Mechanical Properties of Porcelinite Reinforced Concrete Beams

Assist Prof. Dr. Ayad A. Slaby - Al-Anbar university
Dr. Khalil I. Aziz- Al-Anbar university
Ali Farhan Hadeed

Abstract *:The researches in Iraq has expanded in the field of material technology involving the properties of the light weight concrete using natural aggregate aviable in westran of Iraq. Researches work on porcelinite concrete has been carried out in several Iraqi Universities. The study is deals with mechanical properties of porcelinite aggregate concrete by casting (273) different specimens. These properties are, compressive strength, flexurale strength, splitting strength, static modulus of elasticity and absorption. The results indicated that the structural light weight aggregate concrete produced from local porcelinite aggregate is suitable to used as a structural concrete, it can produce structural light weight concrete of compressive strength varies from (23.0 to 29.8) MPa with the density ranges from (1745 to 1855) kg/m^3, by using cement content about (550 and 650) kg/m^3.Such concrete exhibited good mechanical properties. It gave the values of splitting tensile strength, modulus of rupture and modulus of elasticity, 75%, 90% and 60% from those of normal weight concrete respectively owning the same compressive strength and meeting the requirement of ACI-213.*

الخلاصة : جرت بحوث عديدة في العراق حول تكنولوجيا المواد منها المتعلقة بالخرسانة الخفيفة الوزن باستعمال ركام طبيعي. البحوث التي عُمِلت على الخرسانةالمتكونة من الركام البورسلاني المتوفر في المنطقة الغربية من العراق نفذت في العديد من الجامعات العراقية وذلك لاهميتها العملية. في هذه البحث تمت دراسة الخواص الميكانيكية لخرسانة الركام خفيف الوزن عن طريق صب وفحص نماذج قياسية ، حيث تم الحصول على خواص خرسانة البورسيلينايت من خلال (273) نموذج مضافا لها نماذج من الخرسانة الاعتيادية لغرض المقارنة ، وشملت هذه الخواص ، مقاومة الانضغاط ، مقاومة الإنثناء ، مقاومة الانشطار ، معامل المرونة الاستاتيكي والامتصاص. امكن الحصول على مقاومة الانضغاط تراوحت من (23-29.8) ميكاباسكال مع كثافة للخرسانة تراوحت بين (1745 – 1855 كغم/م3 ، وباستخدام محتوى اسمنتي تراوح بين (550-650 كغم/م3) . مثل هذه الخرسانة اعطت خواص ميكانيكية جيدة ، من حيث مقاومة الشد بالانشطار ، معامل الكسر ومعامل المرونة كانت القيم حوالي 75% ، 90% و 60% من تلك القيم المستحصلة للخرسانة الاعتيادية والتي لها نفس مقاومة الانضغاط .

NOTATION

AVG **Average**
HRWA **High range water Reducing Admixture**
HSC **High strength of (LWC)**
C **Cemet**
CA **Coarse aggregate**
COV **Coefficient of variation**
FA **Fine aggregate**
LWA **Light weight aggregate**
LWAC **Light weight aggregate concrete**
LWC **Light weight concrete**
LSC **Low strength of (LWC)**
MSC **Medium strength of (LWC)**
NWC **Normal weight concrete**
NWCB **Normal weight concrete beam**
SD **Standard deviation**
SLWA **Structural light weight aggregate**
SLWAC **Structural light weight Aggregate concrete**
SLWC **Structural light weight concrete**
SLWACB **Structural light weight aggregate concrete beams**

SP Superplasticizer
W/C Water-cement ratio
$€_{top}$ = strain at extreme compressive fiber
$€_{20}$ = strain at 20 mm from the top face of the beam
$€_{80}$ = strain at 80mm from the top face of the beam
$€_{180}$ = strain at 180mm from the top face of the beam
$€_{240}$= strain at 240mm from the top face of the beam

1.Introduction

The use of the porcelinite aggregate in the production of structural light concrete (SLWC) has a wide objective and requires a lot of research to become suitable for practical application. One of the disadvantages of conventional or Normal Weight Concrete (NWC) is the high self weight of concrete. Density of the normal concrete (NWC) is in the order at 2200 to 2600 kg/m^3. This heavy self weight will make it an uneconomical structural material. The light weight concrete (LWC) as call it is a concrete whose density varies from 300 to 1850 kg/m^3 [(1)]. With the introduction of reinforced concrete members employing (LWA), the density limit has had to be revised[(2)]. The draft international standard model code for concrete construction classifies light weight concrete (LWC) as having densities between 1200 and 2000 kg/m^3(cited by Ref. 2). The most obvious characteristic of (LWC) is of course its density which is always considerably less than that of (NWC) as shown in Table (1) and (2)[(2)].It is clear that can be producing larger volume of (LWC) comparing with that of (NWC) for the same weight which will give the economical benefits.

1.1 Classification of (LWC)

It can be classifying the (LWC) according to the its producing:

There are three broad methods of producing (LWC):

1- In the first, porous light weight aggregate of low apparent specific gravity is used instead of ordinary aggregate whose specific gravity is approximately 2.6. This concrete in generally known by the name of the light weight aggregate used.
2- The second method of producing light weight concrete (LWC) relies on introducing large voids within the concrete or mortar mass. These voids should be clearly distinguished from the extremely fine voids produced by air entraining. This concrete is known as aerated, cellular, foamed or gas concrete.
3- The third means of obtaining (LWC) is by simply omitting the fine aggregate from the mix so that a large number of interstitial voids is present, coarse aggregate of ordinary weight is generally used. This called no- fines concrete. [(3)]

Light weight concrete can also be classified according to the purpose of using as:

- Structural light weight concrete with cylindrical compressive strength at 28 days not less than 17MPa and density not exceeding 1850 kg/m^3 [(3)].
- Insulating light weight concrete with density lower than 800kg/m^3 and strength between 0.7 and 7 MPa[(3)].

Also the light weight concrete (LWC) is defined as low strength (LSC) for compressive strength ranging from 17.25 to 27.6 MPa and for compressive strength ranging from 27.6 to 41.4 MPa it is considered medium strength (MSC), finally for compressive strength more than 41.4 MPa is classified as High Strength (HSC) [(5, 6)].

1.2 Advantages of Light Weight Concrete:

There are many advantages of using (LWC) which can be stated as follows:

1- It helps in reduction of dead load[(1)].
2- With the (LWC) the formwork needs to withstand a lower pressure than would be the case with (NWC)[(3,7,8)].
3- Increase the progress of building and lowers haulage and handling costs[(1,2,3)].

4- The important characteristic of (LWC) is the relatively low thermal conductivity, a property which improves with decreasing density. In extreme climatic condition and also in case of building where air conditioning is to be installed, the use of (LWC) with low thermal conductivity will be of considerable advantages from the point of view of the thermal comfort and lower power consumption[1,2,3,4,8].

5- The adoption of (LWC) gives an outlet for industrial wastes such as clinker , fly ash , slag , etc… which otherwise create problems for disposal[1,2].

6- Coefficient of thermal expansion/contraction for light weight aggregate concrete (LWAC) are less than for normal concrete (NWC) made with majority of aggregate types[4]

7- (LWAC) exhibits the excellent behavior under fire and cryogenic conditions. This is significantly better than (NWC) which required lower covers to steel[4,10].

1.3 Light Weight Aggregate Concrete

It has seen that light weight aggregate concrete covers an extremely wide field[3]. Very often light weight concrete (LWC) is made by the use of light weight aggregate. It have seen that the different light aggregates (LWA) have different densities. Naturally when these aggregates are used concretes of different densities are obtained.[1] By using expanded perlite or vermiculite, a concrete of density as low as 300 kg/m^3 can be produced , and by the use of expanded slag , sintered fly ash , bloated clay etc,... a concrete of density 1900 kg/m^3 can be obtained. The strength of (LWC) may also vary from about 3 kg/cm^2 to 400 kg/cm^2. A cement content of 200 kg/m^3 to about 500 kg/m^3 may be used[1]. The variety of purpose of (LWAC) is recognized by RILEM/CEB who proposed the classification given in Table(2) {RILEM 1978} [4,11]

1.4 Light Weight Aggregate Concrete in Iraq:

In Iraq, little has been done on the use of (LWC) in structural members , such as , slabs , beams , columns , foundations,…etc [5] . For a long time , the investigations had shown great interest in heat insulating light weight material. They experimented on many materials as binding material to lighten dead loads on roofs [5,12]. (LWC) use in Iraq is limited to very few buildings and the aggregate used in most cases was imported [5,13] , for example , of the flooring of telephone exchange in Baghdad. Polystyrene aggregate was used in making (LWC) for the penthouse walls in the University of Baghdad in 1980 which are still in good condition[5,12]. During the seventies of the last century there had been an attempt by the Building Research Center to produce such aggregate from clay found in the middle and Southern part of Iraq[5].

1.5 Porcilinite Light Weight Aggregate Concrete in Iraq

Recent research (**12, 14, 15, 16, 17, 18**) has shown that there is an abundant supply of light weight rock that may be used to produce concrete of lower density than the present practice in this country[5]. The aggregate which is used, is quarried from rocks discovered in the Iraqi Western Desert. It is called porcelinite[9]. Since the production of manufactured light weight aggregate (from clay , shale , …etc.) is more costly , successful use of natural light weight will be much more economic , such as porcelinite aggregate. It is more important in Iraq, since much of this country has low soil bearing capacity. In Iraq, in the University of Technology , several researches where done on the properties of Porcilinite light weight aggregate concrete[5]. Also Al-Mustansirya and Al-Anbar University made researches about this subject. Porcilinite rocks were discovered in Traifawi in the Iraqi Western Desert near Rutba in 1986 by the State Company of Geological Survey and Mining [5,20]. Fig. (1) shows the location[9]. Porcilinite rock is one of the important industrial sedimentary rock. It has gone under more than 20 different names , where many are commercial trade marks (e.g diatomite , diatomaceous earth , kieselguhr , cellite , fillate …etc) [9]. There are marine sedimentary deposits associated with clay stone, phosphorite and carbonate. The porcilinite is bedded or lensoid in shape white to creamy in color and highly cracking[9]. The mineralogy of the porcilinite is dominated by opal-CT with variable amounts of dolomite, palyporskite , montmorillonite , appatite , quartz and some gypsum and halite of secondary origin. Chemically they consist of about 63-76% SiO_2 , 2-3% Al_2O_3 , 5-8% CaO , 4-6% MgO , 8-14% L.O.I.[(9)]. Tables (3) and (4) indicate the chemical and mineral composition of porcelinite rock. The porosity of these porcilinites ranges from 46.2 to 55.6% and bulk density ranges from 1.01-1.22 gm/cm^3. Two grades of porcilinites were identified according to their silica contents; grade I ($SiO_2 \geq 70\%$) and grade II (SiO_2 = 60.-69%). Grade I and grade II have total tonnage estimation for the deposit which was as follows:

Grade I = 784674 tons and Grade II = 982346 tons[(9)]

2.Experimantal work

The experimental program including tests for the materials which were used, specimens preparation and test procedures. A total of (273) specimens were made to determine the mechanical properties of each mix proportion. The mechanical properties which were tested in this study were the compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity, unit weight and absorption.

2.1 Materials

2.1.1 Cement

Ordinary Portland cement (type I) according to ASTM C150-86[17] produced by Iraqi State Company at Kubasia Cement Plant was used throughout this work. The chemical and physical properties of such cement are presented in tables (5) and (6) respectively. The results indicate that the adopted cement conformed to the Iraqi specification No.5/1984[18]. These results were conducted by Al-Falluja Cement factory.

2.1.2 Fine Aggregate

Normal weight, natural sand from Al-Anbar west region was used as a fine aggregate. Physical and chemical tests were conducted by the Civil Engineering Laboratory of Al-Anbar University. The results are shown in Table. (7). The grading of sand was conformed to the requirements of B.S.882-1992[19], also the sulfate content test was made according to the I.O.S No.45-84[20], by the same laboratory. Table (8) shows the grading details of the sand.

2.1.3. Coarse Aggregate

2.1.3.1 Porcelinite Aggregate

Local natural (LWA) of porcelinite stone was used as coarse aggregates. It was received in medium lumps from the State Company of Geological Survey and Mining. The quarry of this stone is located in Trefawi area in Rutba at the Western desert in Al-Anbar governorate. The jaw of machine crusher was set up to give a finished product of about 12.5mm maximum aggregate size. The physical and chemical tests were done by the State Company of Geological Survey and Mining (SCGSM). Table (9) and (10) list those properties respectively. Table (11) represents mineral analysis of the porcelinite aggregate. The grading of coarse porcelinite aggregates was conformed to ASTM C330-87[11] as shown in Table (12) .

2.1.3.2 Natural Gravel

Gravel with maximum aggregate size 12.5mm was also used to produce normal weight concrete for comparison with light weight concretes. Table (13), shows the grading details.

2.1.4. High Range Water Reducing Admixture (HRWA)

A high range melamine based super plasticizer (commercially named as RHEOBUID 2000M), type F chemical admixture according to ASTM C494-86 was used in this work. This material may improve and control the rate of hardening and slump loss, and result in accelerated strength gain, better durability and improved workability [21]. (LWC) becomes more workable when (SP) is added, and (LWA) will not float up. The dosage was found to be (2%) by the weight of the cement and the reduction in weight of water was about 20% .Table (14) shows the properties of the admixture according to the catalogue of construction Engineering Group[21] (Baghdad /AL-Harthya) .

2.1.5. Mixing and Curing Water

Ordinary tap water was used in the experimental process as mixing water for all concrete mixes of this work and also for curing.

2.2 Concrete Mixes

Mix design methods applying to (NWC) are generally difficult to use with (LWAC). The lack of accurate value of absorption , specific gravity and the free moisture content in the aggregates make it difficult to apply the water/cement ratio accurately for mix proportioning[1]. Light weight concrete mix design is usually established by trial mixes[1]. Concrete mixes containing porcelinite aggregates as (LWA) should have an oven-dry density < 2000 kg/m^3, and a compressive strength > 15 MPa, in order to meet the class (I) of the RILEM classification[7] which is adopted by CEB-FIP manual. Different trial mixes were made to conform these specifications. Table (15) shows the details of the mixes. (NWC) mixes carried out according to ACI.211[22].

2.2.1 Concrete Mixing Procedure

Mixing methods are important to obtain the required workability and homogeneity of the concrete mix. Mixing was performed using (0.1m^3) mechanical mixer. The mixer was used to mix concrete ingredient after a number of trial mixes has been made. Before using the mixer any remaining concrete from a previous batch was cleaned off. A damp cloth was used to wipe the pan and blades of the mixer. Mixing procedures for (LWC) may vary with different types of aggregate. The general practice for (SLWC) is to mix the aggregate and about 2/3 of the mixing water for a period up to one minute prior to the addition of cement and balanced mixing water. Mixing is done continuously as required for homogeneity. Usually 2 or more minutes are required to get uniform mixing[1]. The (SP) was added to the mixing water in the beginning and the solution was thoroughly stirred before using.

2.2.2 Casting and Compaction

Fresh concrete was powered by the scoop into the steel mould. Two layers approximately of the same depth of fresh concrete were used and each layer was vibrated. For control specimens the table vibrator, (9000 revolution per minute), was used and for beams specimens the internal vibrator was used. The duration of vibration for each layer was limited to the removal of entrapped air as much as possible. After the top layer has been compacted, it is smoothed and leveled by using a steel trowel.

2.2.3 Curing

After casting, the specimens were covered by plastic sheets, to prevent the evaporation of water from fresh concrete. Then after 24 hours they were stripped and kept in the water bath for a curing period of 28 days to ensure that the hydration process was completely carried out under laboratory temperature.

2.3 Concrete Testing Program for Control Specimens

The control specimens were taken out the curing water bath and allowed to dry in the air of the laboratory after 28days, the period of curing. The slump and fresh unit weight tests were done during the cast of all mixes. Other mechanical and physical tests were achieved on the hardened concrete specimens.

2.3.1 Workability

Workability of all mixes was measured by the slump test, which was carried out in accordance with the procedure described in ASTM C143-78[23]. The w/c ratios were adjusted to gain a good workability. The values of slump tests of various mixes are shown in Table(15).

2.3.2 Fresh Density

An average of three cylinders (200x100mm) was used to determine the compacted fresh density according to the ASTM C567-85[24].

2.3.3 Hardened Unit Weight

The test was performed according to ASTM C567-85[24]. Cylindrical specimens measuring (100x200mm) were used in order to suit the available balance in the laboratory. The specimens were left for (1) day in the moulds inside the moisture cabinet, then they were stripped from the moulds and wrapped with polyethylene bag for (6) day. After that they were removed and immersed in water for (1) day. The saturated surface-dry and suspended-immersed weights were then determined. The specimens were left in the laboratory air for (21) days, then air-dry weights were taken.

2.3.4 Absorption

The test was performed on (100mm) cubes in accordance with BS1881 part 122 1989[25] at age of 28 days. (3) Cubes were taken from the water basins and oven-dried to $105\pm5^{o}C$ for $72\pm2h$. Then they were wrapped securely with a polyethylene sheet and left in the laboratory to cool for $24\pm0.5h$. After that, they were weight and , then immersed directly in a tap water basin for $24\pm0.5h$. At the end of the immersion period they were removed and wiped up by a cloth to ensure that no free water remains at the surface of the specimens, then , they were weighed again. The water absorption is determined by dividing the specimens change in weight by its dry weight.

2.3.5 Compressive Strength

Concrete compressive strength was measured by using (150x300mm) cylindrical specimens and was tested according to ASTM C39-86[26]. A compressive machine (ELE) of 1000kN capacity was used to perform this test . Three cylindrical specimens were used to determine the average strength of each beam at 28 days curing age. This test was done in the laboratory of civil engineering department / Al-Anbar University.

2.3.6 Splitting Tensile Strength

The splitting tensile test was carried out on (100x200mm) concrete cylinders for 28 days age according to the ASTM C496-86[16]. The average of three specimens for each mix was adopted. By using testing machine (ELE) of 1000kN capacity, the test was carried out. This test was done in the laboratory of civil engineering department / Al-Anbar University.

2.3.7 Flexural Strength test

Flexural strength test (modulus of rupture) was carried out by using (100x100x500mm) prisms, loaded at 450mm span with two points loading hydraulic machine (ELE) of 50kN capacity. The test was carried out according to ASTM C78-84[15], using three concrete prisms and the average of three results was adopted, plate (3). This test was done in the laboratory of civil engineering department /Al-Anbar University.

2.3.8 Static Modulus of Elasticity (Ec)

The testing machine (ELE) 1000kN capacity was used for the determination of static modulus of elasticity using a compressometer of a gauge length of 150mm and dial gauge of an accuracy 0.002mm. These tests were performed according to ASTM C469-87[27]. Three specimens were tested for each series investigated. This test was done in the laboratory of civil engineering department / Al-Mustansirya University.

3.Results and discussions

3.1 Compressive Strength

The test results which are presented in Table (16) include the experimental values of concrete strength. The strength values are obtained from the average of three cylinders cast for each concrete mix. Table (15) of (experimental mixes) shows the reduction in w/c ratio from 0.44 to 0.32 using superplasticizer (SP) (2% weight of cement) in concrete increases the compressive strength from (20.9 to 26.5) Mpa at age 28 days about (27%) for the same cement content (500 kg/m^3), while Table(16) shows the increase in compressive strength from (23 to 27.2) Mpa under the same conditions (w/c ratio and SP). Table (16) also shows, that the mixes No. (6 and 7) give increase in compressive strength, for increase in cement contents (600-650) kg/m^3. This is due to the increase in bonds between the hydrated cement and aggregates and due to the increase in the strength of mortar.

Figure.(2) shows the relationship between the compressive strength and hardened concrete density at age of 28 days. In general for (LWAC), the lower is the density, the

lower is the compressive strength[3,5]. This is also true for porcelinite aggregate concrete. It is clear that the compressive strength decreases with decreasing cement content. This is in good agreement with Back et. Al[31].
An empirical formula is suggested for this work.

$$f'_c = 0.0464\, r_c - 56.714 \qquad \text{.....(1)}$$

where:

f'_c = compressive strength, Mpa (28 day age)

r_c = density of concrete, kg/m^3 (dry density, 28 day age)

This relationship may be used to predict the compressive strength of porcelinite aggregate concrete from its density, for ($20 \le f'c \le 30$) Mpa.

3.2 Splitting Tensile Strength

The results are presented in Table (17). Fig. (3) shows the relationship between the splitting tensile and compressive strengths. Based on test results in this work the following empirical formula is proposed to predict the splitting tensile strength of porcelinite concrete from its compressive strength.

Where:

$$ft = 0.496\sqrt{f'_c} \quad \text{------(2)}$$

ft = splitting tensile strength , Mpa

R^2 = 0.997 (coefficient of determination)

It is seen that there is an increase in splitting tensile strength due to the increase in compressive strength. For an increment about 29.0% of compressive strength, there is an increment about 27% of splitting tensile strength. Eq. (A7) by ACI code-83 ,Eq.(A6) by Short and Kinniburg and Eq.(A8) by Zhang and Gjorv give underestimated values of splitting tensile strength as shown in Table(17) , thus the porcelinite concrete is regarded as suitable materials for structural purposes and it has the ability for resisting the shear stresses. Eq.(A6) and Eq. (A8) give slight underestimating which is considered as having good agreement with estimated values , Eq. (A7) give (12%-26%) underestimated values.

It is observed that the splitting tensile strength of porcelinite concrete ranges between 9.6% to 9.8% from its compressive strength. (NWC) exhibits in this study the splitting tensile strength by about (11% to 13%) from its compressive strength. (NWC) generally has splitting tensile strength ranging from (7% to 11%)[32].

For the same compressive strength in this work, the splitting tensile strength of (LWAC) is about (75%) of that for (NWC), Table (17). Generally, the splitting tensile strength of all-light weight concrete varies from approximately 70 to 100 percent from that of normal weight concrete. Comparisons are made at equal compressive strength[10]. Again the results of splitting tensile strength obtained throughout this study, satisfy the requirements of ASTM C330-87 section 5.2.1.[11].

3.3 Modulus of Rupture

Table (18) shows the values of experimental modulus of rupture compared with those by Evans and Hardwick[13] , and Slate et al[6] Zhang and Gjorv[12] , ACI 318 M-02 Building Code[46]. The results have good agreement with Eq.(A2) by Slate, et al. and Eq.(A4) by ACI 318M-02 code. The equations give underestimated values ranging about (0-15%), but they are unconservative for predicting the values of (f_r) for the compressive strengths of the lower values which are (23 and 24.3) Mpa. The results indicate the increase in the compressive strength from 23.0 to 29.8 Mpa (30%) leads to an increase in the modulus of rupture from 2.5 to 3.42 Mpa (37%). This means that the modulus of rupture is sensitive to the increase in concrete strength. The values of modulus of rupture are about (11% to 12%) of compressive strength. For (NWC), the (fr) results estimated by Eq. (A5) of ACI-02 code, are close to the experimental values. The experimental results are about (12% to 13%) of its compressive strength.

Fig.(4) shows the relationship between(fr) of porcelinite concrete and its compressive strength.

$$Fr = 0.584\sqrt{f'_c} \quad \text{-----(3)}$$

$R^2 = 0.996$
This equation is close to equation (A5) by ACI 318M -02.

3.4 Modulus of Elasticity

Table (4) shows values of modulus of elasticity for various strength values of porcelinite concrete ranging from (23.0-29.8)Mpa and the comparison between the measured and predicted values of modulus of elasticity using the formulas adopted by Zhang and Gjrov[12] of A10 , ACI 318 M-02 of Eq. (A11) and Al-Musawi equation[8]. The modulus of elasticity for (NWC) also is measured and compared with ACI 318-02[14], Eq. (A12). The results of modulus of elasticity for (NWC) with (LWC) can be also compared. It seems evident that there is a relation between the modulus of elasticity and both, compressive strength and density of porcelinite concrete for this work. It is found that when there is an increase in compressive strength and density simultaneously, the modulus of elasticity increases. In Table (19), the modulus of elasticity for porcelinite concrete increases from (12100 to 17100)Mpa (40%) with the increase in compressive strength from (23 to 29.8)Mpa (30%). By comparing the values of modulus of elasticity for porcelinite concrete and (NWC) at the same compressive strength (approximately) , it is found that the values of modulus of elasticity for (LWA) are less than that of (NWA) by about 50%.

Eqs. (A10) by Zhang and Gjrov[12] , gives underestimated values for modulus of elasticity , where the percent differences are between (8% and 30%). Eq. (A11) by ACI 318-02 gives the overestimated values of elastic modulus for all values of concrete strengths, Percent differences are between (14% - 26%).

Al-Musawi (A9) gives overestimated values of elastic modulus for (LWAC) compressive strengths ranging from (23 to 27.2) Mpa, percent differences are from (1% to 14%), while for ($f'c$) (28.3 and 29.8) Mpa the measured elastic modulus are (9%) more than the predicted (underestimated).

Eq. (A12) gives good agreement between measured and predicted elastic modulus values for (NWC). The percent differences were (6.5% average value),

The conclusion that can be obtained is that the porcelinite aggregate concrete which gives the elastic modulus of elasticity ranging between (12100 and 17100) Mpa, are within the ranges of values for elastic modulus for various concrete mixes of (LWAC).

In the above figure the compressive strengths are from (50-100)Mpa (high strength) which have the elastic modulus values between (12000 and 25000) Mpa. Also the results meet the requirements of reference[10].This means that the porcelinite aggregate concrete is an acceptable and appropriate structural material. Fig.(4) shows the relationship between elastic modulus and compressive strength for porcelinite concrete. An empirical formula is proposed for calculating the elastic modulus of porcelinite aggregate concretes as follows:

$$Ec = 2800\sqrt{f'_c} \qquad \text{-----(4)}$$

$R^2 = 0.997$

When comparing the above formula with the formula of Ec for (NWC) in reference[46] Ec $= 4700\sqrt{f'_c}$ }, it is clear that the (Ec) of porcelinite (LWAC) is approximately equal to 60% of that for (NWC).

3.5 Total Absorption

Test results indicate that all types of (LWAC) have an **a**bsorption value smaller than 10% by weight, which is the maximum acceptable limit [5]. These desirable results may be attributed to the production of high quality mortar matrix that enclosed the porous coarse (LWA) particles, thus reduce the absorption ability. The absorption is decreased with the increase in the cement contents. The absorption values range between

(8.58% and 4.75%) while compressive strength of porcelinite concrete ranges between (23Mpa and 29.8Mpa). For (NWC), the absorption ranges between (4.50% and 4.25%) for compressive strength it ranges from (25.14Mpa to 27.2Mpa). Experimentally, it is clear that the absorption of (LWAC) is more than the absorption of (NWC) for the same strength approximately. The details are shown in the Table (16).

Table (1) Groups of light weight concrete.[1]

No – fines Concrete	Light weight aggregate concrete	Aerated concrete	
		Chemical aerating	Foaming mixture
(a) Gravel	(a) Clinker	(a)Aluminum powder method	(a)Preformed foam
(b) Crushed stone	(b) Foamed slag	(b) Hydrogen peroxide and bleaching powder method	(b)Air-entrained foam
ICoarse clinker	I Expanded clay		
(d)Sintered pulverized fuel ash	(d)Expanded shale		
(e)Expanded clay or shale	(e) Expanded slate		
(f)Expanded slate	(f)Sintered pulverized fuel ash		
(g) Foamed slag	(g)Exfoliated vermiculite		
	(h)Expanded perlite		
	(i) Pumice		
	(j)Organic aggregate		

Table (2) Classification of light weight concrete (RILEM 1978)[4,11]

Property	Class and Type		
	I	II	III
	Structural	Structural Insulating	Insulating
Compressive strength (Mpa)	>15	>3.5	>0.5
Coefficient of thermal conductivity (W/mK)	-	<0.75	<0.30
Approximate density range(kg/m^3)	1600-2000	<1600	<<1450

Table (3) Chemical composition of porcelinite rocks[5,20]

Oxide	%by weight
SiO_2	68.6
CaO	9.25
Al_2O_3	3.38
MgO	3.12
SO_3	0.34
P_2O_5	2.39
L.O.I.	12.61

Table (4) Range and average of mineral composition of porcelinite rock[5, 20]

Mineral	Range	Average
Opal-CT	**17-74**	**43.2**
Quartz	**1-12**	**5.4**
Calcite	**1-12**	**4.6**
Dolomite	**1-44**	**19.8**
Gypsum	**0-3**	**0.8**
Halite	**0-2**	**0.4**
Apatite	**1-12**	**5.0**
Clay	**4-34**	**10.9**

Table (5) Chemical oxide composition and components of Ordinary Portland cement cement

Chemical analysis	Test results percentage By weight	Limits of Iraqi specification No.5/1984[18]
CaO	61.54	
SiO_2	21.70	
MgO	2.71	5% (maximum)
SO_3	2.46	2.8(maximum)
Fe_2O_3	3.18	
Al_2O_3	5.30	
Loss of Ignition	2.2	4%(maximum)
Insoluble Residue	0.5	1.5%(maximum)
Lime saturation factor	0.68	0.66-1.02
Main compounds (Bogue's equation)		
C_3S	38.38	

C_2S	31.59	
C_3A	8.66	
C_4AF	8.87	

*The test was carried out at the falluja cement factory.

Table (6) Physical properties of cement used

Physical properties	Test results	Limits of Iraqi specification No.5/1984[18]
Fineness by Blain method cm^2/gm	**4000**	**2300 (minimum)**
Autoclave expansion %	**0.17**	**0.8 (maximum)**
Setting time (vicat apparatus)		
-Initial setting (min.)	**150**	**45 (minimum)**
-Final setting (min.)	**225**	**600 (maximum)**
Compressive strength for cement-mortar cube at:		
-3 days (Mpa)	**22.1**	**15 (minimum)**
-7 days (Mpa)	**32.3**	**23 (minimum)**

Table (7) Chemical and Physical properties of sand

Property	Specification	Results	Limit of Iraqi specification No.45/1984[20]
Bulk specific gravity	**ASTM C128-88[28]**	**2.55**	**-**
Absorption %	**ASTM C128-88**	**2.1**	**-**
Dry loose unit weight (kg/m^3)	**ASTM C29-89[29]**	**1600**	**-**

Sulphate content (SO_3)%	**I.O.S No.45-84**	**0.14**	**0.5 (max.)**
Material finer than 0.075 mm sieve %	**BS. 882-1965[19]**	**0.7**	**5.0 (max.)**

*The test was carried out at the laboratory al-anbar University.

Table (8) Grading of sand according to BS- 882-1992[107]

Sieve size (mm)	%Passing	B.S 882-1965 specification Limits % passing (zone1)
4.750	91	90-100
2.360	70	60-90
1.18	59	30-70
0.6	34	13-34
0.3	13	5-20
0.15	3	0-10

Fineness modulus = 4.3

Table (9) Physical properties of porcelinite aggregate

Property	Specification	Results
Specific gravity	ASTM C127-84[30]	1.6
Absorption %	ASTM C127-84	37.2
Dry loose unit weight (kg/m^3)	ASTM C29-87[29]	802*
Dry rodded unit weight, (kg/m^3)	ASTM C29-87[29]	838
Aggregate crushing value%	BS812-part110-1990[120]	17

*With in the limit of ASTM C330 (880kg/m^3).
#Tests were carried out by the stat company of geological survey and mining (SCGSM).

Table (10) Chemical analysis of porcelinite aggregate

Oxides	% By weight
SiO_2	69.77
Fe_2O_3	1.48
Al_2O_3	2.78
TiO_2	0.14
CaO	6.52
MgO	5.7
SO_3	0.15
L.O.I	11.45

#Tests were carried out by the SCGSM.

Table (11) Mineral analysis of porcelinite aggregate

Compound	% By weight
Opal-Ct	56
Quartz	3
Dolomite	11
Apatite	4
Clay	25

Table (12) Grading of porcelinite coarse aggregate

Sieve size (mm)	% Passing ASTM C330-87[11]	Coarse aggregate% passing
12.5	100	100
9.5	80-100	84.3
4.75	5-40	33.5
2.36	0-20	10.7
1.18	0-10	0.72

Table (13) Selected grading of coarse normal aggregate

Sieve size (mm)	% Passing Normal aggregate	BS 883-1992 % passing (zone 3) (cited by ref. 5)
20	100	100
10	79.9	85-40
5	9.14	0-10

Table (14) Properties of superplasticizer [21]

Properties	Description
Main action	Concrete super plasticizer
Appearance	Clear turbid liquid
Specific gravity	1.1 at 25°c
Air entrainment	Nil
Chloride content	Nil
Nitrate content	Nil
Handling	No special precautions
Freezing point	0°c. Can be reconstituted if stirred after thawing
Storage life	Shelf life is up to 2 years when stored under cover, out of direct sunlight and protected from extremes of tempreature

Table (15) Mix proportions for (LWAC)

No.		Quantities Kg/m^3			w/c	Sp.% wt. of cements	Density kg/m^3	$f'c$ (Mpa) at 28days	Slump (mm)
		Cement	Natural Sand	Crushed porcelinite					
LWAC	1	550	500	520	0.40	2	1755	23.8	110
	2	550	500	520	0.36	2	1760	24.3	90
	3	550	500	520	0.32	2	1820	26.5	80
	4	550	500	520	0.44	2	1745	20.9	130
	5	550	500	520	0.42	2	1747	23.3	125
	6	600	600	500	0.30	2	1810	28.3	65
	7	650	600	440	0.30	2	1815	29.03	60
NWC	8	350	865	960	0.40	-	2314	25.6	150
	9	400	840	960	0.50	-	2338	25.0	115

Table (16) Measured unit weight, absorption values of different porcelinite concrete strength levels

Mix No.		Beams used	$f'c$ Mpa	Unit weight, kg/m^3		Absorption %
				Fresh	Hardened	
LWAC	1	B1,B2,B3	25.5	1981	1760	8.00
	2	B4	26.7	1985	1772	7.02

	3	B5	27.2	2044	1820	6.72
	4	B6	23.0	1977	1745	8.58
	5	B7	24.3	1980	1751	8.30
	6	B8	28.3	2075	1848	5.00
	7	B9	29.8	2144	1855	4.75
NWC	8	B10	27.2	2412	2360	4.50
	8	B11	25.7	2412	2346	4.35
	9	B12	25.14	2405	2340	4.25

Mix No.		f'_c Mpa	Splitting tensile strength, ft , (Mpa)								$f_{t\cdot M}$ / f'_c
			Measured (Mpa)	Predicted values of (f_t)							
				A7		A6		A8			
				f_t Mpa	$f_{t.M}/f_{t\cdot E}$	f_t Mpa	$f_{t.M}/f_{t.E}$	f_t MPa	$f_{t.M}/f_{t\cdot E}$		
LWAC	1	25.5	2.5	2.07	1.20	2.32	1.07	2.27	1.10		0.098
	2	26.7	2.58	2.11	1.20	2.37	1.09	2.34	1.10		0.096
	3	27.2	2.65	2.13	1.24	2.39	1.11	2.37	1.11		0.097
	4	23.0	2.2	1.96	1.12	2.20	1.00	2.12	1.04		0.096
	5	24.3	2.4	2.02	1.18	2.26	1.06	2.20	1.09		0.098
	6	28.3	2.75	2.18	1.26	2.45	1.12	2.44	1.12		0.097
	7	29.8	2.80	2.23	1.25	2.51	1.115	2.52	1.11		0.097
NWC	8	27.2	3.8	-	-	-	-	-	-		0.13
	9	24.14	3.0	-	-	-	-	-	-		0.11

Table (17) Measured and predicted values of splitting tensile strength of porcelinite concrete and of Normal concrete:

$f_{t\cdot M}$ = Measured value.
$f_{t\cdot E}$ = Estimated value.

Table (18) Comparison between measured and predicted values of modulus of rupture for different porcelinite concrete strength and for different normal concrete strength levels.

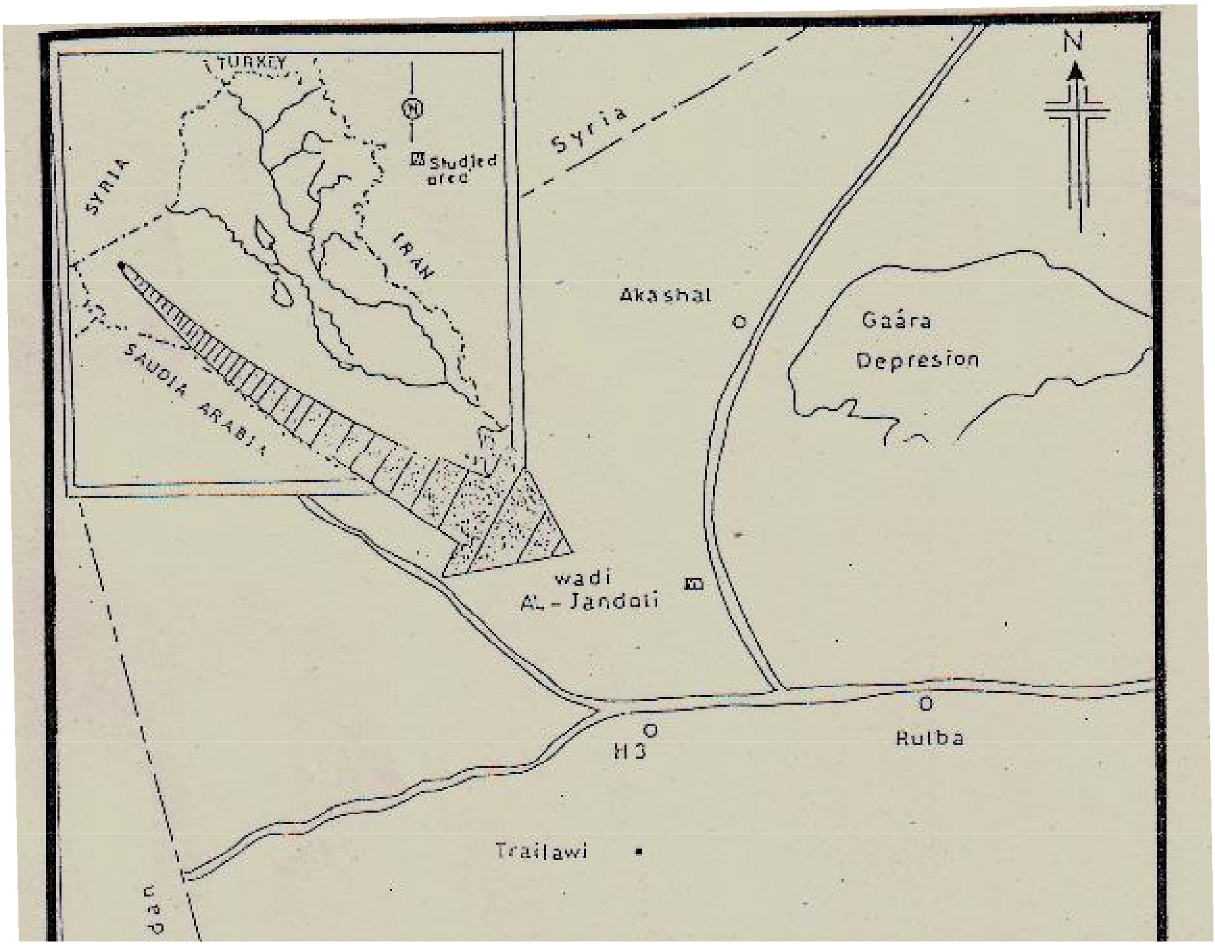
Mix. No.		f'_c MPa	Modulus of rupture f_r (MPa)												
			Measure d (MPa)	Predicted values of (f_r)										
				A1		A2		A3		A5		A4		
				f_r MPa	$f_{r\cdot M}/f_{r\cdot E}$	f_r MPa	$f_{r\cdot M}/f_{r\cdot E}$	f_r MPa	$f_{r\cdot M}/f_{r\cdot E}$	f_r MPa	$f_{r\cdot M}/f_{r\cdot E}$	f_r MPa	$f_{r\cdot M}/f_{r\cdot E}$	$F_{r\cdot M}/f'_c$
LWAC	1	25.5	2.9	3.7	0.78	2.74	1.06	4.0	0.73	3.0	0.96	-	-	0.11
	2	26.70	3.04	3.79	0.80	2.81	1.08	4.13	0.74	3.01	1.01	-	-	0.114
	3	27.20	3.15	3.80	0.83	2.84	1.1	4.17	0.76	3.11	1.02	-	-	0.116
	4	23.0	2.48	3.5	0.71	2.60	0.95	3.8	0.65	2.80	0.89	-	-	0.11
	5	24.3	2.70	3.60	0.75	2.70	1.0	3.90	0.70	2.90	0.93	-	-	0.11
	6	28.3	3.375	3.90	0.86	2.89	1.17	4.25	0.79	3.16	1.07	-	-	0.12
	7	29.8	3.42	4.0	0.86	2.97	1.15	4.36	0.78	3.24	1.06	-	-	0.115
NWC	8	27.2	3.60	-	-	-	-	-	-	-	-	3.60	1	0.13
	9	25.14	3.06	-	-	-	-	-	-	-	-	3.50	0.90	0.12

Table (19) Comparison between measured and predicted values of modulus of elasticity

		Modulus of elasticity Ec, (MPa)				
			Predicted values of (E_c)			
			A10	A11	Al-Musawi Eq. $E_c=2900(f'_c)^{0.5}$	A12 For (NWC)

				E_c (MP	$E_{c\cdot M}$/ $E_{c\cdot E}$	E_c (MPa)	$E_{c\cdot M}$/ $E_{c\cdot E}$	E_c (MPa)	$E_{c\cdot M}$/ $E_{c\cdot E}$	E_c (MPa)	$E_{c\cdot M}$/ $E_{c\cdot E}$
LWAC	1	25.5	13000	11778	1.1	17278	0.75	14644	0.89	-	
	2	26.70	14400	12147	1.18	17895	0.80	14984	0.96	-	
	3	27.20	15100	12299	1.20	18793	0.80	15124	0.99	-	
	4	23.0	12100	10992	1.10	16210	0.75	13907	0.87	-	
	5	24.3	12330	11404	1.08	16770	0.74	14295	0.86	-	
	6	28.3	16870	12779	1.30	19622	0.86	15427	1.09	-	
	7	29.8	17100	13075	1.30	20228	0.85	15830	1.08	-	
NWC	8	25.7	25464	-	-	-	-	-		23826	1.07
	9	25.14	24990	-	-	-	-	-		23565	1.06
		Mean			1.11		0.75		0.91		1.065
		COV			0.1183		0.0816		0.1342		0.0066

$E_{c\cdot M}$ = Measured value.
$E_{c\cdot E}$ = Estimated value.



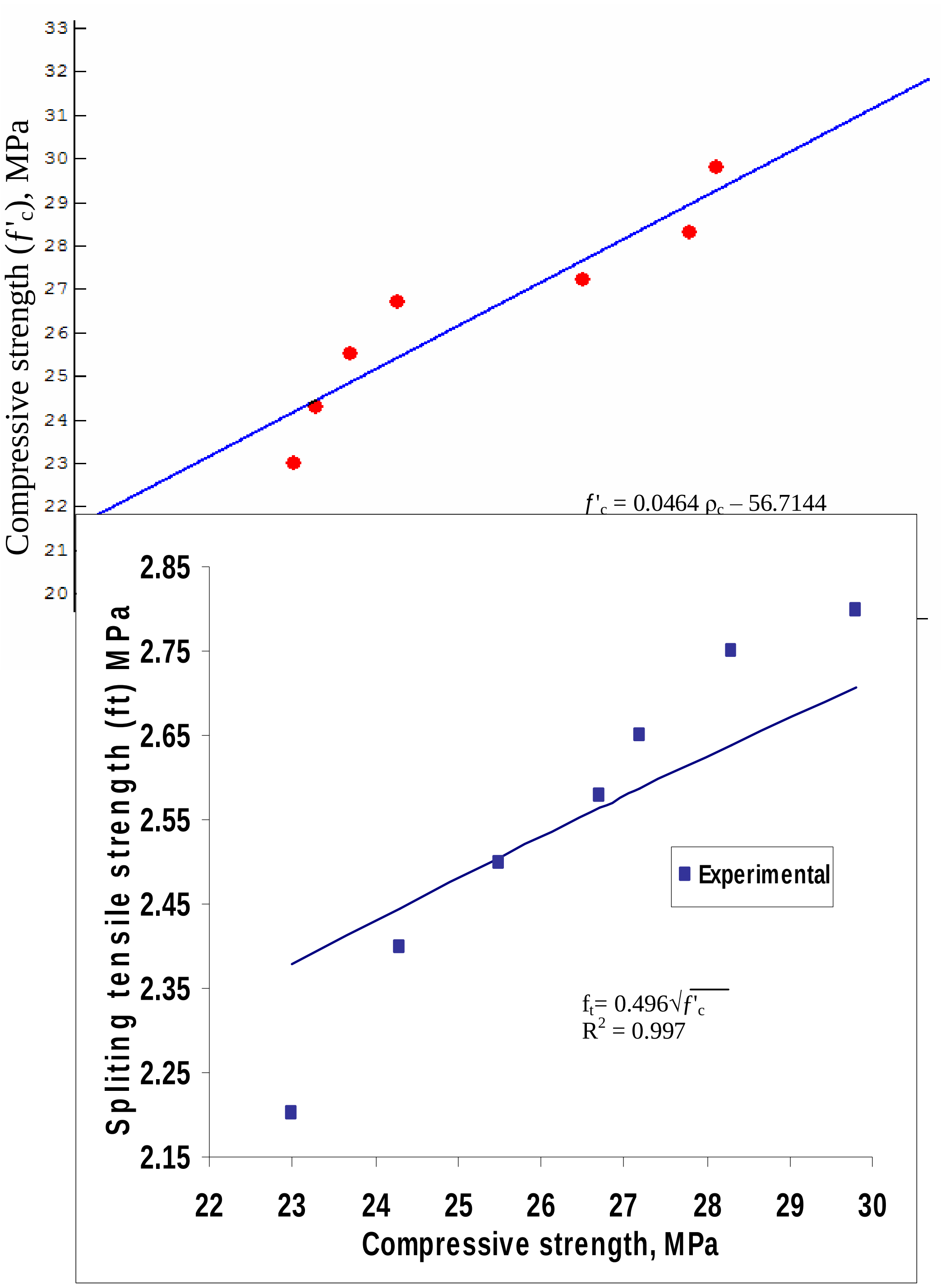


Fig. (3) Relationship between concrete compressive strength and splitting tensile strength for porcelinite concrete

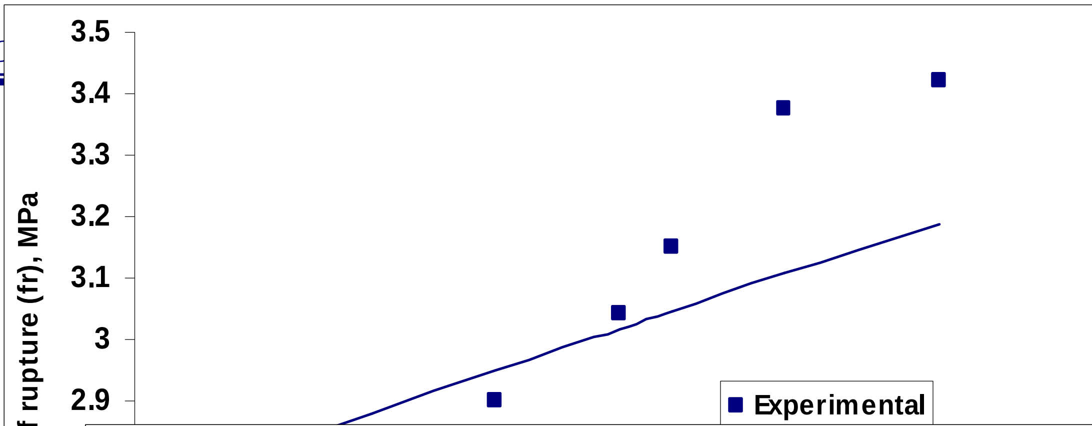


Fig.

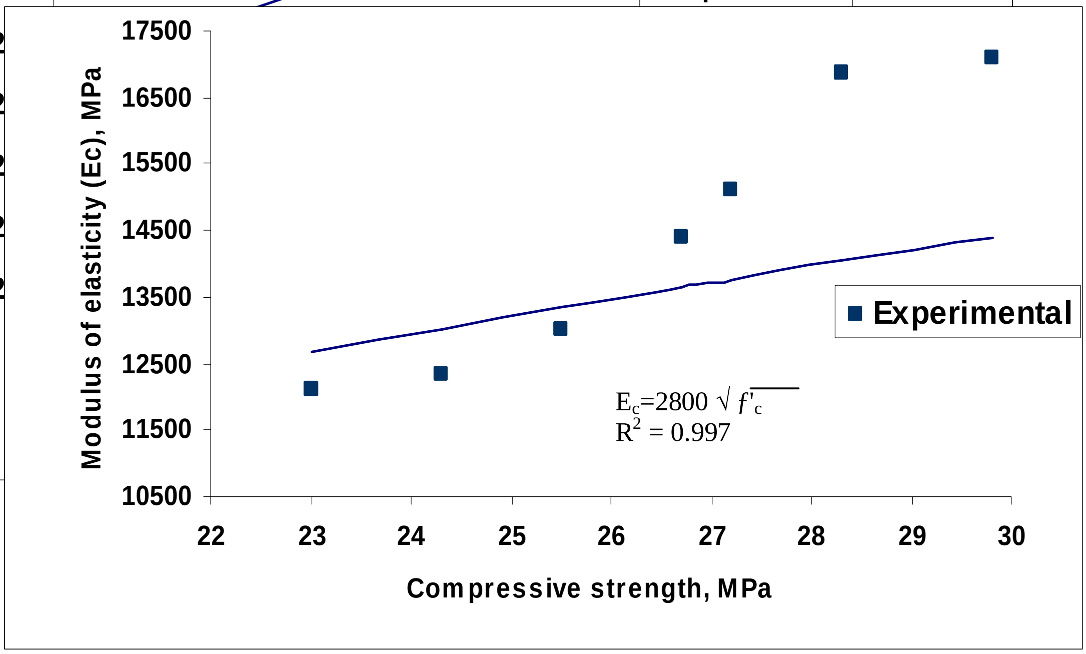
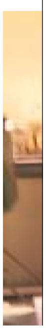


Fig. (5) Relationship between concrete compressive strength and modulus of elasticity for porcelinite aggregate concrete.



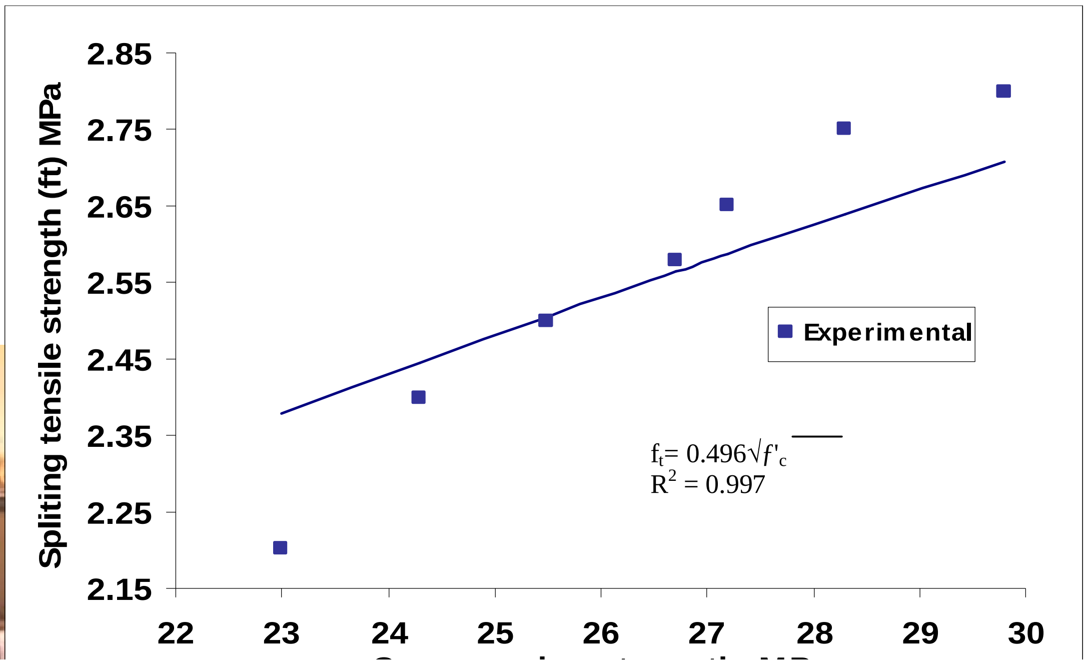


Plate (2) Compressive test machine

Plate (3) Flexural test machine

Conclusions

*Structural light weight aggregate concrete (SLWAC) produced from locally available porcelinite aggregate conforms to the requirements of class I structural (LWAC) according to RILEM classification which is adopted by CEB-FIP manual with regard to compressive strength and unit weight. In this study a compressive strength ranging between (23 and 29.8) MPa has been obtained with unit weight between (1745-1855) kg/m^3. Such concrete was obtained to be suitable for cast-in-situ reinforced concrete.

*With the dosage of superplasticizer (about 2% wt. of cement) and with cement content of (550 , 600 , 650) kg/m^3 , natural sand content of 500 kg/m^3 and porcelinite aggregate content of (520 , 500 , 440) kg/m^3 , it is possible to produce (SLWAC) of 28days cylindrical compressive strength more than 17 MPa. This (LWAC) presents a reduction in density from normal weight concrete between (21% and 26%) and therefore there is an advantage in this country where soil bearing capacity is low in most construction sites.

*All mixes of porcelinite (LWAC) have absorption values less than 10% by weight, which is considered as a maximum limit[5,123]. The absorption of porcelinite (LWAC) shows a decrease with the increase in the density. The absorption values reduce from (8.6%-4.6%) for increasing in density from (1745 to 1855) kg/m^3.

*The compressive strength of porcelinite (LWAC) is affected significantly by the amount of w/c ratio. It increases from (23 to 29.8) MPa due to the decreasing of w/c ratio from (0.44 to 0.32). It is observed that the compressive strength increases due to the increasing of cement content. There is simple increase in compressive strength (28.3 to 29.8) MPa when the cement content increases from (600 to 650) kg/m^3.

*From testes in this work a relationship between compressive strength (cylinder specimen) and density of concrete is suggested as an empirical formula.

$f'_c = 0.0464\rho_c - 56.714$ ------(5)

*Porcelinite (LWAC) gives splitting tensile strength values more than that of predicted equations. It gives average values about (10%, 20%) higher than the predicted values. The splitting tensile strength is about (9.6% to 9.8%) of compressive strength (23 to 29.8) MPa. It increases slightly with the increase of the compressive strength. The following equation is adopted to predict the splitting tensile strength.

$ft=0.496\sqrt{f'_c}$ ------(6)

(NWC) exhibits more values of splitting tensile strength than that of (LWAC) by about 25% for the same compressive strength.

*The measured values of modulus of rupture increase with the increase of compressive strength. When compressive strength increases from (23 to 29.8) MPa, exhibits increase in modulus of rupture from (2.48 to 3.42) MPa. ACI 318-02 A5 and Eq. (2-2) by slate, et al. are good for estimating the (f_r) of porcelinite (LWAC). From the test results, an empirical equation is proposed, which is more close to A5 as follows:

$fr = 0.585\sqrt{f'_c}$ -----(7)

(NWC) exhibits modulus of rupture values slightly more than that of (LWAC) for the same compressive strength. (fr) of (LWAC) is about (11%) of its compressive strength according to the results of this study.

*The measured values of elastic modulus for porcelinite (LWAC) ranged between (12100 and 17100) MPa for compressive strengths ranging between (23 and 29.8) MPa, with its density ranging (1745 to 1855) kg/m^3. It is clear that the Ec of (LWAC) is proportional with ($f'c$) and (ρ_c) simultaneously. A10 by Zhang and Gjorv gives safety estimation for predicting values of (Ec) for porcelinite

(LWAC), (8%-30% underestimating) . Modulus of elasticity for (LWAC) in this study is less than that of (NWC) by about 50%. An empirical equation is detected to predict the elastic modulus for porcelinite (LWAC):

Ec -----(8)

When comparing the above formula with formula of modulus of elasticity for (NWC) (Ec $= 4700\sqrt{f'_c}$) by ACI 318M-02 code, it is clear that the Ec of (LWAC) in this study equals 60% of that of (NWC).

References

1-Shetty, M.S. “Concrete Technology” , S.chand and company (PVT) ltd, New Delhi, 3rd edition (reprinted), 1989, pp. 502-517.

2-Short, A., and Kinniburgh, W., “Light Weight Concrete”, CR Books ltd. 3rd Edition, 1978, 442 pp.

3-Neville, A.M. “Properties of Concrete”, 3rd Edition, UK 1981, 779 pp.

4-Newman, J. and Choo, B.S. (2003) “Advanced Concrete Technology”, 1st Edition, London, part (2), pp. 2/9-2/25.

5-Al-Musawi, J.M., “Flexure Behavior of Porcelinite Reinforced Concrete Beams”, Doctor Philosophy Thesis, University of Technology, November 2004, 189 pp.

6-Slate, F.O., Nilson A.H., and Martinez, “Mechanical Properties of High-Strength Light Weight Concrete”, ACF Journal, Proceeding V.83, No.4, July, August 1986, pp. 606-613.

7-RILEM (1978) Functional Classification of Light Weight Concrete Recommendation LC2., 2nd Edition.

8 -التقرير الفني حول بدالة الأعظمية - بغداد – مكتب الاستشارات الهندسية ، كلية الهندسة ، جامعة بغداد – نيسان 1990.

9-Al-Jabbory, W.M., “Mining Geology of Porcelinite Deposits in - Jandali-Western Desert, Iraq”, M.Sc. Thesis, University of Baghdad, October 1999, 100 pp.

10-ACI Committee 213, “Guide for Structural Light Weight Aggregate Concrete”, American Concrete Insitute, 1987, 24pp.

11- ASTM C330-87, “Standard Specification for Light Weight Aggregates for Structural Concrete”, Annual Book of ASTM Standards, Vol. 04-02, 1988, pp. 187-189.

12- Zhang, M.H., and Gjorv, O.E., “Mechanical Properties of High-Strength Light Weight Concrete”, ACI Materials Jornal, Vol.88, No.3, May-June 1991, pp. 240-247.

13- Evans, R.H., and Hardwick, T.R. “Light Weight Concrete with Sintered Clay Aggregate”, Reinforced Concrete Review, 5(6), 1960.

14- ACI Committee 318, “Building Code Requirements for Structural Concrete (318M-02) and Commentary (318RM-02)” American Concrete Institute, 2002, 443 pp.

15-ASTM Designation C78-1984, “Flexural Strength of Concrete Using Simple Beam With-Third Point Loading”, Annual Book of ASTM Standards, Philadelphia, 1988. Vol.04-02, pp. 31-33.

16-ASTM C496-86, “Splitting Tensile Strength of Cylindrical Concrete Specimens”, Annual Book of ASTM Standards, 1988, pp. 256-259.

17-ASTM C150-86, “Standard Specification for Portland Cement” Annual Book of ASTM Standards, Vol.04.02, 1988, pp. 89-93.

18-المواصفة القياسية العراقية (I.O.S) رقم (5) لسنة 1984 ، السمنت البورتلاندي ، الجهاز المركزي للتقييس والسيطرة النوعية ، بغداد ، 8 صفحات.

19-BS 882, 1965 “specification for Aggregate from Natural Sources for Concrete”, British Standards Institution 98 pp.

20- المواصفة القياسية العراقية (I.O.S) رقم (45) لسنة 1984 "ركام المصادر الطبيعية المستعمل في الخرسانة والبناء" ، الجهاز المركزي للتقييس والسيطرة النوعية ، بغداد ، 4 صفحات.

21-RHEOBUILD 2000M, "A High Range Melamine Based Superplasticiser", Construction Engineering Group, Construction, Chemical and Maitenance, Baghdad,Al-Harthiya-Kendy St., pp. 71-73.

22-ACI Committee 211, Recommended Practice for Selecting Proportions for normal and heavy Weight Concrete (ACI 211, 1-77), *j. Amer. C0ncr. Inst.*,66,No.8, pp.612-29(1969); 70, No. 4, pp.577-8 (1974); 74, No. 2 pp. 59-60 (1977).

23-ASTM C143-78, "Standard Test Methods for Slump of Portland Cement Concrete", Annual Book of ASTM Standards, Vol. 04-02, 1988, pp. 85-88.

24-ASTM C567-85, "Standard Test Method for Unit Weight of Structural Light Weight Concrete", Annual Book of ASTM Standards, Vol. 04-02, 1988, pp. 272-274.

25-BS 1881, Part 122, 1989, Methods for Determination of Water Absorption, British Standards Institution, 2 pp.

26-ASTM C39-86, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens", Annual Book of ASTM Standards, Vol. 04-02, 1988, pp. 19-23.

27-ASTM C 469-87, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression", Annual Book of ASTM Standards, Vol.04-02, 1988, pp. 233-236.

28-ASTM C128-84, "Standard Test Method for Specific Gravity and Absorption of Fine Aggregate", Annual Book of ASTM Standards, Vol.04-02, 1988, pp. 69-72.

29-ASTM C29-87, "Standard Test Method for Unit Weight and Voids in Aggregate", Annual Book of ASTM Standards, Vol.04-02, 1988, pp. 1-3.

30-ASTM C127-84, "Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate", Annual Book of ASTM Standards, Vol.04-02, 1988, pp. 64-68.

31-Back, H.H., and Nepper, Christensen, P., "Observation on Strength and Fracture in Light Weight and Ordinary Concrete", The Structure of Concrete, Proceedings of International Conference London, Sep. 1965 Cement and Concrete Association, 1968, pp. 93-108.

32 - جلال بشير سرسم ، "تكنولوجيا الخرسانة" ، 1984 ، الطبعة الأولى ، دار التقني للطباعه والنشر،مؤسسة المعاهد الفنيه، الصفحات 149-152 .

Appendix A

$$fr = 0.67\,(f_{ck})^{0.5} \qquad \text{------ (A1)}$$

Where:

fr = modulus of rupture , MPa

f_{ck} = compressive strength for 100mm cube, (MPa)

$$fr = 0.544\,(f'_{c})^{0.5} \qquad \text{------ (A2)}$$

Where:

$f'c$ = compressive strength (152x305) mm cylinder, (MPa).

$$fr = 0.73\,(f_{ck})^{0.5} \qquad \text{------ (A3)}$$

$$fr = 0.7\,(fc)^{0.5} \qquad \text{------ (A4)}$$

$fr = 0.595\ (f c)^{0.5}$ ------ (A5)

$ft = 0.42\ (f c)^{0.5}$ ------ (A6)

Where:

ft = splitting tensile strength ,MPa.

$f$ck = compressive strength for 100mm cube , MPa

$ft = 0.41\ (f c)^{0.5}$ ------ (A7)

$ft = 0.23(f c)^{0.67}$ ----- (A8)

$E_c = (3320)\ (f_c)^{0.5} + (6895)\ (\rho_c /2320)^{1.5}$ $21 < f_c < 62$MPa ---(A9)

$Ec = 0.043\ (f_c\, \rho_c^{3})^{0.5}$ ------(A10)

$Ec = 4700\ (f_c)^{0}$ -----(A11)

$E_{c\,=}\ 2900\ (f'_c)^{0.5}$ ------(A12)