Properties of High Strength Structural Lightweight Mortar Using Perlite as Partial Replacement of Fine Aggregate

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ABSTRACT

In this research high strength structural lightweight mortar with compressive strength in the range of 33.5-52.5 MPa and unit weight in the range of 1625-2105 kg/m^3 is produced using perlite as fine aggregate. The current investigation deals with using perlite fine aggregate as replacement of silica sand with different rates. These rates are taken as percentage rates from the sand volume with values 15, 30, 45, 60 & 75%. Compressive strength, flexural strength, modulus of elasticity and unit weight are conducted. The relation between these properties and the percentage of replacing of silica sand with perlite is obtained. The results show that using perlite as fine aggregate and as a replacement of silica sand reduces the unit weight of mortar with linear rate and at the same time producing high strength mortar, which can be used as structural lightweight mortar compared with normal weight mortar.

خصائص المونة الانشائية عالية المقاومة خفيفة الوزن باستخدام البيرلايت كبديل جزئي عن الركام الناعم

الخلاصة

يتناول البحث انتاج مونة انشائية عالية المقاومة خفيفة الوزن بمقاومة انضغاط تتراوح بين (33.5-52.5 MPa) وبكثافة تتراوح بين (1625-2105 kg/m^3) بإستخدام مادة البيرلايت كركام ناعم. حيث يهدف البحث إلى إستخدام البيرلايت كبديل عن الرمل السيليكوني بمعدلات مختلفة، هذه المعدلات اخذت كنسب مئوية من حجم الرمل بقيم (75,60,45,30,15%). تم فحص مقاومة الانضغاط، مقاومة الانثناء، معامل المرونة والكثافة. وتم ايجاد العلاقة بين هذه الخصائص ونسب استبدال الرمل بالبيرلايت. حيث بينت النتائج بأن استعمال البيرلايت كركام ناعم واستبداله بالرمل السيليكوني يقلل من كثافة المونة بمعدل خطي وبنفس الوقت يساعد في انتاج مونة عالية المقاومة وبالتالي ممكن استعمالها كمونة إنشائية خفيفة الوزن مقارنة مع المونة الاعتيادية.

INTRODUCTION

Structural lightweight aggregate concrete is an important and versatile material, which offers a range of technical, economic, environmental-enhancing and preserving advantages. It is designed to become a dominant

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material in the new millennium. It has many and varied applications: multistory building frames, floors, curtain walls, shell roofs, folded plates, bridges, pre-stressed and pre-cast elements of all types and others [1].

Structural lightweight concrete has an in-place density (unit weight) in the range of 1440 to 1840 kg/m^3 compared with normal weight concrete with a density in the range of 2240 to 2400 kg/m^3. For structural applications the concrete strength should be greater than 17.0 MPa. The concrete mixture is made with a lightweight coarse aggregate. In some cases, a portion or the entire fine aggregate may be a lightweight product. Lightweight aggregates used in structural lightweight concrete are typically expanded shale, clay, perlite or slate materials that have been fired in a rotary kiln to develop a porous structure. Other products such as air-cooled blast and furnace slag are also used. There are other classes of non-structural lightweight concretes with lower density made with other aggregate materials and higher air voids in the cement paste matrix, such as in cellular concrete. These are typically used for their insulation properties [2].

H. Katkhuda, et al. [3] investigated the effect of silica fume on tensile, compressive and flexure strengths on high strength lightweight concrete. Many experiments were carried out by replacing cement with different percentages of silica fume at different constant water-binder ratio keeping other mix design variables constant. The results demonstrated that the tensile, compressive and flexure strengths increased with silica fume incorporation but the optimum replacement percentage is not constant because it depends on the water–cementitious material (w/cm) ratio of the mix.

The lower density and higher insulating capacity are the most obvious characteristics of Light-weight Aggregate Concrete (LWAC) distinguishing itself from ‘ordinary’ Normal Weight Concrete (NWC). However, these are by no means the only characteristics, which justify the increasing attention for this (construction) material. This case is most of the design, production and execution rules will apply for LWAC as for normal weight concrete, without any amendments [4].

MESUT [5] designed the structural lightweight aggregate concrete with the use of natural perlite aggregate that will provide the advantage of reducing dead weight of structure and to obtain a more economical structural lightweight concrete by the use of perlite powder as a replacement of the cement. According to the results of experimental study, he concludes that natural perlite aggregate can be used in the production of structural lightweight aggregate concrete. Based on the strength and density results of the experimental work, it is possible to produce lightweight concrete with

20-40 MPa cylindrical compressive strength by using natural perlite aggregate. Also, the use of perlite powder, providing economy, reduce dead weight further and increase performance [5].

Lightweight concrete can be manufactured with a combination of fine and coarse lightweight aggregate or coarse lightweight aggregate and normal weight fine aggregate. Complete replacement of normal weight fine aggregate with a Lightweight aggregate will decrease the concrete density by approximately 160 kg/m^3 [2].

STRUCTURAL LIGHTWEIGHT CONCRETE

Concrete is classified into three groups according to their unit weights:

1. Heavy concrete: The unit weight is in the range of 3200 kg/m^3-4000 kg/m^3 and this kind of concrete mainly used in nuclear reactors.
2. Normal concrete: The unit weight is in the range of 2400 kg/m^3-2600 kg/m^3.
3. Lightweight concrete: The unit weight is less than 2000 kg/m^3.

Lightweight concrete can be divided into structural lightweight concrete and ultra-lightweight concretes for non-structural purposes. ACI Committee 213 [1] makes three divisions (Figure 1.) on the basis of strength and unit weight:

- Low-density, low-strength concrete used for isolation.
- Moderate-strength lightweight concrete used for concrete block and other applications where some useful strength is desirable.
- Structural lightweight concrete.

STRUCTURAL LIGHTWEIGHT AGGREGATE

According to ACI 213 [1], structural lightweight aggregates are grouped into two:

1. Naturally occurred and unprocessed aggregates.
2. Processed aggregates.

Natural lightweight aggregates are mostly of volcanic origin and, thus, found only in a certain parts of the world. Pumice and scoria are the oldest known LWA. These are light and strong enough to be used in their natural state, but their properties are variable.

Perlite is, a hydrated volcanic glass, commonly has a pearly, vitreous luster characterized by concentrating onionskin fractures. A relatively high water content of 2 to 5 percent distinguishes perlite from other hydrous volcanic glasses, such as obsidian, hydrated volcanic ash and pumicites [6]. It is an aluminosilicate material characterized by its upon structure which has interconnected cavities that can be accessed by molecular, atomic and ionic species. Their structure allows unique adsorptive properties, which provide catalytic abilities. Natural zeolite contains large quantities of reactive SiO_2 and Al_2O_3. [7].

EXPERIMENTAL WORK

Materials

Cement: Ordinary Portland cement was used which conforms to Iraqi specifications (IQ-5) [8]. Tables (1) and (2) show the physical and chemical properties of the cement used respectively.

Silica sand: High purity silica sand was processed from the quality silica stone, for its high content of SiO_2 and low impurity. It can be used as fine aggregate and graded according to IQS 45/1984 for fine aggregate. Tables (2) and (3) show it's chemical composition and grading. Sieve analysis results show that silica sand used is located within zone (3).

Quartz flour: Fine ground quartz sand [passed from sieve No 50. (0.3 mm)]With a specific gravity of (2.7) g/cm^3 was used as filler material. Table (2) shows its chemical composition.

Silica fume: Silica fume is an extremely fine, spherical powder that is used as an additive for improving concrete performance. Gray colored silica fume is used . The percentage of Sio_2 is 98.5% .Table (2) shows it's chemical composition. The results show that silica fume used is conforms to ASTM C1240.

Perlite: perlite powder which used as lightweight aggregate conforms to ASTM C332 replaced by part of silica sand. The used perlite powder passed from sieve No 30. (0.6 mm). It has specific gravity 1.263 according to ASTM C128, absorption ratio
39.83 %, fineness modulus 1.61 and loose bulk density 111.42 kg/m^3 according to ASTM C29. Tables (2) and (4) show the chemical composition and sieve analysis of perlite respectively. This material imported from Aleppo-Syria - Mihran Company.

Superplasticizer: (Rheobuild 181 R) high range water reduces is used as superplasticizer with dosage 1% by weight of cement. Its color is brown and has a density of 1.102-1.162 kg/L.

Water: potable water is used through this investigation.

Mix design

In this work, six mixtures of lightweight aggregate mortar were cast and prepared by volumetric method according to ACI 211.2-98 [9]. Dry ingredients were mixed manually at the beginning until a homogeneous mixture without silica fume was prepared, then the silica fume separated homogenously in the dry mix and then adding the amount of water mixed with the superplasticizer. The steel mold was placed on a vibrating table and the mixture was added in portions while the mold was being vibrated. After (24) hours the specimens were demoulded and cured in water at room temperature (21)C^o till the test time.

The reference mix was prepared using cement, silica sand as fine aggregate without perlite powder, quartz flour as filler, silica fume as additive, water and superplasticizer, the other mixes were prepared by replacing the silica sand with perlite powder in ratios (15, 30, 45, 60 and 75% by volume). The mix proportions adopted are reported in Table (5).

Testing and Specimens

a: Fresh mortar test: flow ability test for all mixes was done by flow table according to ASTM C1437. The ratio of flow for reference mix was 112.5 % and decrease gradually with increase the replacement ratio of perlite. This attribute to the high absorption of perlite to water mix. The results of the flow ability for different mixes is shown in Table (5).

b: Hardened mortar Tests

Compressive Strength: Compressive strength test according to BS 1881: part 116. were carried out. Cube specimens (100mm) were tested under compression at ages 7,28 and 56 days.

Flexural Strength: Prisms of 100×100×400 mm for flexural test, which used two prisms at age 28 days tested by one central loading according to ASTM C293-94.

Modulus of Elasticity: Cylinders of 100mm diameter and 200 mm height were used for modulus of elasticity test at age (28 days) according to BS 1881-121:1983.

Unit weight: At age of 28 days, the oven dry unit weight determined for structural lightweight mortar according to ASTM C642.

TEST RESULTS AND DISCUSSION

The results of compressive strength, flexural strength, modulus of elasticity and unit weight of the structural lightweight mortar made with perlite in different proportion are given in the Table (6) and represented in Figures (2 to 10). From these results the following observations and discussions can be listed.

1. All mixes show a continuous increasing in compressive strength with age.

2. Fig. (2) represents the relationship between replacement ratios of perlite with silica sand and the compressive strength at 7, 28 and 56 ages. This figure shows the gradual decrease in compressive strength with increase the replacement ratio of perlite. This is attribute to the decreasing of density due to increasing ratio of perlite [5].
3. Figure. (3) represents the relationship between the variation of replacement ratios of the perlite with silica sand and the flexural strength in 28-day. This Fig. shows the gradual decreasing in flexural strength with increase the replacement ratio of perlite from 4.94 MPa for reference mix to 3.035 MPa for the mix with (75%) perlite.
4. The modulus of elasticity ($Ec_{measured}$) for structural lightweight mortar, at the age of 28-day, decrease by about (43%), from (35.7 GPa) for the reference mix to (15.67 GPa) for mix (F). Figure. (4) shows the gradual decreasing in the modulus of elasticity with increasing of perlite replacement ratio. This attribute to the decrease in compressive strength [5].
5. Figure (5) shows the nearest of the values of modulus of elasticity for lightweight mortar measured in this research ($Ec_{measured}$) from the values calculated by the equation of ACI Code [10],[$Ec_{calculated} = Wc^{1.5} \times 0.043\sqrt{f'c}$], where:Wc (kg/m^3) is the unit weight of concrete. This equation is used for the concrete with density ranging from 1440 – 2560 kg/m^3,(the density for lightweight mortar in this investigation is ranging from 1625 – 2225 kg/m^3). The closet in the values which shown in Figure.(5) increase due to increasing the rates of perlite and decreasing the unit weight of the lightweight mortar. The modulus of elasticity of concrete is sensitive for the modulus of elasticity of aggregate and may differ from the specified value [10] . Table (6) shows the values of $Ec_{calculated}$ and the ratio between $Ec_{measured}$ and $Ec_{calculated}$.
6. The range of oven dry unit weight of structural lightweight mortar in this investigation is between (2225 kg/m^3) for reference mix with 0% perlite to (1625 kg/m^3) for mix F with 75% perlite as shown in Figure. (6). This decrease in the unit weight is due to the difference of density between silica sand and perlite.
7. The relationship between the oven dry unit weight and the compressive strength in (7, 28, 56 days) is shown in Figure. (7), which represent the increase of compressive strength with the increase of unit weight. When the unit weight of the mix of (75% perlite) was (1625 kg/m^3), the compressive strength was 32.5 MPa at 28-day and 33.5 MPa at 56-day. These results indicated acceptable compressive strength with low unit weight.
8. For reference mix, when the unit weight was (2225 kg/m^3) the compressive strength was 52 MPa at 28-day and 55.8 MPa at 56-day. These results indicated a high compressive strength with normal unit weight.
9. Figure (8) represents the relationship between the unit weight and the flexural strength at 28-day, the figure shows the gradual increase in flexural strength with increase the unit weight from (3.035 MPa at 1625 kg/m^3) to (4.94 MPa at 2225 kg/m^3).
10. Figure (9) shows that The modulus of elasticity ($Ec_{measured}$) for structural lightweight mortar, at age 28-day, increase from (20.371 GPa) to (35.7 GPa) when the unit weight increases from (1625 kg/m^3) to (2225 kg/m^3).

CONCLUSIONS

Based on the results of this experimental investigation of compressive strength, flexural strength, modulus of elasticity and unit weight of structural lightweight mortar, the following conclusions are drawn:-

- Using perlite as fine aggregate to replace silica sand reduces the unit weight of mortar with linear rate. At the same time it can be used for structural purpose.
- Structural lightweight mortar with perlite powder as fine aggregate has an advantage of reduced density since density of normal weight concrete is about 2225 kg/m^3. As a result of this, Structural lightweight mortar has an advantage of reduced dead weight of the structure as well as reduced risk of earthquake damages to a structure because earthquake forces are proportional to the mass of the structure.
- Lightweight mortar, with strength (33.5-52.5MPa) at age of 56days can be produced, by using (60-75%) perlite as a replacement to silica sand with unit weight of mortar less than (1800 kg/m^3), the compressive strength was within the limits of structural concrete (33.5-43MPa).
- Modulus of elasticity of structural lightweight mortar decreased linearity when the percentage of perlite increases.
- The convergence between the experimental values of modulus of elasticity ($Ec_{measured}$) and ACI equation results increases when the unit weight of mortar decreases (increasing the percentage of perlite).
- The flexural strength of mixes containing perlite with different percentage is varies from (3.035 – 4.62 MPa), which shows a gradual increasing of flexural strength due to decreasing the perlite percentage.
- The unit weight of light weight mortar, which produced using perlite was within the limits of structural lightweight concrete .

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Table (1) Physical Properties of Cement.

Physical property	Results obtained	IQS 5/1984
Fineness (m^2/kg)	245	230 min
Vicat initial setting time (minutes)	55	45 min.
Vicat final setting time (hours)	6:45	10 max.
Compressive strength 7-days (MPa)	17.1	15 min
Compressive strength 28days(MPa)	27.3	23 min
Specific gravity	3.15	

Table (2) Chemical composition of the materials.

Composition (%)	Portland cement	perlite	Silica fume		Silica sand	Quartz flour
			Used in this investigation	ASTM C1240		
Sio_2	21.2	71.0-75.0	98.5	Min. : 85	98.50	99.5
Al_2o_3	6.5	12.5-18.0	0.01	---	0.22	0.2
Fe_2o_3	2.5	0.5-1.5	0.01	---	0.74	0.08
Cao	63	0.5-2.0	0.25	---	---	---
Mgo	2.75	0.1-0.5	0.01	---	---	---
K_2o	0.45	4.0-5.0	0.01	---	0.026	---
Na_2o	0.24	2.9-4.0	0.01	Max. : 1.5	0.032	---
So_3	3.1	0-0.2	0.24	---	---	---
C_3A	13.6	---	---	---	---	---
Tio_2	---	0.03-0.2	---	---	0.03	---
Feo	---	0-0.1	---	---	---	---
Cr	---	0-0.1	---	---	---	---

Table (3) Silica sand sieve analysis.

Sieve size (mm)	Percentage Retained	Cumulative Percentage Retained	Percentage Passing	IQS 45/1984 Graded Reign No. 3
1.18	0	0	100	75-100
0.6	37.95	37.95	62.05	60-79
0.3	48.34	86.29	13.71	12-40
0.15	11.26	97.55	2.45	0-10
0.075	1.83	99.38	0.62	-----

Table (4) Perlite sieve analysis.

Sieve size (mm)	Percentage Retained	Cumulative Percentage Retained	Percentage Passing
1.18	0	0	100
0.6	2	2	98
0.3	21.75	23.75	76.25
0.15	22.75	46.5	53.5

0.075	**43**	**89.5**	**10.5**

Table[5] Flow ability for different mortar mixes.

Mixes	Cement/ Perlite Volume	Cement/ Silica Sand Volume	Cement/ Quartz Flour Volume	Perlite/ cement vol.	% Silica -fume from cement volume	W/C	% Mortar Flow ability ASTM C1437
A	**1:0**	**1:1**	**1:0.23**	٠	٠,٢١	٠,٣	**112.5**
B	١:٠,١٥	**1:0.85**	**1:0.23**	٠,١٥	٠,٢١	٠,٣	**63.75**
C	**1:0.3**	**1:0.7**	**1:0.23**	٠,٣	٠,٢١	٠,٣	**52.5**
D	١:٠,٤٥	**1:0.55**	**1:0.23**	٠,٤٥	٠,٢١	٠,٣	**37.5**
E	١:٠,٦	**1:0.4**	**1:0.23**	٠,٦	٠,٢١	٠,٣	**17.5**
F	١:٠,٧٥	**1:0.25**	**1:0.23**	٠,٧٥	٠,٢١	٠,٣	**5**

Table (6) Physical properties for different mortar mixes

Mix	Compressive strength (MPa)			Flexural strength (MPa) at 28 days	Modulus of elasticity (GPa) at 28 days $Ec_{measured}$	Modulus of elasticity (GPa) by ACI code equation $Ec_{calculated}$ [10]	$Ec_{measured}$/ $Ec_{calculated}$	Oven dry unit weight (kg/m^3)
	7 days	28 days	56 days					
A	40	52	55.8	4.94	35.7	32.54	1.09	2225
B	35	49.5	52.5	4.62	25.55	29.217	0.87	2105
C	33	47.5	49.8	4.42	21.65	26.11	0.82	1980
D	26	42.6	46.9	3.62	19.54	22.513	0.86	1860
E	20	39	43	3.48	17.78	19.57	0.90	1745
F	19	32.5	33.5	3.035	15.67	16.057	0.97	1625

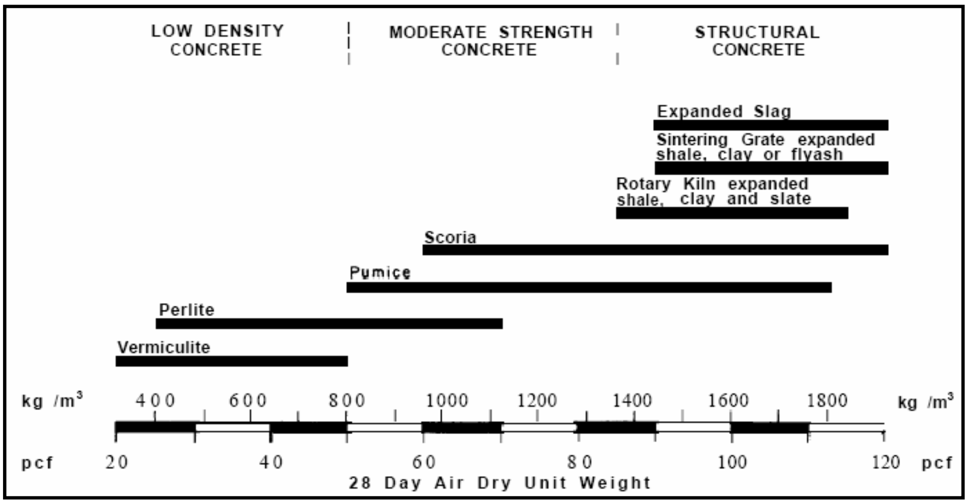

Figure (1): Approximate Unit Weight and Use Classification of Lightweight Aggregate Concrete [1].

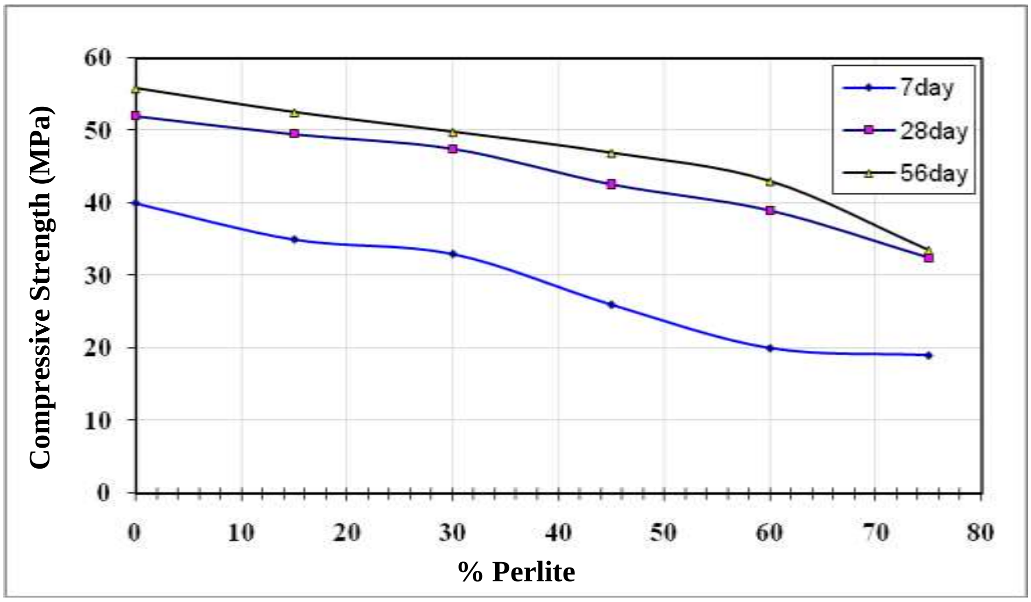

Figure (2): Relationship between the compressive strength and content of perlite as a partial replacement by volume of silica sand

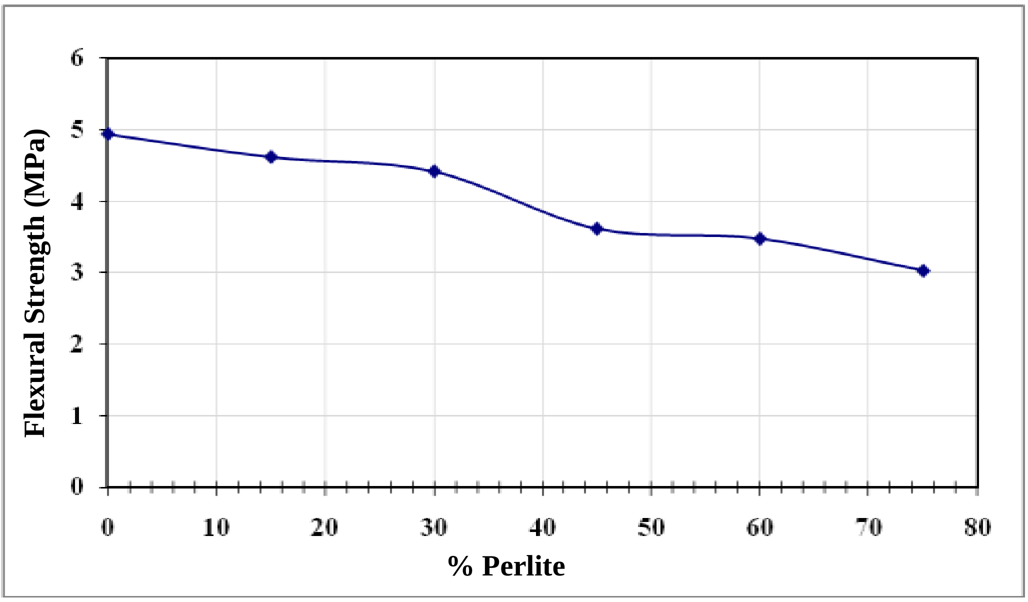

Figure (3): Relationship between the flexural strength and content of perlite as a partial replacement by volume of silica sand

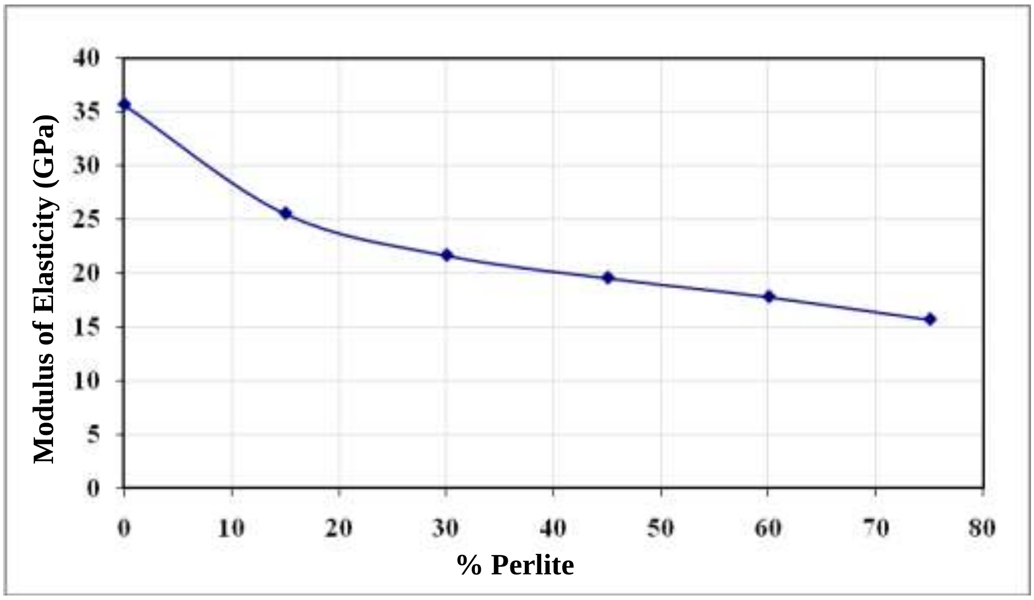

Figure (4): Relationship between the modulus of elasticity and content of perlite as a partial replacement by volume of silica sand

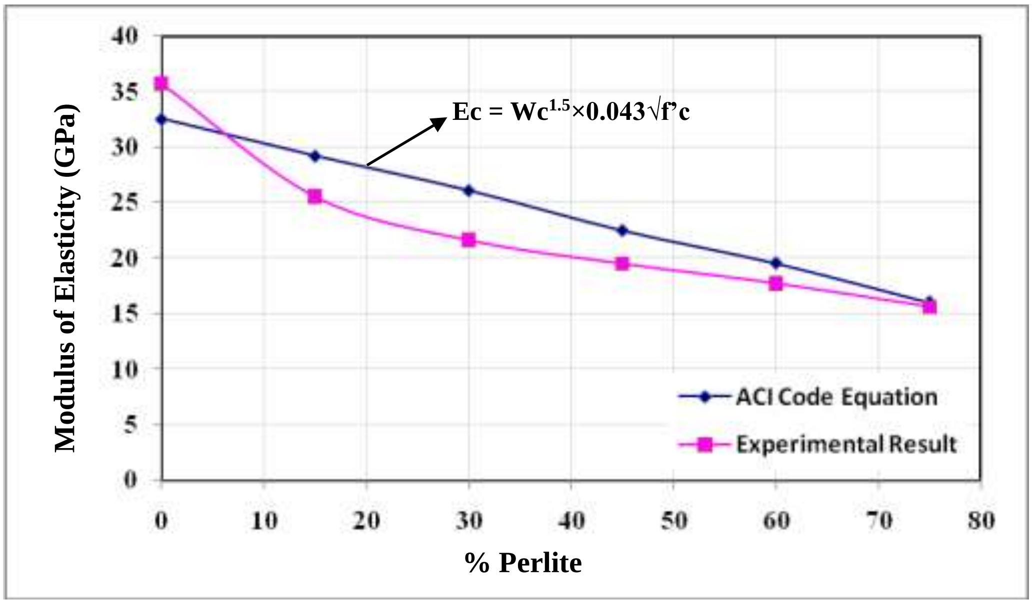

Figure (5): Relationship between the modulus of elasticity (for experimental result & ACI equation) and content of perlite as a partial replacement by volume of silica sand

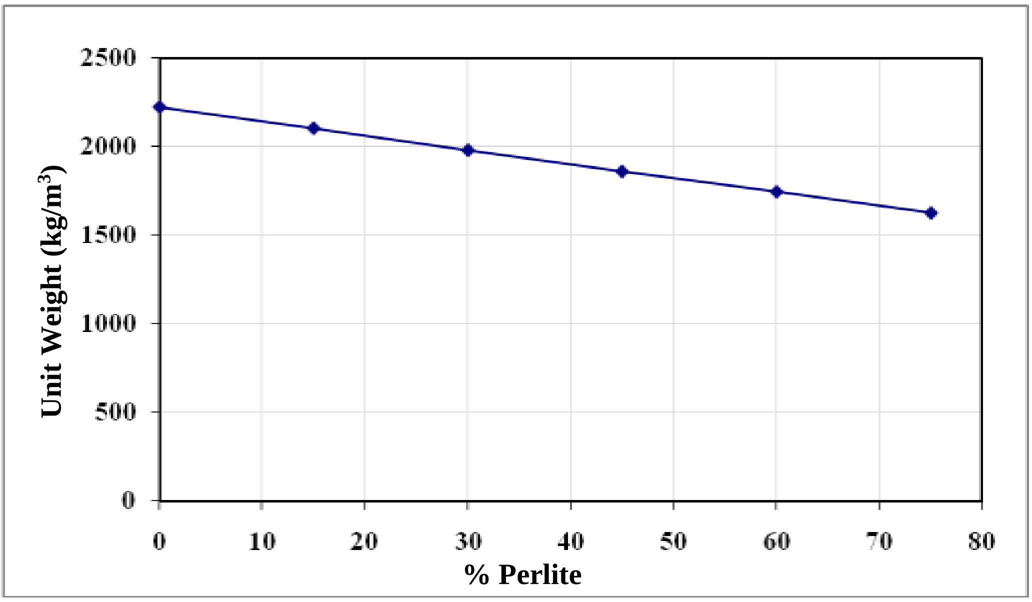

Figure (6): Relationship between the oven dry unit weight and content of perlite as a partial replacement by volume of silica sand

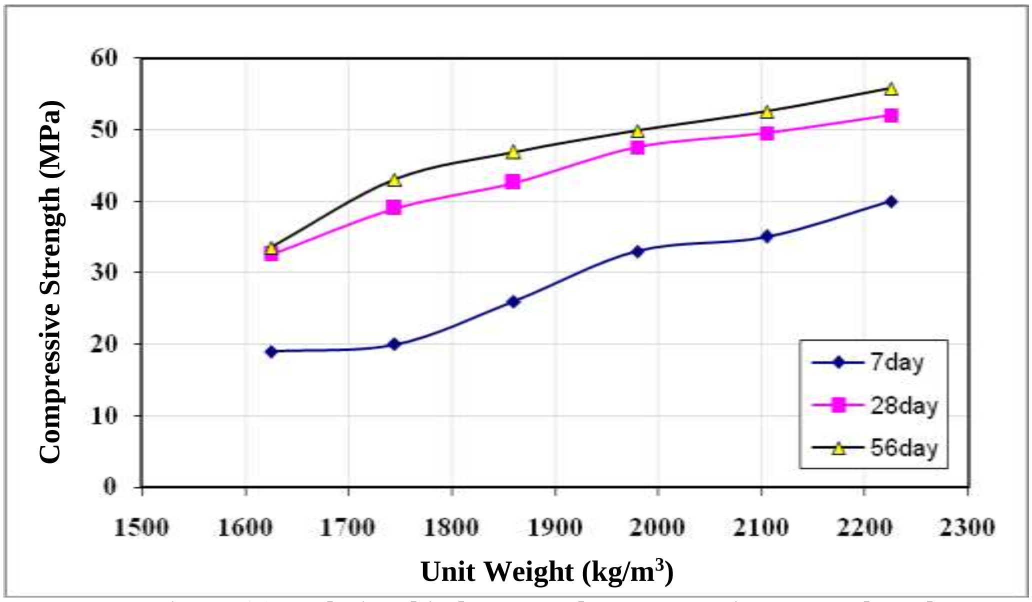

Figure (7): Relationship between the compressive strength and oven dry unit weight

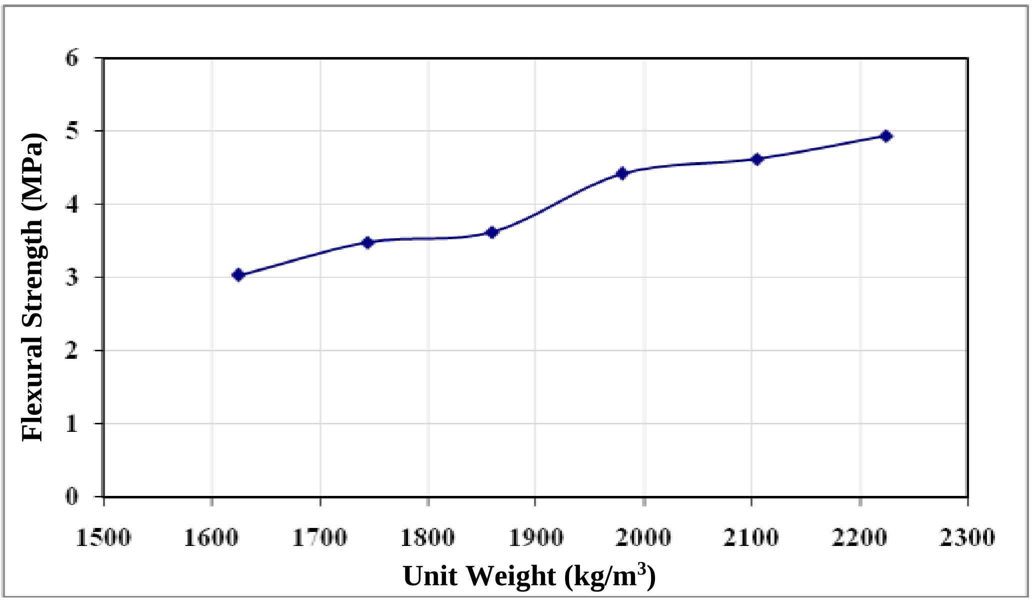

Figure (8): Relationship between the flexural strength and oven dry unit weight

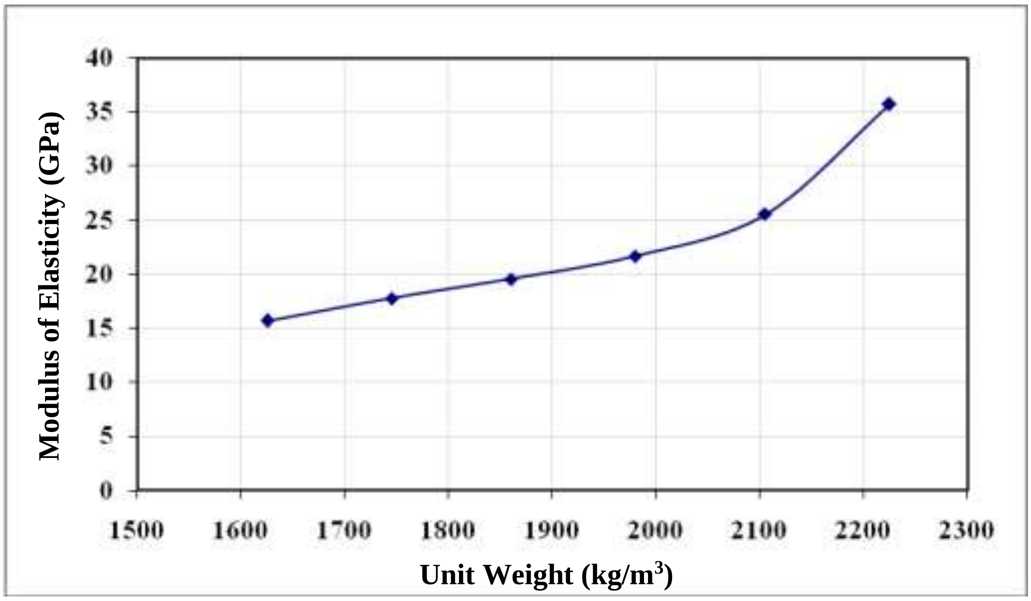

Figure (9): Relationship between the modulus of elasticity and oven dry unit weight