R^{٢}$) and smallest amount of C.O.V. and S.E.

$$fct = \frac{٠.٤٠٠٣٥٩}{\left(\frac{W}{C}\right)^{٠.٨٥٧٤٦}} \qquad \ldots(١٢)$$

But the most general equation for same purpose is:

$$fct = ٤.٩٣٨٩٨ * \left(\frac{W/C * G/M * MSA}{A/C * Gel/A} \right)^{٠.٠٠١٠٩٦} \qquad \ldots(١٣)$$

Conclusions:

This work applies to explain the effect of some variables on the mechanical properties of HSC. The effects of these variables concluded briefly in the following items:

١. Effect of water cement ratio:

Water to cement ratio is more effective variable which have affect on the value of splitting tensile strength and compressive strength as described in chapter five by figures and equations, decreasing in this ratio corresponds increasing in compressive and splitting tensile strength (i.e.; inverted relation between w/c ratio and them).

٢. Effect of aggregate to cement ratio:

Relation between aggregate to cement ratio with compressive and splitting tensile strength is inverted .But this relation limited this ratio ranged from [٣] to [٤].

٣. Effect of gravel to sand ratio:

Gravel to sand ratio is effective to obtain high strength concrete due to reducing required water in the mix, thus increasing in this ratio required to increase in water to cement ratio; therefore, compressive and splitting tensile strength decreased. To attain high strength concrete this ratio must be ranged between [١.٥-١.٧].

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