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Compressive Strength of Lightweight Porcelanite Aggregate Concrete -New Formulas

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ABSTRACT

From the various kinds of concrete, lightweight concrete (LWC) is one of the most interesting subjects for researchers because of its advantages such as the savings in concrete member size, reinforcement, formwork and scaffolding , foundation costs as well as the savings derived from the reduced cost of transport and erection. The reduction of dead load due to a lower density of concrete allows for smaller and lighterweight structural members. Reductions in the dimensions of columns and beams result in more available space, and reductions in their selfweight can improve the seismic resistance capacity of building structures. Furthermore, better fire resistance, heat insulation, sound absorption, frost resistance, and increased damping are other advantages of lightweight concrete. Lightweight aggregate concrete (LWAC) is not new in concrete technology; it has been used since ancient times. The fact that some of these structures are still in good condition validates the durability of concrete. The paper presents the results of testing 30 specimens (15 cylinders and 15 cubes) according to ASTM for determining the mechanical properties of sand lightweight aggregate concrete (SLWAC)made from Porcelanite (as a natural local material). The paper further presents new empirical predicted formulas for cylinder compressive strength, cube compressive strength; and relationship between them.

Keywords: Lightweight Concrete, Porcelanite, Cylinder Compressive Strength, Cube Compressive Strength, Cylinder-Cube Compressive Strength Relationship.

مقاومة إنضغاط خرسانة البورسيلانايت خفيفة الوزن – معادلات جديدة

الخلاصة

من بين ألانواع المختلفه من الخرسانه تعتبرالخرسانه خفيفة الوزن(LWC) من أكثر المهمة المواضيع إثاره للاهتمام للباحثين بسبب مزاياها مثل التوفير في كمية خرسانة الصب، حديد التسليح, قالب الصب، وتكاليف الأساس، فضلا عن التوفير المستمد من انخفاض تكلفة النقل والإنشاء. التقليل من الحمل الميت نتيجة لانخفاض كثافة الخرسانه تسمح بتقليل أبعاد مقاطع الأعضاء الهيكليه. نتيجة إجراء هذه التخفيضات في أبعاد الأعمده والعتبات سوف يوفر المزيد من الحيز المتاح، وتحسين

قدرة مقاومة الزلازل لهياكل المنشأ .وعلاوه على ذلك، تحسين مقاومة الحريق، العزل الحراري، وامتصاص الصوت، ومقاومة الصقيع، وكذلك زيادة التخميد التي تعتبر من المزايا الأخرى للخرسانة خفيفة الوزن .والخرسانة خفيفة الوزن (LWAC) ليست جديده في مجال تكنولوجيا الخرسانه، إلا أنها استخدمت منذ القدم .من المعلوم أن بعض هذه الهياكل الخرسانيه لا تزال في حالة جيده من سلامة وقوة التحمل مع مرور الزمن. يقدم البحث نتائج اختبار 30 عينه خرسانيه تتضمن (15 اسطوانه و 15 مكعب) وفقا للمواصفات الاميركيه لفحص المواد ASTM لتحديد الخواص الميكانيكية للخرسانه خفيفة الوزن (SLWAC) مصنوعه من البورسيلانايت (صخور طبيعية محلية). كذلك يعرض البحث الصيغ الجديده التجريبيه لتوقع مقاومة انضغاط, عينة الاسطوانة, مقاومة انضغاط عينة المكعب والعلاقة بينهما.

Notation

f_c' = Cylinder compressive strength of concrete, MPa.
f_{cu} = Cube compressive strength of concrete, MPa.
HSC = High-strength concrete
LSC = Low-strength concrete
MSC = Medium-strength concrete
LWC = Lightweight concrete
LWAC = Lightweight aggregate concrete
SLWAC = Sand Lightweight aggregate concrete
w_c = Density of concrete, kg/m^3

INTRODUCTION

There are several structural advantages for using lightweight concrete (LWC) as a building material. The reduction of dead load due to a lower density of concrete allows for smaller and lighter-weight structural members. Reductions in the dimensions of columns and beams result in more available space, and reductions in their self-weight can improve the seismic resistance capacity of building structures. Furthermore, the smaller and lighter elements of precast concrete members are preferred because the handling and transporting system becomes less expensive, and offshore structures mostly used for oil production require LWC elements to provide easier towing and greater buoyancy. One prominent example of this is Norwegian oil platform experience. Lightweight aggregate concrete in addition provides better heat insulation and is more resistant to fire than concrete of normal density. As a result, there has been a growing interest in the practical application of LWC for structural members.

Lightweight Concrete is considered as having a density not exceeding 1920 kg/m^3, while normal density concrete is considered to have the usual density ranging from 2240 to 2480 kg/m^3 [1]. Lightweight concrete has a minimum 28-day cylinder compressive strength of 17.0 MPa. When the compressive strength ranges from 17 to 27 MPa, the concrete is defined as low- strength concrete (LSC). For compressive strength ranging from 27 to 41 MPa lightweight concrete is classified as medium-strength concrete (MSC). However, for compressive strength greater than 41 MPa the lightweight concrete is classified as high-strength concrete (HSC)[2]. Recent researches [3-12] have shown that there is an abundant supply of lightweight rocks that may be used to produce concrete of lower density than the present practice in this country. The aggregate, which is used, is quarried from rocks discovered in the Iraqi Western Desert. It is called Porcelanite [13]. Figure 1, shows the location of Porcelanite rocks.

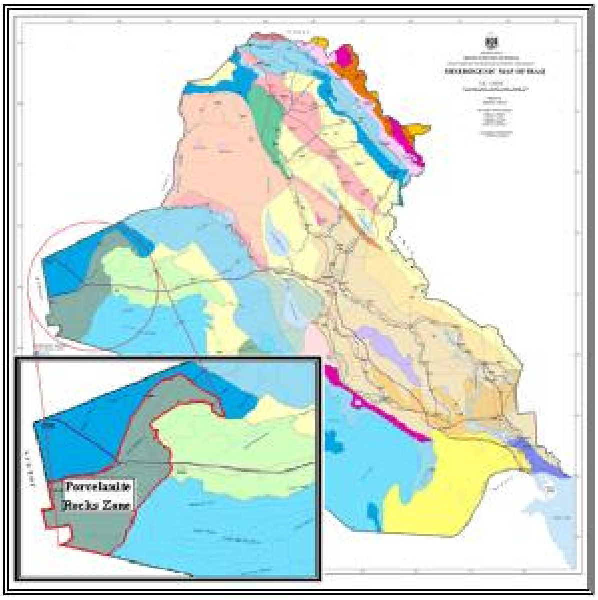

Figure (1) Map of Porcelanite rocks zone location. State Company of Geological Survey and Mining, Ministry of Industry and Minerals, Baghdad-IRAQ.

RESEARCH SIGNIFICANCE

In concrete construction, selfweight represents very large proportions of the total load on the structure, and there are clearly considerable advantages in reducing the density of concrete. As a result of this weight reduction, smaller sections are obtained with corresponding reduction in the size of foundations. With lightweight concrete (LWC) the formwork needs to withstand a lower pressure than would be the case with normalweight concrete (NWC). Also, the total weight of material to be handled is reduced with a consequent increase in productivity. In Iraq, using lightweight aggregate concrete (LWAC) in structures is still limited to some antecedent buildings that were erected in the past by using imported types of lightweight aggregate (LWA). This paper presents the compressive strength test results of LWAC produced from the locally available natural Porcelanite aggregate [14].

EXPERIMENTAL WORK

The characteristics of concrete types were designed to cast five series of concrete specimens. The type of concrete depends on the basis of volumetric fractions, for concrete containing normalweight fine aggregate (sand) and a blend of lightweight (100%, 75%, 50%, 25% and 0% of graded Porcelanite) and normalweight coarse aggregates (0%, 25%, 50%, 75%, 100% of graded gravel) according to ACI 318M-11[15].

Ordinary Portland cement (Type-1) produced by United Cement Company (Tasluga-Bazian), Sulymania-IRAQ, was used throughout this work. The chemical and physical properties of such cement are presented in Tables (1) and (2), respectively. Test results indicate that the adopted cement conformed to ASTM C150-04[16] and Iraqi Standard Specifications IQS No. 5/1984[17].

Table (1)Chemical requirements of cement.

No.	Compound Composition	Chemical composition	weight %	ASTM C150 – 04(16)	IQS 5/1984(17)
1	Lime	CaO	63.19	***	***
2	Silicon Dioxide	SiO_2	21.60	20.0 min	***
3	Aluminum oxide	Al_2O_3	4.10	6.0 max	***
4	Ferric oxide	Fe_2O_3	4.48	6.0 max	***
5	Magnesium oxide	MgO	2.28	6.0 max	5 max
6	Sulfur trioxide	SO_3	1.98	3* max	2.5**max
7	Loss on ignition	L.O.I	2.45	3 max	4 max
8	Insoluble residue	I.R	0.47	0.75 max	1.5 max
9	Lime saturation factor	L.S.F	0.905		0.66-1.02

Table (2) Physical requirements of cement.

Physical Properties	Test Results	ASTM C150 – 04(1)	IQS 5/1984(17)
Fineness using Blaine air permeability apparatus (m^2/kg)	332	280 min	230 min
Soundness using autoclave method(%)	0.19	0.8 max	0.8 max
Time of setting (Vicat) Initial time(minutes) Final time (minutes)	 175 225	 45 min 375 max	 45 min 600 max
Compressive strength-MPa for cement paste cube mold (50 mm) at: 3 days 7 days 28 days	 19.4 32.4 40.5	 12 min 19 min ***	 15 min 23 min ***

* when $C_3A \leq 8\%$ then max. $SO_3 = 3.0\%$, when $C_3A > 8\%$ then max. $SO_3 = 3.5\%$
**when $C_3A \leq 5\%$ then max. $SO_3 = 2.5\%$, when $C_3A > 5\%$ then max. $SO_3 = 2.8\%$
*** Not applicable

Normalweight natural sand from Al- Akhaider region was used as fine aggregate. Before its incorporation into the concrete mix, sand was sieved on 9.5 mm sieve. Grading of the sand to be accomplished according to the requirements of ASTM C136-05[18], is shown in Figure (2). Physical and chemical tests on sand used throughout this work are shown in Table 3. The obtained results indicate that the fine aggregate grading and the sulfate content were within the requirement of ASTM C33-03[19] and IQS No. 45/1984[20] specifications.

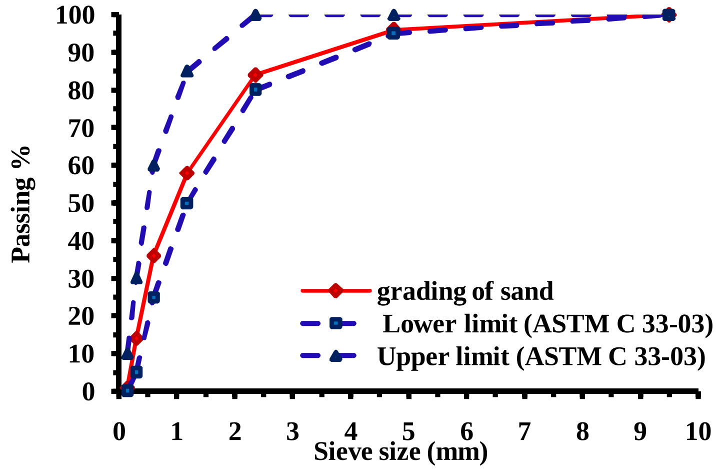

Figure (2) Sieve analysis of fine aggregate.

Table (3) Chemical and physical requirements of fine aggregate.

Type of test	Test Results	Specification
SO_3 (%weight)	0.166	IQS 45/1984 (20)
Material finer than 75 µm (%weight)	3.5	ASTM C 33-03 (19) & IQS 45/1984 (20)
Specific gravity (SSD)	2.53	ASTM C 128-04(21)
Absorption %	2.2	ASTM C 128-04(21)
Dry loose unit weight (kg/m^3)	1585	ASTM C 29-03 (22)

Local naturally occurring lightweight aggregate of Porcelanite stone (has a white color) was used as coarse aggregate. It was received in large lumps from the State Company of Geological Survey and Mining, Ministry of Industry and Minerals. The quarry of this stone occurs in Wadi Mallusa (Rutba) at Western Desert of Al-Anbar Governorate, Plate 1. The lumps were firstly crushed into smaller sizes manually by means of a hammer in order to facilitate the insertion of lumps through the feeding openings of the crusher machine. The jaw crusher was set up to give a finished product of about 19 mm maximum aggregate size. The aggregate taken from the crusher was screened on a standard sieve series complying with ASTM C330-05[24] specifications, as indicated in Figure (3). The test results of chemical compositions and physical properties determined for coarse Porcelanite aggregate are shown in Tables (4 and 5).

Plate (1) Natural Porcelanite stone.

Table (4) Chemical analysis of Porcelanite stone.

No.	Chemical compositions (%)	X-Ray analyzer *	S.C.G.S.M.•
1	SiO_2	74.0313	62.02
2	CaO	5.6296	11.55
3	MgO	3.6556	7.20
4	Al_2O_3	3.6539	2.71
5	P_2O_5	1.1600	-----
6	Fe_2O_3	0.9794	0.87
7	TiO_2	0.1773	0.18
8	K_2O	0.1707	-----
9	Na_2O	0.0662	-----
10	Cr_2O_3	0.0245	-----
11	SO_3	0.0090	0.30
12	MnO	0.0043	-----
13	L.O.I	11.2000	13.86
	Sum	100.7617	98.21

*Cimenterie National S.A.L. plant, Lebanon
•State Company of Geological Survey and Mining, Baghdad, IRAQ.

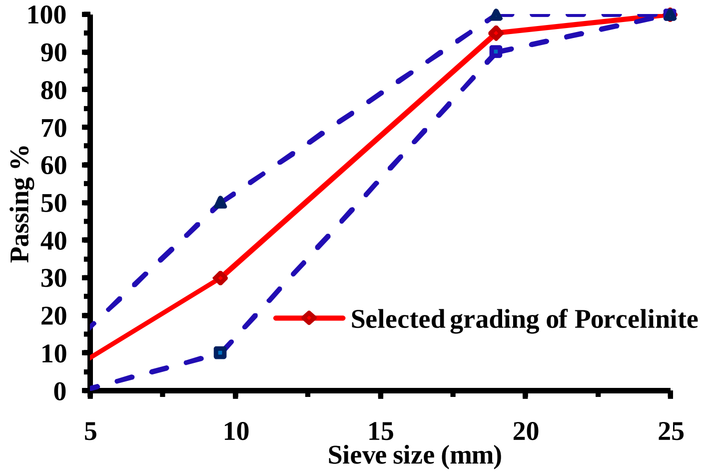

Figure (3) Adopted grading of coarse Porcelanite aggregate.

Table (5) physical properties of Porcelanite stone.

No.	Property	Test Result	Specification
1	Density (OD) - kg/m^3	1447	ASTM C 127-04[23]
2	Density (SSD) - kg/m^3	1860	
3	Apparent Density - kg/m^3	2397	
4	Relative density (Specific gravity)-(OD)	1.48	
5	Relative density (Specific gravity)-(SSD)	1.86	
6	Apparent relative density	2.4	
7	Absorption %	32%	
8	Saturation %	3.6	
9	Loose Bulk Density (Apparent) - kg/m^3	721	ASTM C 29-03 [22]
10	Rodding Bulk Density(Apparent) - kg/m^3	791	
11	Dry Loose unit weight - kg/m^3	708	
12	Dry Rodded unit weight - kg/m^3	785	
13	Loose Bulk density (SSD) - kg/m^3	891	
14	Rodding Bulk density (SSD) - kg/m^3	989	
15	Voids (Loose) - %	52	
16	Voids (Rodding) - %	47	

River gravels were used in this work with a maximum size of 19 mm, specific gravity of 2.65, bulk density of 1670 kg/m^3, Absorption % of 0.64, SO3 content of 0.052% (< 0.1% limit [(20)]), irregular, rounded shape, having smooth surface texture. According to nominal size of aggregate 19.0 to 4.75 mm as indicated in Table (2) of ASTM C33-03[(24)], the average of lower and upper limits of % passing gradations of aggregate was adopted to find % retained, by sieve shaker screening performed manually. The selected grading of gravel according to ASTM C33-03 [(19)] is indicted in Figure (4).

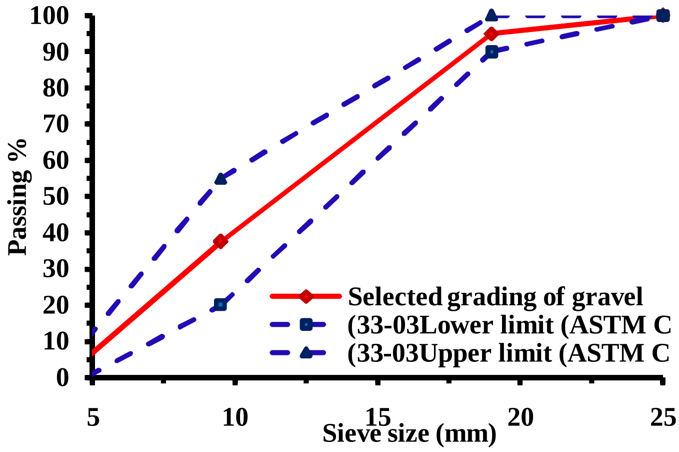

Figure (4) Adopted grading of coarse.

Concrete mixes containing Porcelanite aggregate as lightweight aggregate should have an oven - dry density < 2000 kg/m^3, and 28-day cylinder compressive strength > 17.0 MPa. These mixes were designed in accordance with ACI Committee 211-2-98. They fall in class I of the RILEM classification, which is adopted by CEB/FIP Manual of Concrete Design and Technology. To produce Sand-Lightweight Aggregate Concrete (SLWAC), the mixing proportion [cement: sand: aggregate] was 1:1.12:0.84 by weight (or 1:1.36:1.42 by volume) and the water–cement ratio was 0.4. It was found that the used mixture produces good workability, uniform mixing of concrete without segregation and conforms to density and compressive strength requirements of ACI 213-03[1]. Table (6) shows mix proportions (by weight), which were used in this work.

Table (6) Selected concrete mixes proportion.

No.	Mix proportion, by weight (Cement: Sand: Gravel: Porcelanite)	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Porcelanite kg/m^3
1	**1:1.12: 0.0 : 0.84**	540	605	0	454
2	**1:1.12: 0.4767 : 0.63**	540	605	257	340
3	**1:1.12: 0.9534 : 0.42**	540	605	515	227
4	**1:1.12: 1.4301 : 0.21**	540	605	772	112
5	**1:1.12: 1.9068 : 0.0**	540	605	1030	0

The control specimens for each different batch included at least three standard cylinders 300 mm high with 150 mm diameter, three cubes of 150 mm sides. All specimens were cast and compacted on a vibrating table. After 24 hrs, the specimens were removed from molds and immersed in water at room temperature [25]. Plate 2 shows all control specimens of this work.

Plate (2)Total control specimens (15 cylinders and 15 cubes).

Cylinder compressive strength test

The compressive strength test of concrete (f'_c) was carried out according to ASTM C39/C39M-05[26]. 150×300 mm cylindrical specimens were used to determine the compressive strength of hardened concrete using a hydraulic compression testing machine (Digital Display Building Material Compression Testing Machine) of 3000 kN capacity, available at the concrete laboratory of the Building & Construction Engineering Department, University of Technology, Baghdad, IRAQ, Plate 3. Three cylinders from each mix batch are tested at the age of testing.

Plate (3) Digital compression machine used for cylinder concrete compressive strength test.

Cube compressive strength test

A digital compressive testing machine with a capacity of 3000 kN at a nominal loading rate within the range 0.2 MPa/sec to 0.4 MPa/sec was used for testing the compressive strength of concrete, as shown in Plate 4. Standard cubes measuring 150 mm according to BS 1881-part 116:2000[27] were used by applying load perpendicular to the direction of casting. The average value of three specimens for each batch mix at the age of testing each specimen was determined and recorded.

Plate (4) Digital compression machine used for cube concrete compressive strength test.

Cylinder compressive strength results

Table (7) shows the experimental compressive strength results of 150×300 mm cylinders for concrete mixes series 1 to 5 on the basis of volumetric fractions replacement of Porcelanite coarse aggregate by natural gravel coarse aggregate. The results indicate nonlinear increases of the compressive strength with the increase of concrete density, as shown in Figure (5). The proposed expression obtained using nonlinear regression of exponential fit with $R^2 = 0.9785$, correlation coefficient (0.9908) and Standard Error (0.8794):

$$f'_c = 2.3487 * e^{0.0011*wc} \quad \ldots (1)$$

Table (7) Compressive strength test results of control cylinder specimens for different concrete mixes.

Series No. (mix proportions by weight) (cement: sand: gravel: Porcelanite)	cylinder	Density (kg/m^3)	f'_c (MPa)
(1) (100% Porc.+ 0% gravel) (SLWAC) (1 : 1.12 : 0 : 0.84)	A	1846	18.5
	B	1836	16.9
	C	1842	17.1
	Average	1841	17.5
(2) (75% Porc.+ 25% gravel) (1 : 1.12 : 0.4767 : 0.63)	A	1961	17.2
	B	1978	20.3
	C	1977	18.9
	Average	1972	18.8
(3) (50% Porc.+ 50% gravel) (1 : 1.12 : 0.9534 : 0.42)	A	2126	23.6
	B	2115	19.4
	C	2122	23.5
	Average	2121	22.1
(4) (25% Porc.+ 75% gravel) (1 : 1.12 : 1.4301 : 0.21)	A	2233	24.6
	B	2251	30.1
	C	2250	26.8
	Average	2245	27.1
(5) (0% Porc.+ 100% gravel) (NWAC) (1: 1.12 : 1.9068 : 0)	A	2404	28.1
	B	2392	26.8
	C	2407	37.5
	Average	2401	30.8

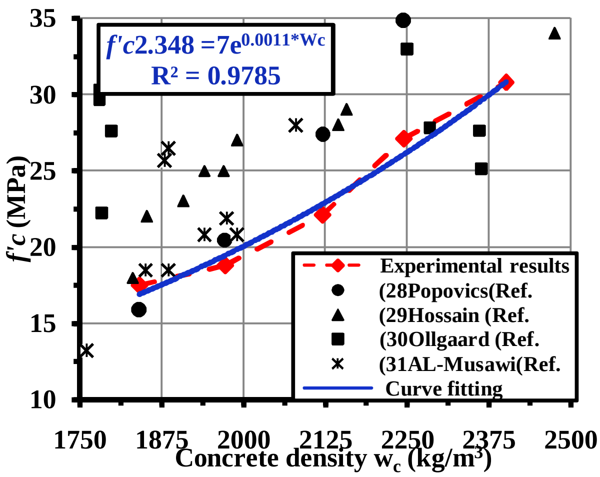

Figure (5)Relationship between concrete density (w_c) and cylinder compressive strength (f'_c) for different concrete mixes.

Table (8) Compressive strength test results of control cube specimens for different concrete mixes.

Series No. (mix proportions by weight) (cement: sand: gravel: Porcelanite)	cube	Density (kg/m^3)	f_{cu} (MPa)
(1) (100% Porc.+ 0% gravel) (SLWAC) (1 : 1.12 : 0 : 0.84)	A	1954	21.9
	B	1939	21.7
	C	1858	21.3
	Average	1917	21.6
(2) (75% Porc.+ 25% gravel) (1 : 1.12 : 0.4767 : 0.63)	A	1988	22.2
	B	2044	22.4
	C	2045	22.9
	Average	2026	22.5
(3) (50% Porc.+ 50% gravel) (1 : 1.12 : 0.9534 : 0.42)	A	2200	26.8
	B	2244	30.3
	C	2221	27.1
	Average	2222	28.0
(4) (25% Porc.+ 75% gravel) (1 : 1.12 : 1.4301 : 0.21)	A	2335	37.7
	B	2304	34.4
	C	2237	32.5
	Average	2292	34.9
(5) (0% Porc.+ 100% gravel) (NWAC) (1: 1.12 : 1.9068 : 0)	A	2489	40.3
	B	2452	36.5
	C	2427	35.2
	Average	2456	37.4

Cube compressive strength results

According to BS 1881- part 116:1983[27], the experimental compressive strength results of 150mm cubes for concrete mixes of series 1 to 5 on the basis of volumetric fractions replacement are shown in Table 8 and their behavior in Figure 6. The proposed expression obtained using nonlinear regression of exponential fit with R^2 = 0.9398, correlation coefficient (0.9917) and Standard Error (2.1427):

$$f_{cu} = 2.4137 * e^{0.0011 * wc} \quad \dots (2)$$

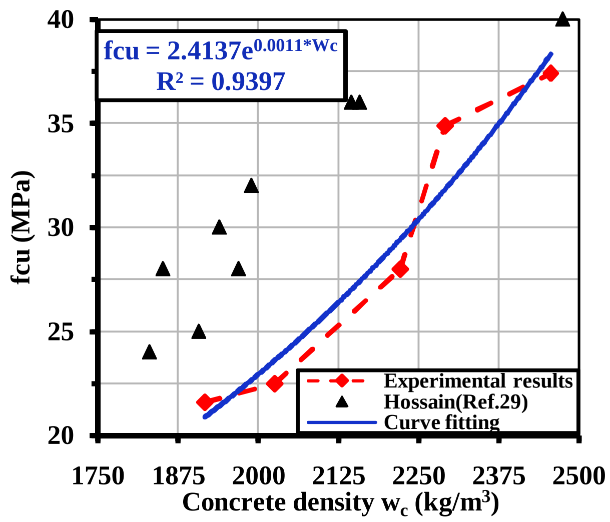

Figure (6) Relationship between concrete density (w_c) and cube Compressive strength (f_{cu}) for different concrete mixes.

Relationship between cylinder and cube compressive strength

From the Eq. (1) and (2) the adopted relationship of cylinder compressive strength (f'_c) and cube compressive strength (f_{cu}) for sand-lightweight aggregate concrete (SLWAC) by using Porcelanite coarse aggregate is shown in Figure (7). Eq. (3) and (4) indicated that, the linear regression of linear and power expression may be used to predict cylinder compressive strength (f'_c) of Porcelanite aggregate concrete from cube compressive strength (f_{cu}) with ($R^2 = 1$),

$$f'_c = 0.8269 * f_{cu} + 1.0899 \quad \text{(model-1)} \qquad \ldots(3)$$

$$f'_c = 1.0144 * f_{cu}^{\;0.9528} \quad \text{(model-2)} \qquad \ldots(4)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{N}(y_i - \bar{y})^2}$$

R^2: Statistical measure of how well a regression line approximates real data points; an r-squared of 1.0 (100%) indicates a perfect fit, where N is the number of observations in the model, y is the dependent variable, y-bar is the mean of the y values, and y-hat is the value predicted by the model. The numerator of the ratio is the sum of the squared differences between the actual y values and the predicted y values. The denominator of the ratio is the sum of squared differences between the actual y values and their mean. Based on Tables (7) and (8) the values of f'_c and f_{cu} are calculated using Eqs. (1) and (2), respectively. This leads to the ratio of f'_c/f_{cu} in the 4th column of Table (9). If Eqs. (3) and (4) are used to predict f'_c (based on f_{cu}) the ratio of f'_c/f_{cu} is as shown in columns 7 and 8, respectively.

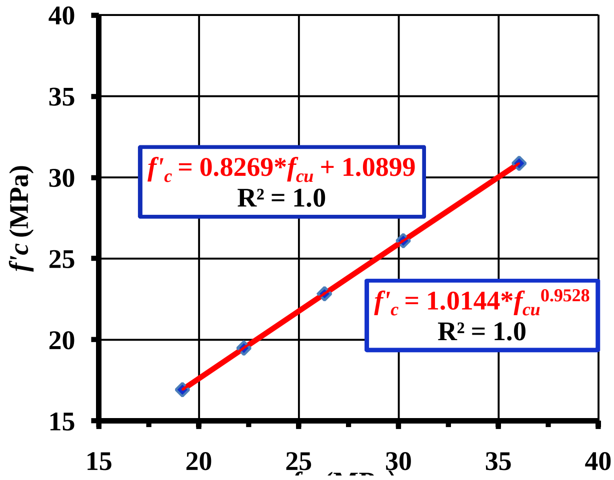

Figure (7) Relationship between cylinder and cube compressive strength for different concrete mixes.

Table (9) f'_c/f_{cu} ratio predicted from Eqs. (model-1 and model-2) for different concrete mixes.

Density (kg/m^3) Table(7)	f'_c Eq.(1)	f_{cu} Eq.(2)	$f'c/f_{cu}$	f'_c model-1 Eq.(3)	f'_c model-2 Eq.(4)	f'_c/f_{cu} model-1	f'_c/f_{cu} model-2
1841 (SLWAC)	16.92	19.18	0.882	16.95	16.92	0.884	0.882
1972	19.48	22.23	0.876	19.47	19.48	0.876	0.876
2121	22.85	26.29	0.869	22.83	22.85	0.868	0.869
2245	26.10	30.23	0.864	26.09	26.11	0.863	0.864
2401 (NWC)	30.86	36.03	0.856	30.88	30.86	0.857	0.857

CONCLUSIONS

Based on the results of this work, the following conclusions are made.

1. Structural lightweight aggregate concrete (SLWAC) produced from locally available Porcelanite aggregate conforms to the requirements of structural lightweight concrete (SLC) according to ACI 213R-03 "Guide for Structural Lightweight-Aggregate Concrete" classifications and ASTM 330-05 "Standard Specification for Lightweight Aggregates for Structural Concrete" with regard to concrete compressive strength f'_c. In this work the minimum value is 17.5 MPa, complying with ACI 213R-03 lower limit of 17.0 MPa. The concrete dry density is in the range 1787 – 1917 kg/m^3 complying with the Committee value of 1680 – 1920 kg/m^3.

2. The cylinder compressive strength f'_c and cube compressive strength f_{cu} of both lightweight and normalweight concretes seems to be in direct proportion to the density of concrete.
3. When comparing the above formula for estimating f'_c in Eq. (1) with the other experimental results adopted by other researchers [28-31], Fig. 5 indicates that the proposed expression leads to acceptance prediction of f'_c.
4. Fig. 6 shows that the proposed expression [Eq. (2)] leads to acceptable prediction for f_{cu}. This compares favorably with the proposal by Hossain[28] which significantly over estimates the values of f_{cu}.
5. Table (9) shows that, the predicted ratio of f'_c/f_{cu} for SLWAC to NWC ranged between 0.88 to 0.86.

FUTURE RESEARCH

Since several design methods, as well as cases in practice, lead to design of beams with stirrups which need the compressive strength of concrete, this type of research is indicated for future work.

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