Fabricating a new Rheometer for Concrete

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ABSTRACT

A new concrete rheometer is introduced including its innovation, actual design, working rules, calibration, and reliability. A modified design of Tattersall two-point device is created. Some of components are purchased from local and foreign markets, while other components and the manufacturing process are locally fabricated. The matching viscosity method of determining the mixer viscometer constants is demonstrated and followed to relate torque and rotational speed to yield stress and viscosity (Bingham parameters). The calibration procedures and its calculation are explained. Water is used as a Newtonian fluid, while; cement paste (cement + water) with w/c ratio equal to (0.442) is used as a non-Newtonian fluid. The cement paste is tested in "Petroleum Research and Development Center" by "OFITE Model 800 Viscometer". In order to verify the reliability of the new rheometer, an Artificial Neural Network (ANN) model with a well selected bank of data is constructed; and (16) Mixes of Self Compacting Concrete (SCC) are constructed, mixed and tested by the new Rheometer. The results from model (predicted) and those from the experimental work (measured) were found to have very good degrees of correlation and matching, which indicates that the new rheometer can be reliable.

Key Words: rheology, rheometer, SCC, yield stress, viscosity, ANN.

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الخلاصة

تضمن البحث عرض علمي لعملية تطوير وتصنيع جهاز جديد لقياس الانسيابية (Rheometer) خاص بالخرسانة الطرية بما في ذلك الابتكار والتجديد في التصاميم السابقة للجهاز وبيان مباديء التشغيل والاسس النظرية والعملية للمعايرة والموثوقية. تم إعتماد تصميم محدث ومطور لجهاز (Tattersall two-point device). تم شراء بعض من الاجزاء الخاصة بالجهاز من الاسواق المحلية والاجنبية ، في حين تم تصنيع الاجزاء الاخرى وأجراء عملية الربط والتصنيع الكاملة محليا. تم توضيح واعتماد نظرية (مماثلة اللزوجة) المستندة الى ايجاد الثوابت التي تربط مابين قيم العزم والسرعة الدورانية وبين قيم إجهاد الخضوع واللزوجة. تم توضيح عملية المعايرة والنتائج الخاصة بها. تم استخدام الماء كسائل نيوتييني ، في حين تم استخدام عجينة (الاسمنت - الماء) وبنسبة (0.442) (ماء/اسمنت) كسائل لا نيوتييني. تم فحص عجينة (الاسمنت – الماء) في مركز البحوث والتطوير النفطي ، حيث تم الفحص بجهاز "OFITE Model 800 Viscometer". لغرض التحقق من موثوقية عمل الجهاز الجديد تم تصميم وتنفيذ موديل من نوع الشبكات العصبية الصناعية ، كما تم تصميم وخلط وفحص (16) خلطة من الخرسانة ذاتية الرص بواسطة جهاز الانسيابية الجديد. تم مقارنة النتائج المستحصلة من الموديل مع تلك المستحصلة من الجزء العملي وكانت النتائج ذات درجات ارتباط وتطابق عالية مما يؤشر امكانية الاعتماد على عمل الجهاز.

الكلمات الرئيسية: الانسيابيه ,الريوميتر،الخرسانه ذاتية الراس،أجهاد الخضوع،الزوجه،برنامج احصائي.

1. INTRODUCTION

Rheology is the science of the deformation and flow of matter, and the emphasis on flow means that it is concerned with the relationships between stress, strain, rate of strain, and time. Fluid rheology is well established, widely used science that is directly applicable to workability of fresh concrete. The characterization of rheology of fresh concrete is complicated by the fact that concrete is a complex material with time-dependent properties and includes wide range of particle sizes. In measuring rheological parameters of concrete, it is essential to know the flow properties over a wide range of shear stresses and shear strain rates. Various constitutive equations have been developed, the listing of such equations are given by **Whorlow, 1992. Ferraris, 1999. and Hackley, and Ferraris, 2001.** However, the most commonly used equation that is applied to fresh concrete is the Bingham Equation, where flow is described by the Eq. (1).

$$\tau = \tau_o + \mu\dot{\gamma} \qquad \text{Eq. (1)}$$

where :

τ = shear stress;

μ = plastic viscosity;

τ_o = yield stress; and

$\dot{\gamma}$ = shear strain or shear rate = $d\nu / dy$

2.RHEOLOGY OF SCC

SCC is a highly flowable concrete that is able to flow into places without vibration. Because SCC is essentially defined in terms of its workability, the characterization and control of rheology is crucial for the successful production of SCC. In terms of rheology, SCC exhibits a yield stress near zero and a moderate plastic viscosity. **Ferraris at al., 2000. and Koehler and Fowler, 2007.** stated that if the rheological properties that characterize SCC are examined, the yield stress must be zero or very low and the viscosity must be controlled. Empirical tests simulate a field condition and measure a quantity, such as a distance or time that is related to an aspect of workability. Empirical tests measure values that are related to fundamental rheological properties only indirectly, **Koehler and Fowler, 2007**. In empirical tests, the geometry of the concrete and the stresses acting on it at any given time are changing and not fully known, making it difficult to isolate the effects of fundamental flow properties. Therefore, rheological parameters can be preferable to empirical parameters, provided they can be measured in a practical manner and related to field placement requirements. **Fig.1** shows how two concretes could have one identical parameter and a very different second parameter. Therefore, it is important to use a test that will describe the concrete flow, by measuring (at least) both factors, **Ferraris, 1999.**

3.RHEOMETRIC APPARATUS

In order to determine real values of stress and rate (at the same point) an absolute instrument is needed, where the determination is made on the basis of a known mathematical description of flow occurring in the instrument and on the basis of its geometry. The measuring techniques can be divided into four principal ones, as shown in **Fig. 2** ,**Oskar, 2007.**

The instrument used these techniques is called ,**Rheometer. Leslie and Ji ,2001.** defined rheometer as the instruments for measuring flow behavior, which usually operate in rotation and measure torque and rotational speed and the rheological parameters of stress and strain rate are computed from these measurements.

According to **Hackley and Ferraris,2001.** rotational methods are generally better for concentrated suspensions, gels, and pastes despite the fact that capillary tube methods tend to be more precise in measuring viscosity.

“Impeller rheometers”, can be defined as rotational rheometers which consist of an impeller that is rotated in a concrete specimen. Impeller rheometers can be simple to use; however, the shear rate and shear stress in the material around the impeller is unknown and the direct analytical calculation of fundamental rheological parameters is not possible. Although calibration procedures have been suggested to relate the intercept and slope of the torque versus rotation speed plot to yield stress and plastic viscosity, the accuracy of such procedures is debatable. Instead, results are often presented in terms of the slope *('h-value')* and intercept *('g-value')* of the torque versus rotation speed plot **Tattersall and Banfill,1983. Whorlow,1992. Ferraris ,1999. and Koehler and Fowler, 2006.**

3.1 Tattersall Two-Point Rheometer

The Tattersall two-point device was reportedly the first rheometer to measure concrete as a Bingham fluid. The device has been refined over the years by Tattersall and other researchers and continues to be widely used in research, **Tattersall and Bloomer,1979; Cabrera and Hopkins, 1984; Tattersall 1990; Bartos, Sonebi, and Tamimi, 2002; Ferraris and Brower,2004; Koehler and Fowler, 2006 and Josef , 2006.**
The original version of the two-point device, the MK I apparatus, was first presented in 1971 and consisted of a Hobart food mixer with a hook-shaped impeller moving in a planetary motion. The device, however, could not be used for high workability mixes.

Based on additional research, the MK I apparatus was later replaced by the MK II apparatus **Fig.3** for high workability mixes and the MK III for low to medium workability mixes.
MK II measures the pressure in a variable hydraulic transmission when turning an impeller in concrete at different speeds. Torque/Pressure calibration constant should be determined, **Tattersall and Banfill 1983.**

3.2 Laskar and Talukdar Rheometer

The rheometer which is designed by **Laskar and Talukdar , 2007.** .**Fig. 4** has the same concept of Tattersall two-point device. However, they used flat circular vane plate impeller, and the circuit for the purpose of calibration consists of a wattmeter, voltmeter, ammeter, and a 10 A variac. A spring balance anchored to a fixed object is fitted to the pulley of the spindle. When the motor is switched on, the spring balance blocks its rotor and the spring balance reading is noted. This arrangement gives the braking torques at different voltages. Thus for a set of voltages, braking forces or torques can be obtained.

4. ARTIFICIAL NEURAL NETWORKS

A neural network consists of a number of interconnected processing elements, commonly referred to as neurons. The neurons are logically arranged into two or more layers and interact with each other via weighted connections. These scalar weights determine the nature and strength of the influence between the interconnected neurons. Each neuron is connected to all the neurons in the next layer. There is an input layer where data are presented to the neural network and an output layer that holds the response of the network to the input. It is the intermediate layers, also known as hidden layers, which enable these networks to represent and compute complicated associations between patterns. Each hidden and output neuron processes its inputs by multiplying each input by its weight, summing the product, and then passing the sum through a nonlinear transfer function to produce a result, **Goh ,1995.**

The neural network "learns" by modifying the weights of the neurons in response to the errors between the actual output values and the target output values. At the end of the training phase, the neural network should correctly reproduce the target output values for the training data, provided the errors are minimal, i.e., convergence occurs, **Kwan , 2000.**

5. NEW RHEOMETER DESIGN

Through searching in local engineering colleges, no available concrete rheometer exists in Iraq. Therefore, it is decided to adopt one of the available rheometer designs and fabricates a concrete rheometer. The modified design of Tattersall two-point device MK II is chosen for this purpose. The simple design and its continuously development through researches are the main are the main reasons for this choice.

5.1 First Adopted Design

The design of the Tattersall two-point device MK II that was donated for research purpose of **Josef, 2006.** work's **Fig. 5** is the first adopted design for current research purpose. This design consists of:

1. Electrical Motor which is used to generate the required rotation.
2. Variable Hydraulic Transmission Unit which is used to generate a pressure when turning the impeller in concrete.
3. Speed Control which is used to control and measure the speed of rotation.
4. Reduction Gear Box which is used to reduce the speed of motor rotation and increase the generated torque.
5. Pressure Gauge which is used to measure the generated pressure in the variable hydraulic transmission unit.
6. Interrupted Helical Impeller which is used to rotate the concrete sample.
7. Sample Holder which is used to hold the concrete sample.
8. Torque Calibration System **Fig. 6** which is used to determine the torque/pressure calibration constant. This system consists of an adjustable metal clamp with a copper sleeve, fixed so that the impeller drive shaft passes through it, and is used.

5.2 Modified Adopted Design

The first design and all of its components are studied carefully. The next step is going to be search for the availability of those components and the possibilities of fabrication. Through this search two important notes are recorded:

1. Instead of using an electrical motor and a reducing gear box as a separator device, a one unit that consists of both devices can be used. This has a big benefit of reducing the problems of coupling between the electrical motor and the reducing gear box.
2. Instead of using the variable hydraulic transmission unit, pressure gauge, and the torque calibration system which are used to measure and calibrate the generated torque, a Rotary Torque Transducer that measures the speed and torque strain in a rotating shaft can be used.

Taking previous two notes in consideration, the design is modified. The sketch of the modified adopted design is shown in **Fig.7**. The completed fabricated rheometer is shown in **Fig.8**. This design consists of below parts.

5.3 Electrical Motor and the Redaction Gearbox Vertical Unit (Figure 9):

This unit is chosen from Web-Drive which is a European company. The specifications of this unit are listed in **Table 1**.

5.4 Rotary Torque Transducer

This component is chosen from a British company, and it consists of three units; M420 Rotary Torque Transducer, Transducer Interface, and software package “TorqueLog”. The specifications of these units are:

A - M420 Rotary Torque Transducer:

The Series M420 Rotary Torque Transducer **Fig.10**. measures the speed and torque strain in a rotating shaft. Signal output is transmitted directly from the shaft as serial data and providing clean and definitive data transmission. M420 rotary torque transducer is connected with the gearbox by a locally made stainless steel connector see **Fig. 11**. The specifications of M420 rotary torque transducer and its dimensions according to **Fig.12** are listed in **Table 2**. The purchased M420 rotary torque transducer is calibrated by Datum Electronics Ltd, and a Torque Calibration Certificate **Fig.13** is supplied with the device.

B - Transducer Interface:

This unit **Fig.14** receives the signal output from the transducer and converts it digitally through a USB converter to PC. The Transducer interface requires 15-24Volts dc supply power. The M420 connects directly to this interface.

C - Software Package “TorqueLog”:

Datum Electronics TorqueLog software is an easy and convenient way of collecting data. This software provides a direct readout of Torque, Speed and Power on a PC with additional facilities to read peak torque and log data to other applications including Microsoft Excel. The features of this software include:

- Calibrated Display of Torque in Nm or lb/ft
- Display of Speed (rpm)
- Display of Power in kW or HP
- Peak Torque, Speed and Power Capture Facility
- Data logging of Torque (or Torque, Speed and Power)

Fig. 15. shows the interface window for this software.

D - AC Frequency Conversion Speed Regulator:

AdvanCon-SID32-G-S2 series **Fig.16** high functional conversion regulator is chosen to be the speed controller.

E - Interrupted Helical Impeller:
An axial stainless steel impeller with four angled blades set in a helical pattern around a central shaft which imparts a stirring and mixing action to the concrete is designed, fabricated and used for the purposes of this study. This type of impeller is chosen because it is suitable for slumps in excess of about 100 mm as referred to by **Ferraris and Brower , 2001.** The impeller is made in two parts. The first upper part is fixed to the body by a stainless steel ring that contains a bearing fixture in the middle and through this bearing it connects with the torque transducer **Fig.7.** This arrangement provides good support and free movement to the impeller and assures no direct load on the transducer. The other (lower) end of this part is externally threaded See **Fig.18**. The second lower part of this impeller is a free part that can be screwed to the upper part during running the rheometer or it can be removed out for cleaning. The lower end of this part contains four trapezoidal blades, right angled in its position, set and welded in a helical pattern around the central shaft. Total length of the shaft is (850 mm) and its diameter is (50 mm). Larger base of the blade is (65 mm), while smaller base is (35 mm), and the height of the base is (55 mm).
F - Sample Holder Fig. 9.

This is a metal cylindrical container with (254 mm) diameter and (305 mm) height. It is provided with vertical metal ribs at a pitch of 60 mm along the circumference. Ribs are welded at the wall of the cylinder. The effective gap between the bottom and the shearing surface is 60 mm. The effective concrete height above the vane plate is 75 mm. The no-slip condition at top of the cylinder is achieved by providing the mesh of blades.

5.5 Calibration of the Rheometer
Since it is shown through the literature that the flow properties of concrete conform to the Bingham model, the flow curves are taken as linear, the intercept on the torque axis and the reciprocal slope can also be calculated using the least squares method. The flow curve is represented by:

$$T = g + hN \qquad \text{Eq. (2)}$$

Where *(T)* is the torque at speed *(N)*, *(g)* is a measure of the yield value and *(h)* is a measure of plastic viscosity.

The values of *(g)* and *(h)* are calculated mixer viscometry method. Extensive work has been conducted on mixer viscometry **Castell and Steffe 1992.** This technique has been used mostly for non-reacting biological materials. But also it is applied in evaluating the workability of fresh concrete **Tattersall and Banfill , 1983** , and to chemo-rheological studies involving starch gelatinization **Dolan and Steffe 1990 and Steffe et al., 1989.**
The specific technique used in the current study for applying the matching viscosity method was developed by **Mackey et al 1987**and later described as the torque curve method by Castell-Perez and **Steffe 1990.** The following analysis is based on the work of those researchers.
5-6 Power Number (N_{Po}) & Reynolds Number (N_{Re})

Those dimensionless numbers are defined to the impeller, which takes the power "*P*" whose diameter is *"d"* whose rotational speed is *"N"* in fluid, and whose density and viscosity are *"ρ"* and *"η"*, by following equations:

$$N_{Po} = \frac{P}{N^3 d^5 \rho} \qquad (3) \qquad \text{and} \qquad N_{Re} = \frac{N d^2 \rho}{\eta} \qquad (4)$$

The power is equal to the product of torque and angular velocity: $= T * N$, where T is the torque. Thus, the Eq. (3) can be written with respect to the torque, rotational speed, effective diameter, density, and viscosity as:

$$N_{Po} = \frac{T}{N^2 d^5 \rho} \qquad (5)$$

With a single phase fluid operating at low speed, or in a baffled system, the power number can be expressed with the impeller Reynolds number alone:

$$N_{Po} = f(N_{Re})$$

$$N_{Po} = A * (N_{Re})^B \qquad (6)$$

Where *"A"* and *"B"* are constants depending on the geometry of the system and the flow regime present during mixing. *"B= -1"* when *"N_{Re} < 10"*, and *"B= 0"* when *"N_{Re} > 10 000"*. The values of *"A"* and *"B"* in the intermediate region will depend on the particular mixing system under consideration.

5.7 Apparent Viscosity

Apparent viscosity has a precise definition. It is shear stress divided by shear rate:

$$\eta = f(\dot{\gamma}) = \frac{\tau}{\dot{\gamma}} \qquad (7)$$

With Newtonian fluids, the apparent viscosity and the Newtonian viscosity (μ) are identical but for a power law fluid is:

$$\eta = f(\dot{\gamma}) = \frac{\tau}{\dot{\gamma}} = \frac{K(\dot{\gamma})^n}{\dot{\gamma}} = K(\dot{\gamma})^{n-1} \qquad (8)$$

Apparent viscosity for Bingham plastic fluids is determined in a like manner:

$$\eta = f(\dot{\gamma}) = \frac{\tau}{\dot{\gamma}} = \frac{\mu_{pla}(\dot{\gamma}) + \tau_o}{\dot{\gamma}} = \mu_{pla} + \frac{\tau_o}{\dot{\gamma}} \qquad (9)$$

5.8 Average Shear Rate

Newtonian fluid viscosity (μ) is replaced by an apparent viscosity (η) evaluated at an average shear rate *($\dot{\gamma}_a$)* defined as:

$$\dot{\gamma}_{av} = k' * N \qquad (10)$$

where *(k′)* is the mixer viscometer constant having units of 1/rad or 1/rev. *(k′)* is unique for any particular physical system and must be determined from experimental data.

In mixer viscometry, there are two primary techniques for determining *(k′)* the "Slope Method" and the "Viscosity Matching Method." Viscosity Matching Method is a technique that involves the comparison of power curves for Newtonian and non-Newtonian fluids using the idea of matching viscosities. The phrase "matching viscosities" refers to the assumption that the average shear rate for a non-Newtonian fluid is equal to the average shear rate for a Newtonian fluid when the Newtonian viscosity equals the apparent viscosity of the non-Newtonian fluid. The technique is excellent for determining the average shear rate in a mixer and is also useful to rheological process engineers in evaluating the performance of commercial equipment (Rheometers) having poorly defined shear fields.

5.9 Derivation of Mixer Viscometry Relations

1- Power Flow Fluids: Working equations are developed starting with the assumption that surface tension, elastic, and vortexing effects are insignificant, the physical variables involved in mixing Newtonian and Non- Newtonian fluids in the laminar flow regime where $(N_{Re} < 10)$, then:

$$N_{Po} = \frac{A}{N_{Re}} \tag{11}$$

Substituting with **Eqs. (4)** and **(5),** gets

$$N_{Po} = \frac{\eta A}{Nd^2\rho} \tag{12}$$

using the definition of apparent viscosity for a power flow fluid **Eq. (8)**

$$N_{Po} = \frac{AK(\dot{\gamma})^{n-1}}{Nd^2\rho} \tag{13}$$

using the definition of average shear rate

$$N_{Po} = \frac{AK(\dot{\gamma}_{av})^{n-1}}{Nd^2\rho} \tag{14}$$

and solve for the average shear rate:

$$\dot{\gamma}_{av} = \left(\frac{Nd^2\rho N_{Po}}{AK}\right)^{1/n-1} \tag{15}$$

2- Bingham Plastic Fluids: Using the same assumption in above paragraph and the Eq**. (11)** and **(12)** and the definition of apparent viscosity for a Bingham plastic fluid (Eq.(9)):

$$\frac{T}{N^2 d^5 \rho} = \frac{A(\mu_{pla} + \tau_o/\dot{\gamma})}{Nd^2\rho} \tag{16}$$

using the definition of average shear rate and **Eq. (10)**

$$\frac{T}{N^2 d^5 \rho} = \frac{A(\mu_{pla} + \tau_o/k'N)}{Nd^2\rho} \tag{17}$$

then simplifying the resulting equation gives an expression relating torque and speed in a mixer viscometer:

$$T = \frac{Ad^3}{k'}\tau_o + Ad^3\mu_{pla}N \tag{18}$$

Collecting mixer rheometer data of torque versus angular velocity for a Bingham plastic and plotting the result will provide a slope $(Ad^3\mu_{pla})$ and an intercept $(Ad^3\tau_o/k')$ that reflect the rheological properties of the fluid. If *(A)* and *(k′)* are known, plastic viscosity and the yield stress can be calculated. Comparing between Equation (1) and Equation (18):

$$g = \frac{Ad^3}{k'}\tau_o \qquad (19)$$

then
$$\tau_o = \frac{gk'}{Ad^3} \qquad (20)$$

$$h = Ad^3\mu_{pla} \qquad (21)$$

then
$$\mu_{pla} = \frac{h}{Ad^3} \qquad (22)$$

5.10 Determination of Parameters

1- Using Water as a Newtonian fluid in the mixer rheometer, the constant *(A)* is determined from the experimental data.

a. Involving **Eq.(4)** to determine (N_{Re}), where, "ρ" for water is (1000 kg/m3), "η" for water is (0.001 kg/m.s), "N" the rotational speed in (rad/sec.), and the effective diameter for the impeller (d) is (0.16 m). **Table 3** shows that the average value of (N_{Re}) is about (120637).

b. Involving **Eq.(5)** to determine (N_{Po}), where, "T" units is (Nm), "ρ" for water is (1000 kg/m3), "N" is the rotational speed in (rad/sec.), and the effective diameter for the impeller (d) is (0.16 m). **Table 3** also, shows that the average value of (N_{Po}) is (0.095).

c. Since "$N_{Re} > 10000$", then "B= 0". Substituting this value in **Eq. (6)** yields (A) equal to (N_{Po}). Then (A = 0.09499).

2- Determination value of (k′), a non-Newtonian power flow fluid (or pseudo-plastic fluid) should be tested in a routine viscometer (like a concentric cylinder or cone and plate system). Through the traditional rheological techniques, the properties (K) and (n) of a power law fluid can be determined. This reference power law material is then tested by the rheometer (under study), and mixed at a several speeds. Next, the matching viscosity assumption is applied and an average shear rate ($\dot{\gamma}_{av}$) and (k′) values are calculated. (k′) is calculated {as it is equal to ($\dot{\gamma}_{av}/N$)} at numerous impeller speeds to determine how (k′) may vary with (N). An average value of (k′) may be taken to represent the constant required in **Eqs. (19)** and **(20).**

a. Cement slurry (cement + water) with w/c ratio equal to (0.442) is used as a power flow fluid. This slurry is tested in "Petroleum Research and Development Center". Their "OFITE Model 800 Viscometer" which is a Coaxial Cylinder Viscometer. The cement slurry is tested at seven speeds (6, 30, 60, 100, 200, 300, and 600 rpm). Obtained shear stress and shear rate values are plotted in Figure (20). This power flow curve show that (K) is equal to (10.63) and (n) is equal to (0.305). The shape of the curve and (n) value which is less than (1) indicates that the tested cement slurry is a "Shear Thinning" fluid.

b. The cement slurry with same materials and proportions that used in the previous paragraph is tested by this study's rheometer. The specimen is sheared at seventeen speeds **Table 4**. Values of ($\dot{\gamma}_{av}$) and (k′) at those seventeen speeds and their averages are determined by using **Eq.s (10) and (15)** and listed in **Table 4**, also.

3- As (A= 0.09499) and ($k' \approx 0.0958$) values are calculated, and as (d = 0.16 m), then ($Ad^3 \approx 0.000389$), by using Equations (20) and (22):

$$\tau_o \approx 246\, g \qquad (23) \qquad \text{and} \qquad \mu_{pla} \approx 2570\, h \qquad (24)$$

6.EXPERIMENTAL PROGRAM

In order to evaluate and verify the rheological properties of SCC mixtures by the new Rheometer, (16) mixes of SCC are designed, mixed and tested. A detailed description of the experimental work carried out in the present study is demonstrated below.

6.1 Materials

1- Iraqi ordinary Portland cement (Taslogah) type (I). This cement is tested and checked according to IOS 5:1984. **Table 5** shows the chemical and physical properties of this cement and the criteria of IOS 5:1984 for each one.
2- Natural sand is used in this work. **Table 6** shows the grading of the fine aggregate and the limits of the Iraqi specification No.45/1984; and the physical properties of the fine aggregate.
3- Rounded gravel of nominal size (5-14) mm is used. **Table 7** shows the grading of this aggregate which conforms to the Iraqi specification No.45/1984, the specific gravity, sulfate content and absorption of coarse aggregate.
4- Tap water is used for both mixing and curing of concrete.
5- A third generation admixture for concrete and mortar named Sika ViscoCrete Hi-Tech 32 is used.

6.2 Concrete Mix Design

Initially EFNARC (2005) first approach for mix design method is used, and then the proportions of materials modified after the evaluation by fresh tests is done. The modifications are made according to EFNARC (2005) also.

6.3 Mix Proportions

In order to achieve the scopes of this study, the mixes are categorized into five groups. Each group represents one of the factors that affects rheology and strength of SCC. These groups are listed in **Table 8. Tables 9 and 10** show mix proportions. All proportions are based on volumetric mix design procedure.

6.4 Mixing Procedure

The mixing procedure that used in this study is briefly stated in the following:

1. The fine aggregates are added to the mixer with 1/3 quantity of water and mixed for 1 minute.
2. The cement and mineral admixtures are added with another 1/3 quantity of water. Then the mixture is mixed for 1 minute.
3. After that, the coarse aggregate is added with the last 1/3 quantity of water and 1/3 dosage of superplasticizer, and the mixing lasts for 1 ½ minute then the mixture is left for ½ minute for rest.
4. Then, the 2/3 leftover of the dosage of superplasticizer is added and mixed for 1 ½ minute.
5. The mixture is then discharged, tested and cast.

6.5 Workability (Empirical) Measurements

These tests include slump-flow (SFD), L-box, U-box and V-funnel (TV) tests. All of these tests are used to verify the filling ability, passing ability, and segregation resistance of all mixes of this study. The apparatus and the tests procedure are made according to the specifications and requirements mentioned in **Efnaec, 2005.** These apparatus are made from steel plate in the local market.

6.6 Procedure of Rheological Tests

Before testing can be done, the hardware (the torque transducer and its interface) should be connected and installed on the PC. Also, the TorqueLog software should be installed on the PC. The apparatus must be set up to be leveled. The procedure for testing is as follows:

1. Turn on the power source and let the impeller to rotate at speed of 15 rpm.
2. Fill the sample holder gradually with concrete to about 75 mm from the rim while the impeller rotates.
3. Increase the speed each 1 minute by steps 25, 35, 45, 55, 65, and 75 rpm.
4. The results are automatically fed to the PC in Microsoft Excel spreadsheet.

6.7 Verifying Reliability of Rheometer

In order to verify the reliability of the new rheometer, the following steps are followed:

1- Construct an ANN model with a well selected bank of data. This bank of data should have a suitable volume (number of mixes) that the better performance of the model can be achieved. Experimental data from (35) different sources is used to check the reliability of the model. In all about (700) SCC samples are evaluated. The evaluation processes are done in two stages. The first stage is involved with the input parameters, while the second stage is involved with the input and output parameters. After these two stages of evaluation, only (541) sets are adopted to be the model data base. (22) Variables (masses of constituents) are chosen to be as the input variables. While (8) variables represent the rheology, fresh and hardened properties of SCC are considered as the output variables.

2- These (16) sets of mixes are used as a validation set in the ANN model. This validation set does not have any effect on the training of the model. The predicated results of the validation set are compared with the experimentally measured results of the rheological tests.

6.8 Results of ANN Model

ANN model is fed forward neural network, which are trained by the (BFGS) optimization algorithm. The topography and training parameters obtained through trial and error for the ANN model thus developed are done with the aid of a commercial analytic software package called "StatSoft Statistica version 8" which is used to analyze, design and execute these models.
ANN model is constructed to predict yield stress and viscosity. The best performance is found to be the architecture of Multi Layers Perceptron (MLP) 22-35-8 (one input layer that contains 22 elements; one hidden layer that contains 35 elements; and one output layer that contains 8 elements).

Results of this model are listed in **Table 11**, and **Figs. 21 and 22** show correlation diagrams between train and test values for this model. The results show, very good percentages of correlation between target and output values with very low values of errors, and high percentage of matching between targets and outputs, and no clear trend to overestimation or underestimation. The results proved that these models are able to predicate SCC rheological parameters effectively, and the ANN model can be a good tool to verify the performance of the new rheometer.

6.9 Results of Experimental Rheological Tests

According to the procedure of testing with rheometer, every specimen is sheared under (7) speeds. However, the first and lowest speed is not adopted as a factor. The rest six speeds are (25, 35, 45, 55, 65, and 75 rpm). The specimen is sheared for (1) minute at each interval of speed. The output file of "TorqueLog" software provides about (5400) readings of (T) and (N) for each minute. Average readings for (T) and (N) at each speed are adopted and plotted as scatter-plots. Square of correlation coefficient "R^2" values and equation of linear regression fit are listed in Table (12). The intercept and

slope values of each linear regression equation are respectively used as *(g)* and *(h)* values in Equations (23) and (24). The calculated values of Yield Stress (τ_o) and Viscosity (μ) are listed in **Tables 13 and 14,** respectively, which also showed the predicted values of those two properties.
Figs. 23 and 24 show the correlation diagrams between predicted and measured results. The correlation coefficient between results of yield stress and viscosity are ($R^2 \approx 0.91$) for both of them. These figures demonstrate that the values of parameters of Bingham model (yield stress and viscosity) can be determined with high accuracy with correlation coefficients. The arrangements of points of results and the nature of predicted and measured results are displayed in **Figs. 25 and 26.** These figures show a very high percentage of matching between predicted and measured results.

7.CONCLUSIONS

The conceptual and new design of Tattersall two-point rheometer suitable for concrete has been outlined. The rheometer has been built up and used to obtain Bingham parameters related to SCC.
The proposed rheometer considers frictional resistance between concrete and vertical wall of cylindrical container. An expression for shear stress has been derived in terms of torque and average shear strain rate in terms of rotational speed have been obtained for given geometrical parameters of the rheometer. Torque and rotational speed have been measured using a Rotary Torque Transducer. The rheometer has been validated by testing (16) mixes of SCC and compared their measured results with the predicted measures that obtained by ANN predicting model. Very good percentages of correlation coefficient (0.91for both) are shown between measured and predicted results of yield stress and viscosity. All of the results indicate that the new rheometer able to be relied on.

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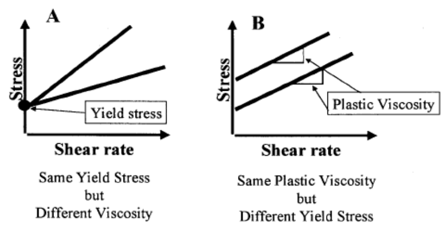


Figure 1. Concrete Rheology.

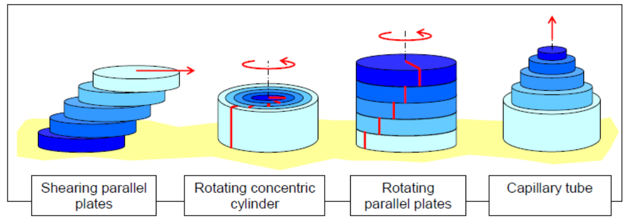


Figure 2. Four Main Rheological Techniques **.**

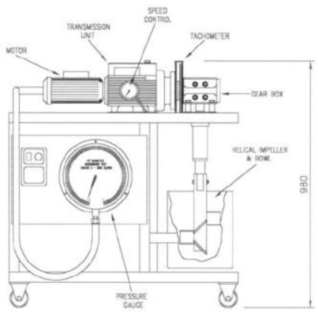


Figure 3. Mk II Apparatus.

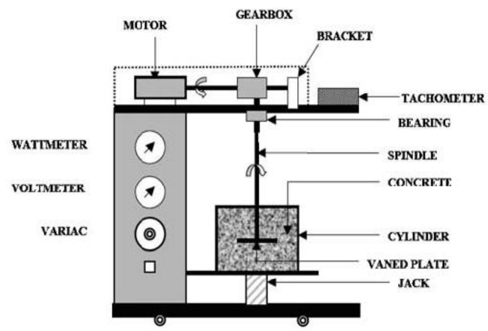


Figure 4. Schematic diagram of Laskar and Talukdar Rheometer.

Figure 5. First adopted design of Mk II apparatus.

Figure 6. Side view of torque calibration equipment.

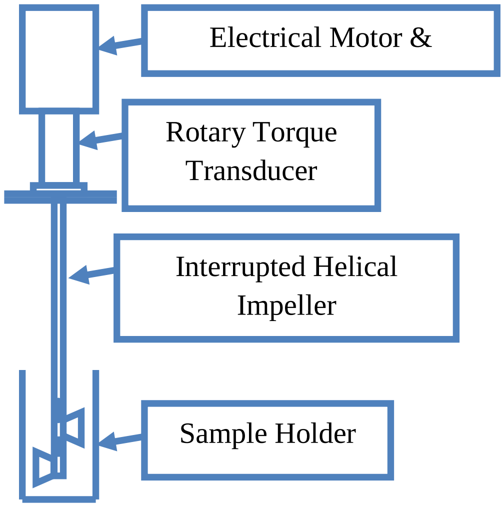


Figure 7 . Sketch of modified design**.**

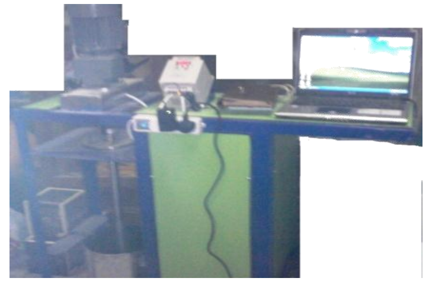


Figure 8. Completed new Rheometer

Figure 9. Vertical unit of electrical motor & reduction gearbox.

Figure 10. M420 rotary torque transducers.

Figure 11. Connection between M420 rotary torque transducers and gearbox**.**

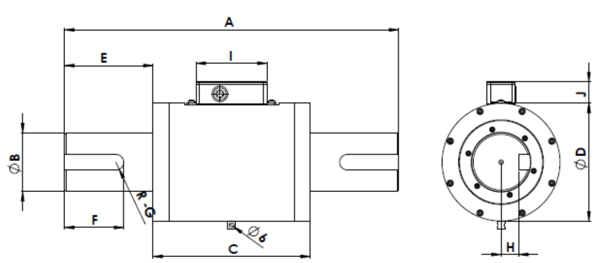
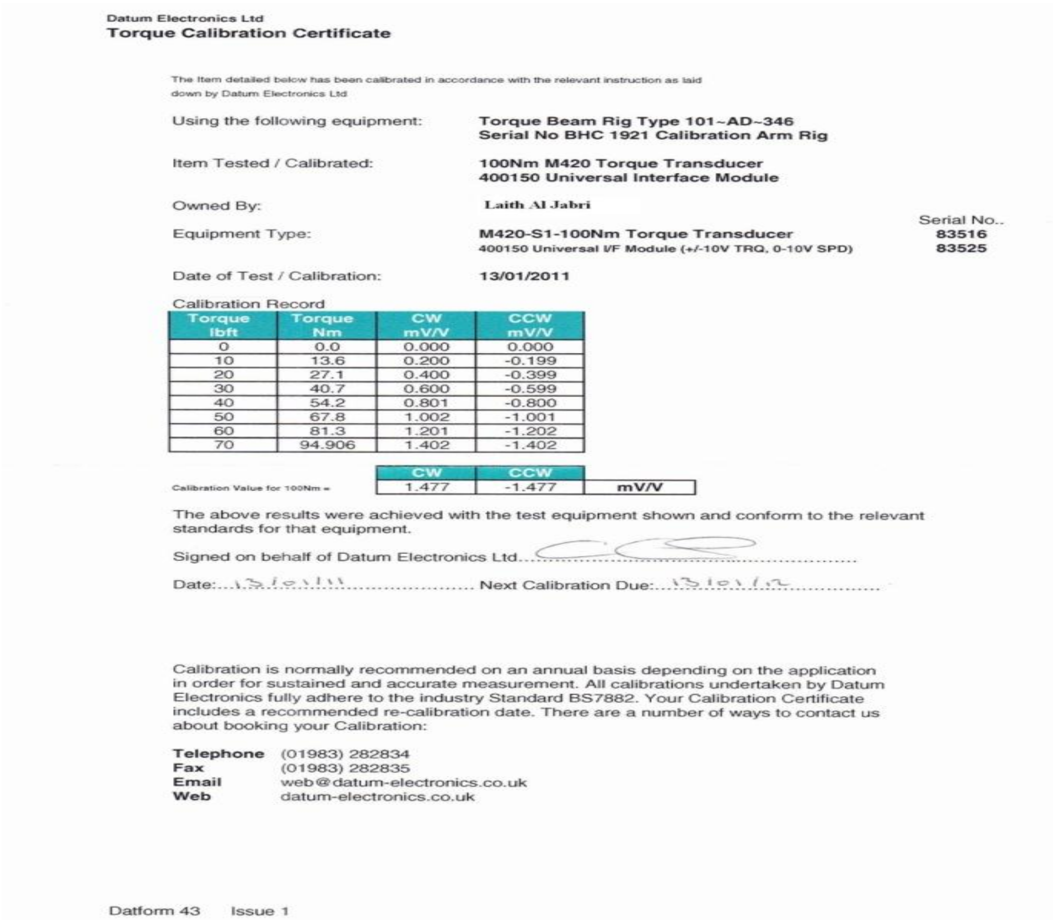


Figure 12. Front and side diagrams of M420 rotary torque transducers.



Datum Electronics Ltd
Torque Calibration Certificate

The Item detailed below has been calibrated in accordance with the relevant instruction as laid down by Datum Electronics Ltd

Using the following equipment:	**Torque Beam Rig Type 101~AD~346** **Serial No BHC 1921 Calibration Arm Rig**
Item Tested / Calibrated:	**100Nm M420 Torque Transducer** **400150 Universal Interface Module**
Owned By:	**Laith Al Jabri**
Equipment Type:	**M420-S1-100Nm Torque Transducer** — Serial No.. **83516** **400150 Universal I/F Module (+/-10V TRQ, 0-10V SPD)** — **83525**
Date of Test / Calibration:	**13/01/2011**

Calibration Record

Torque lbft	Torque Nm	CW mV/V	CCW mV/V
0	0.0	0.000	0.000
10	13.6	0.200	-0.199
20	27.1	0.400	-0.399
30	40.7	0.600	-0.599
40	54.2	0.801	-0.800
50	67.8	1.002	-1.001
60	81.3	1.201	-1.202
70	94.906	1.402	-1.402

	CW	CCW	
Calibration Value for 100Nm =	1.477	-1.477	mV/V

The above results were achieved with the test equipment shown and conform to the relevant standards for that equipment.

Signed on behalf of Datum Electronics Ltd..

Date:...13/01/11..................... Next Calibration Due:...13/01/12..............

Calibration is normally recommended on an annual basis depending on the application in order for sustained and accurate measurement. All calibrations undertaken by Datum Electronics fully adhere to the industry Standard BS7882. Your Calibration Certificate includes a recommended re-calibration date. There are a number of ways to contact us about booking your Calibration:

Telephone (01983) 282834
Fax (01983) 282835
Email web@datum-electronics.co.uk
Web datum-electronics.co.uk

Datform 43 Issue 1

Figure 13. Torque calibration certificate.

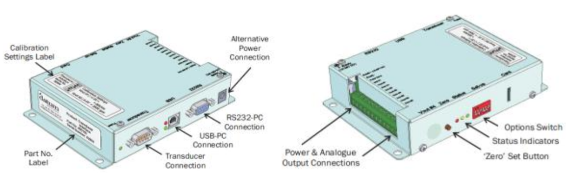


Figure 14. Transducers interface**.**

Figure 15. Torque log interface window.

Figure 16. Advanon AC frequency conversion speed regulator.

Figure 18. Lower part of impeller.

Figure 17. Upper part of impeller**.**

Figure 19. Sample holder.

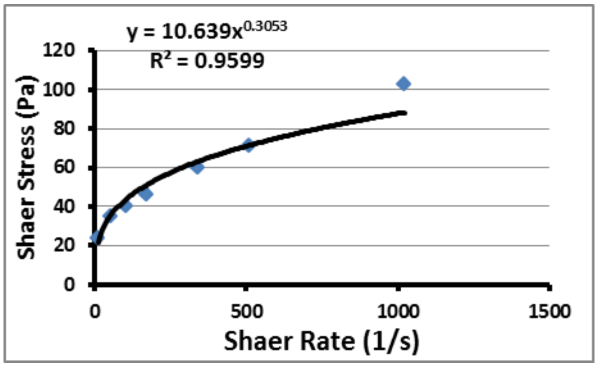


Figure 20. Shear stress vs. shear rate of cement slurry: OFITE model 800 viscometer.

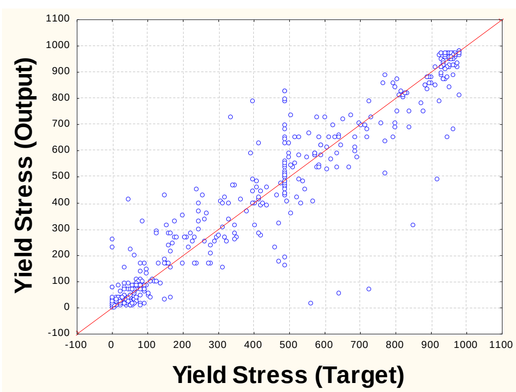


Figure 21. Correlations diagram of RP-CS model (Yield Stress)

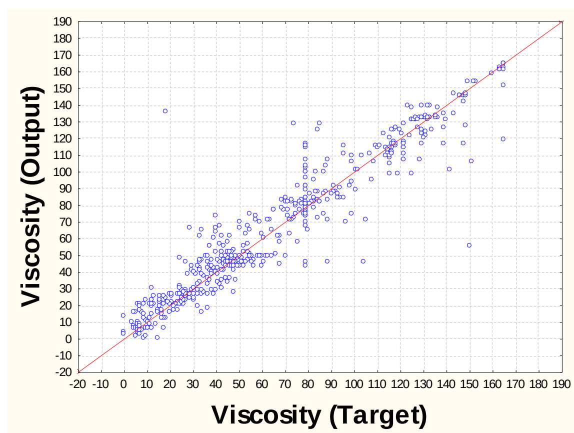


Figure 22. Correlations diagram of RP-CS model (Viscosity).

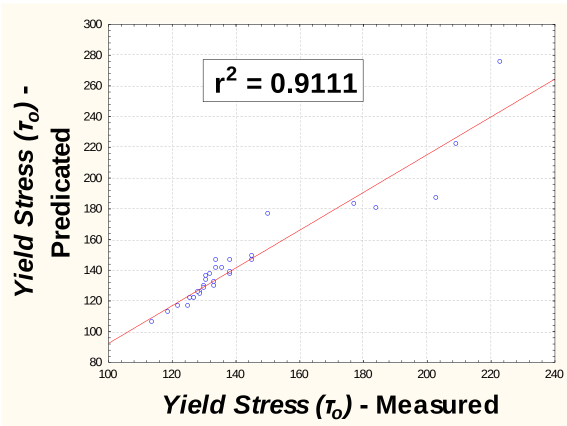


Figure 23. Correlations diagram between predicated and measured: yield stress (τ_o).

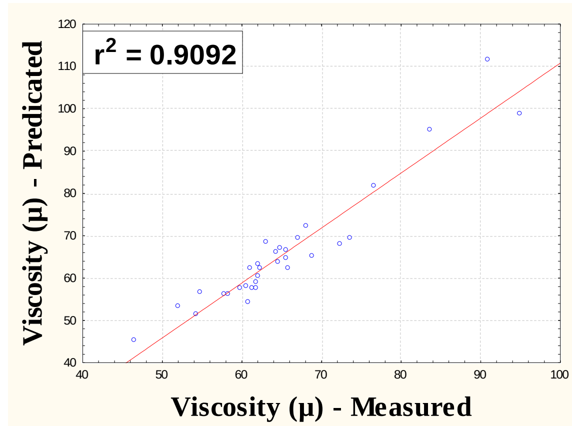


Figure 24. Correlations diagram between predicated and measured: Viscosity (μ).

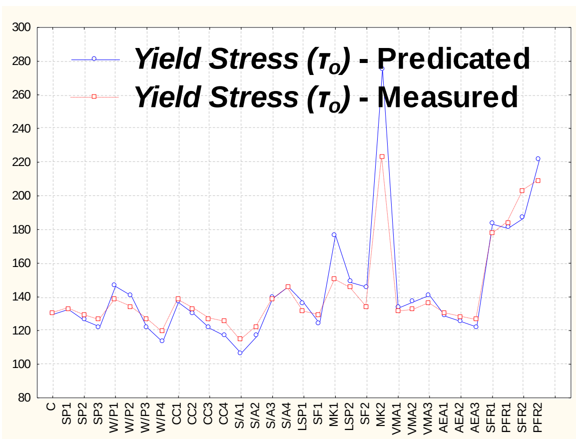


Figure 25. Points of predicated and measured results: Yield stress (τ_o)

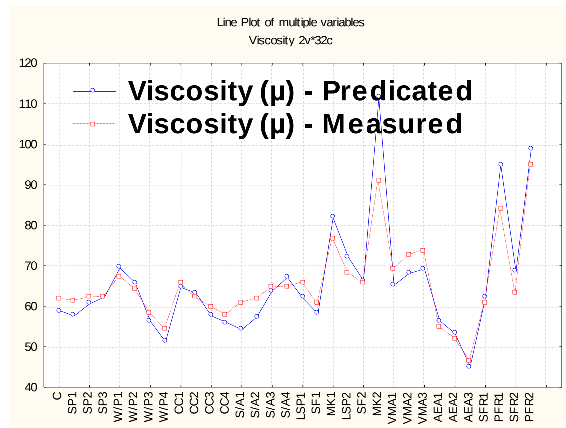


Figure 26. Points of predicated and measured results: Viscosity (μ).

Table 1. Specifications of Electrical Motor & Gearbox.

a- Electrical Motor:	
Power	0.75 kw
Amp.	3.6 – 2.1
Voltage	220 – 380
Frequency	50 Htz
Speed	1645 RPM
b- Gearbox:	
Power	0.75 kw
Speed	126 RPM
Reduction Ratio	1:14

Table 2. Specifications and dimensions of M420 rotary torque transducer (Size1).

Specifications	
Torque Ratings	0-100Nm
Max Rotation Speed	0-10,000 rpm
Accuracy	0.1%
Operating Temp	0-70ºC
Supply Voltage	15-24VDC
Cable Length	4 metre to interface (Standard)
Dimensions	
A: Overall Length	184 mm
B: Shaft Diam	15 mm
C: Body Length	129 mm
D: Body Diam	60 mm
E: Exposed Shaft Length	27.5 mm
F: Keyway Length	22.5 mm
G: Keyway Width	5 mm
H: Keyway Depth off centre	4.3 mm

Table 3. Experimental data for water test: (N_{Re}) & (N_{Po}) values.

N(rad/s)	**d (meter)**	**ρ (kg/m³)**	**η (kg/m.s)**	**T (Nm)**	**N_{Re}**	**N_{Po}**
1.570796327				0.070581	40212.39	0.272803
2.617993878				0.084697	67020.64	0.117851
3.665191429				0.105872	93828.9	0.07516
4.71238898	0.16	1000	0.001	0.155278	120637.2	0.066685
5.759586532				0.176453	147445.4	0.0 0728
6.806784083				0.211743	174253.7	0.043584
7.853981634				0.247034	201061.9	0.038192
				Average	**120637.2**	**0.09499**

Table 4. Experimental data for cement slurry: Study's Rheometer.

N (rpm)	N (rps)	$\dot{\gamma}_a$ (1/s)	k' (1/rev)
25	0.416667	0.34229433	0.821506393
35	0.583333	0.210670077	0.361148704
45	0.75	0.146701589	0.195602119
55	0.916667	0.109885039	0.119874588
65	1.083333	0.086390424	0.079745007
75	1.25	0.070302799	0.05624224
85	1.416667	0.05870804	0.04144097
95	1.583333	0.050019442	0.031591227
105	1.75	0.043306018	0.024746296
115	1.916667	0.037988833	0.01982026
125	2.083333	0.03369073	0.01617155
135	2.25	0.03015645	0.013402867
145	2.416667	0.027207643	0.011258335
155	2.583333	0.024716285	0.009567594
195	3.25	0.017758693	0.005464213
225	3.75	0.014451669	0.003853778
235	3.916667	0.013574477	0.003465824
250	4.166667	0.012417301	0.002980152
275	4.583333	0.010824847	0.002361785
Average			0.095802311

Table 5. Chemical and physical composition of cement.

<table>
<tr><td colspan="7">Chemical Composition</td></tr>
<tr><td>Oxides</td><td>Test Results</td><td>IOS 5:1984 criteria</td><td>Oxides</td><td>Test Results</td><td colspan="2">IOS 5:1984 criteria</td></tr>
<tr><td>SiO_2</td><td>19.22</td><td>-</td><td>SO_3</td><td>2.03</td><td colspan="2">< 2.8</td></tr>
<tr><td>Fe_2O_3</td><td>3.34</td><td>-</td><td>L.S.F</td><td>1.01</td><td colspan="2">0.66 - 1.02</td></tr>
<tr><td>Al_2O_3</td><td>4.51</td><td>-</td><td>L.O.I</td><td>3.72</td><td colspan="2">< 4</td></tr>
<tr><td>CaO</td><td>63.26</td><td>-</td><td>I.R</td><td>0.84</td><td colspan="2">< 1.5</td></tr>
<tr><td>MgO</td><td>2.62</td><td>< 5</td><td>C_3A</td><td>6.59</td><td colspan="2">-</td></tr>
<tr><td colspan="7">Physical Properties</td></tr>
<tr><td colspan="4">Properties</td><td>Test Results</td><td colspan="2">IOS 5:1984</td></tr>
<tr><td colspan="4">Specific surface area (Blaine Method), m2/kg</td><td>352</td><td colspan="2">> 230</td></tr>
<tr><td colspan="4" rowspan="2">Mortar Compressive strength (MPa) at</td><td>3 days</td><td>20.8</td><td>> 15</td></tr>
<tr><td>7 days</td><td>26.00</td><td>> 23</td></tr>
<tr><td colspan="4" rowspan="2">Setting Time(min)</td><td>Initial</td><td>141 min.</td><td>≥ 45 min.</td></tr>
<tr><td>Final</td><td>320 min.</td><td>≤10 hours</td></tr>
<tr><td colspan="4">Soundness: autoclave %</td><td colspan="2">0.03</td><td>< 0.8</td></tr>
</table>

Table 6. Grading and physical properties of fine aggregate.

Sieve size (mm)	% Passing by weight	Limits of the Iraqi specification No.45/1984 (zone 3)
10	100	100
4.75	97	90-100
2.36	91	85-100
1.18	84	75-100
0.60	71	60-79
0.30	18	12-40
0.15	7	0-10
Physical Properties	Test Results	Limits of the Iraqi specification No.45/1984
Specific gravity	2.60	-
Sulfate content	0.17 %	≤ 0.50 %
Absorption	0.75 %	-

Table 7. Grading and physical properties of coarse aggregate.

Sieve size (mm)	% Passing by weight	Limits of the Iraqi specification No.45/1984
20	100	100
14	98	90-100
10	84.6	85-100
5	10.0	0-10
2.36	0	0-5
Physical Properties	Test Results	Limits of the Iraqi specification No.45/1984
Specific gravity	2.63	-
Sulfate content	0.06 %	≤ 0.1 %
Absorption	0.63 %	-

Table 8. Categories and description of variables in mixes.

Group No.	Mix Symbol	Description of Variables in Mixes
1	C	Reference Mix
2	SP1	0.8 % SP (by cement weight)
	SP2	1.2 % SP (by cement weight)
	SP3	1.4 % SP (by cement weight)
3	W/P1	w/p = 1 by volume
	W/P 2	w/p = 1.05 by volume
	W/P 3	w/p = 1.15 by volume
	W/P 4	w/p = 1.20 by volume
4	CC1	Decrease Cement Content by (4.58%); [w/p constant]
	CC2	Decrease Cement Content by (1.56%); [w/p constant]
	CC3	Increase Cement Content by (2.6%); [w/p constant]
	CC4	Increase Cement Content by (5%); [w/p constant]
5	S/A1	S/A = 0.425 by volume
	S/A 2	S/A = 0.450 by volume
	S/A 3	S/A = 0.500 by volume
	S/A 4	S/A = 0.525 by volume

Table 9. Details of C, SP1, SP2, SP3, W/P1, W/P 2, W/P 3 & W/P 4 mixes (Category 2).

		C	SP1	SP2	SP3	W/P 1	W/P 2	W/P 3	W/P 4
Materials	**Unit**	**Quantity**	**Quantity**	**Quantity**	**Quantity**	**Quantity**	**Quantity**	**Quantity**	**Quantity**
Water	Liter/m^3	168	168	168	168	168	168	168	168
Cement	Kg/m^3	480	480	480	480	529	504	460	441
Sand	Kg/m^3	814	814	814	814	795	805	822	830
Gravel	Kg/m^3	910	910	910	910	889	900	919	928
Super-Plasticizer	% of cement mass	1	0.80	1.20	1.40	1	1	1	1

Table 10. Details of CC1, CC 2, CC 3, CC 4, S/A 1, S/A 2, S/A 3 & S/A 4 mixes (Category 4).

		CC 1	CC 2	CC 3	CC 4	S/A 1	S/A 2	S/A 3	S/A 4
Materials	**Unit**	**Quantity**	**Quantity**	**Quantity**	**Quantity**	**Quantity**	**Quantity**	**Quantity**	**Quantity**
Water	Liter/m^3	160	165	172	176	168	168	168	168
Cement	Kg/m^3	458	472.5	492.5	504	480	480	480	480
Sand	Kg/m^3	833	821	805	795	728	771	857	900
Gravel	Kg/m^3	931	918	900	889	997	954	867	824
Super-Plasticizer	% of cement mass	1	1	1	1	1	1	1	1

Table 11. Results of RP-CS model.

Item	Value
Training Performance	0.950237
Test Performance	0.921961
Validation Performance	0.900702
Training Error	0.025069
Test Error	0.035493
Validation Error	0.051216
BFGS Algorithem Cycles	BFGS 106
Hidden Activation	Tanh
Output Activation	Logistic

Table 12. R^2 & Regression equations for (T) and (N) relations.

Mix	R^2	Regression Equation
Mix C	0.9570	T = 0.5285+0.024*N
Mix SP1	0.9554	T = 0.5391+0.0239*N
Mix SP2	0.9831	T = 0.5233+0.0241*N
Mix SP3	0.9578	T = 0.5128+0.0242*N
Mix WP1	0.9692	T = 0.5595+0.0262*N
Mix WP2	0.9787	T = 0.5454+0.025*N
Mix WP3	0.9877	T = 0.5167+0.0227*N
Mix WP4	0.9924	T = 0.4836+0.0211*N
Mix CC1	0.9778	T = 0.5559+0.0256*N
Mix CC2	0.9610	T = 0.5401+0.0241*N
Mix CC3	0.9560	T = 0.5182+0.0233*N
Mix CC4	0.9611	T = 0.5064+0.0225*N
Mix SA1	0.9943	T = 0.4651+0.0236*N
Mix SA2	0.9751	T = 0.4968+0.024*N
Mix SA3	0.9312	T = 0.5594+0.0251*N
Mix SA4	0.9690	T = 0.5885+0.0252*N

Table 13. Measured and predicted yield stress (τ_o).

Mix	Yield Stress (τ_o) (Pa)	
	Measured	Predicted
C	129.558	130
SP1	132.594	133
SP2	126.082	129
SP3	122.233	126
W/P1	146.262	138
W/P 2	140.704	134
W/P 3	121.914	127
W/P 4	113.223	119
CC1	136.745	138
CC2	129.893	133
CC3	121.401	127
CC4	116.649	125
S/A1	106.440	114
S/A 2	116.584	122
S/A 3	138.880	138
S/A 4	146.041	145

Table 14. Measured and predicted viscosity (μ).

Mix	Viscosity (μ) (Pa s)	
	Measured	Predicted
C	59.005	61.75
SP1	57.553	61.25
SP2	60.579	62.00
SP3	62.282	62.25
W/P1	69.436	67.25
W/P 2	65.919	64.25
W/P 3	56.296	58.25
W/P 4	51.245	54.25
CC1	64.653	65.50
CC2	63.258	62.00
CC3	57.628	59.75
CC4	55.996	57.75
S/A1	54.206	60.75
S/A 2	57.375	61.5
S/A 3	63.808	64.50
S/A 4	67.087	64.75