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Development Insulation Performance of Concrete Masonry Units

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ABSTRACT

Thermal insulation of buildings takes more of researchers' interest because of different economical and ecological considerations. Thermal insulation of walls is a principal part of thermal insulation system for any building.

This paper includes production of four types of no-slump concrete including, normal weight concrete, semi-lightweight concrete, no-fines concrete and lightweight concrete. Their properties including, density, compressive strength and absorption were studded and their thermal conductivity were calculated. Concrete oven-dry densities range was 1664.2-2141.6 kg/m^3, compressive strength was 5.3-15.7 N/mm^2, absorption was 6.3-16.7 % and their thermal conductivity was 0.576-1.047 W/m.K. In addition, the research includes production two types of concrete masonry units (CMU) from each type of concrete and studies their properties including, compressive strength and absorption. The overall heat transfer coefficient for each type was calculated. The results show that the reduction in concrete density by 22% results a reduction in overall heat transfer coefficient for CMU by about 28% for CMU type I and 15% for CMU type II, the results also show that the change in cavities sizes and their arrangements into CMU reduces the overall heat transfer coefficient between 11-28% depends on concrete density. The combination between the two strategies results to optimum reduction in overall heat transfer coefficient of about 36%.

Keywords: Lightweight Concrete, Concrete Blocks, Thermal Insulation.

تطوير أداء العزل لوحدات البناء الخرسانية

الخلاصة

يلاقي موضوع العزل الحراري للأبنية إهتماماً متزايداً من قبل الباحثين وذلك لعدة اعتبارات إقتصادية وبيئية. ويعتبر العزل الحراري للجدران جزءاً رئيسياً من نظام العزل الحراري لأي بناية.

تضمن هذا البحث إنتاج أربعة أنواع من الخرسانة عديمة الهطول هي الخرسانة إعتيادية الوزن، الخرسانة نصف خفيفة الوزن، الخرسانة الخالية من الركام الناعم والخرسانة خفيفة الوزن ودراسة خواصها المختلفة وتشمل الكثافة، مقاومة الإنضغاط والإمتصاص، وحساب موصليتها الحرارية. تراوحت كثافة الخرسانة المجففة بالفرن بين 2141.6-1664.2 كغم/م^3 ومقاومة إنضغاطها بين 15.7-5.3 نت/مم^2 وإمتصاصها بين 6.3-16.7% وموصليتها الحرارية بين 1.047-0.576 واط/م.كلفن. تضمن البحث أيضاً إنتاج نوعين من وحدات البناء الخرسانية من كل نوع من أنواع الخرسانة أعلاه ودراسة خواصها وهي مقاومة الإنضغاط والإمتصاص ثم حساب معامل انتقال الحرارة الكلي لكل نوع. بينت النتائج ان انخفاض كثافة الخرسانة بنسبة 22% يؤدي إلى انخفاض معامل إنتقال الحرارة الإجمالي للوحدة البنائية بحدود28 % للنوع الأول و 15% للنوع الثاني ، كما بينت النتائج أيضاً أن تغيير حجم وترتيب الفجوات ضمن الوحدة البنائية يقلل معامل إنتقال الحرارة الإجمالي بنسبة تتراوح بين11-28 % وحسب كثافة الخرسانة. كما أن الجمع بين الطريقتين أدى الى الحصول على أقصى تخفيض في المعامل الإجمالي لانتقال الحرارة بنسبة 36%.

الكلمات الرئيسية : الخرسانة الخفيفة، الكتل الخرسانية، العزل الحراري.

Abbreviations

A%: absorption percentage.

Ac: percentage of concrete area to total area of thermal layer.

Av: percentage of cavities area to total area of thermal layer.

FC: no-fines concrete.

fcu: compressive strength of 150mm cube - N/mm^2.

LC: lightweight concrete.

NC: normal weight concrete.

Rair: thermal resistance of air space- m^2.K/W.

Rc: thermal resistance of concrete thermal layer - m^2.K/W.

Res: thermal resistance of exterior surface - m^2.K/W.

Ris: thermal resistance of interior surface - m^2.K/W.

Rc&air: thermal resistance for thermal layer contain cavity (ies) - m^2.K/W.

RT: total thermal resistance - m^2.K/W.

SC: semi-lightweight concrete.

tc: thickness of concrete thermal layer - m.

U: overall heat transfer coefficient- W/m^2.K.

λc: coefficient of thermal conductivity of concrete - W/m.K.

ρ: oven dried density - kg/m^3.

ρs: saturated density - kg/m^3.

Introduction

The solid portions of walls contribute by 15-25% of total heat transfer through the buildings[1]. Different strategies were developed to achieve thermal insulation for walls. One of these strategies is reducing the overall heat transfer coefficient (U-value) of units that used in process of wall construction. The reduction of U-value can achieve by different methods: reduce unit density, adjustment on unit geometry and/or insert insulation fillers into unit cavities.

The insulation lightweight aggregate CMUs are well known to Iraqis researchers. As examples of Iraqi studies in this field are the works done by Esmail and Dawud[2], and Dhaher[3].

The role of unit geometry in insulation performance of masonry units was investigated by some foreign researchers. As examples of these studies are the works done by Arsenovic et al.[4], Yaşar and Erdoğan[5], and Pierzchlewicz[6]. The effect of cavities fillers was explained in ACI 122R-02[7] and NCMA TEK 6-2B (2009)[8].

The purpose of this paper is to study the effect of concrete type and unit geometry on the properties of hollow concrete masonry units (CMU) especially the insulation performance of the unit represented by overall heat transfer coefficient.

The study includes production of four types of concrete: NC, SC, FC and LC, and specify their properties: fcu, A%, ρs, ρ and λc using Valore equation[7]. Two types of CMU from each concrete type were produced. They are different in their cavities sizes and cavities arrangements as shown in Figs. (1) and (2). The properties of CMUs are specified and compared with requirements of Iraqi standard specifications; also the U-value of each CMU is calculated using the series-parallel method or isothermal planes which are one of two methods, suggested by ACI 122R-02, for calculating thermal resistance of CMUs. The other method is known as "The parallel-path method".

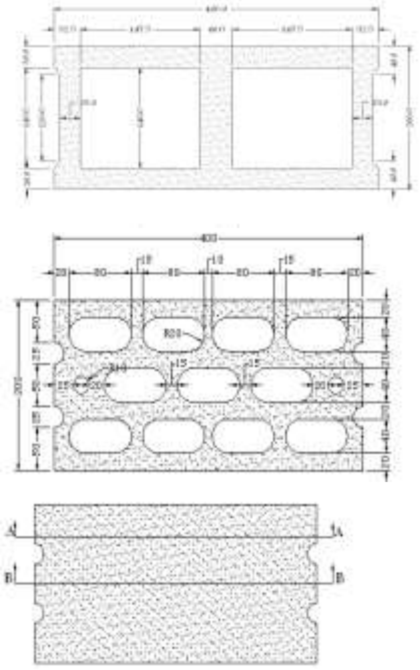

Fig.1. CMU type II.

Experimental Program

Materials

Cement

Ordinary Portland cement produced by Al-Najaf Al-Ashraf factory was used in all concrete mixes. The chemical and physical properties of cement are listed in Tables (1) and (2) respectively. The results show that the cement is conforms to IQS 5/1984.

Coarse Aggregate

Natural terrestrial gravel (Bany-Selama quarries / Al-Muthanna governorate) was used. The properties of gravel are listed in Table (3) which show that the gravel used conforms to IQS 45/1984 for single size coarse aggregate 10mm.

Fine Aggregate

Natural sand (Husaiya quarries/Al-Muthanna governorate) was used. The properties of the sand are listed in Table (4) which shows that the sand used conforms to IQS 45/1984 for fine aggregate zone (3).

Lightweight Aggregate

Crushed porcelinite rocks were used as lightweight concrete aggregate. The quarry of these rocks occurs in Trefawi area at western desert of Iraq (Al-Anbar governorate). The stones was firstly cleaned in order to remove clays, gypsum and other surface adhered impurities, then washed, dried and crushed to required sizes. Table (5) shows the properties of crushed porcelinite lightweight aggregate. It conforms to ASTM C331-00 for combined fine and coarse aggregate (9.5- 0) mm.

Water

Tap water was used in concrete mixes and curing.

Concrete Mixes

Concrete used in production CMU is one type of no-slump concrete that characterized by special consistency: stiff, very stiff or extremely dry. ACI 211.3R-02 cover mix design procedures for this types of concrete. The procedure of ACI 211.3R-02 was carried out for trial mixes. Some adjustments were done to achieve optimum workability and minimum acceptable level of strength. The details of mix proportions are listed in Table (6). Cement content specified by strength requirements, while water content specified by workability requirements. The water content is adjusted until the mixture will "ball" in the hand. It has sufficient cohesion to hold its shape when squeezed but will not exhibit any free moisture [7].

Specimens Preparation, Curing and Testing

Standard procedures were followed in preparation, curing and testing concrete specimens (150mm cubes). CMU specimens were manufactured using electrical machine. Loose semi-dry concrete was poured in steel molds with quantity more than mold volume then vibration process was started. When concrete fill all mold corners, pressing process was applied. Vibration and pressing continued together until some mortar leaked from mold base then the two processes were stopped. The molds removed immediately after compaction was completed. Concrete block specimens leaved for 24±2 hours then they were covered with wet jute and continuously spread with water for entire period of curing (28 dayes).

Results and Discussion

Properties of concrete mixes and CMUs are listed in Tables (7) and (8) respectively. Table (7) shows the properties of different types of concrete mixes used in this investigation. The results show that the highest compressive strength is reported for normal weight specimens, in this type of concrete, the strength of cement matrix is controlled the specimen strength. The strength of specimens contains lightweight aggregate is lower than the strength of all normal weight aggregate, in this case the strength of lightweight aggregate particles is controlled. Also all lightweight aggregate specimens show lower strength than partial lightweight aggregate specimens; in all lightweight specimens the content of weak particles is higher. The lowest compressive strength is reported for no-fines specimens.

Table (8) shows that the compressive strength of CMUs is less than the compressive strength of standard cubes for the same type of concrete. The reason of relatively low strength of CMUs is due to specimen volume and specimen's geometry especially the slenderness of shells and webs. On the other hand the reduction in strength is different according to concrete type. The highest reduction reported for lightweight CMUs due to interaction between the roles of lightweight particles and unit geometry. No-fines CMUs show little change in strength due to change in specimen geometry because of low strength of concrete that controlled on specimen strength. Generally, the results show that the strength of CMUs type II is lower than that for CMUs type I. This is because of the highest webs slenderness for CMUs type II. Fig.(3) shows the variation in strength due to concrete type and specimen geometry.

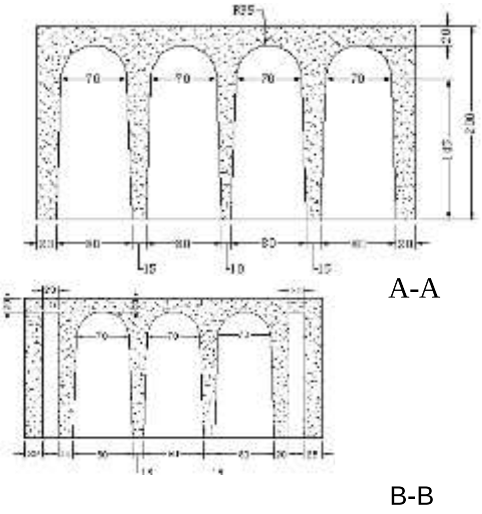

Fig. 2. CMU type I.

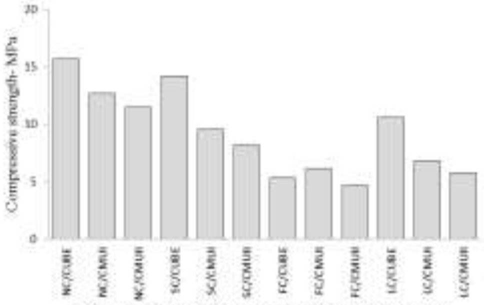

Fig.3. Effect of concrete type and specimen geometry on comprehensive strength

The overall heat transfer coefficient (U-value) was calculated using the following equations:

$$U = \frac{1}{R_T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$R_T = R_{es} + \Sigma R_c + \Sigma R_{c\&air} + R_{is} \ldots . (2)$$

$$R_c = \frac{t_c}{\lambda_c} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$R_{c\&air} = \frac{1}{\Sigma(\frac{A_v}{R_{air}} + \frac{A_c}{R_c})} \ldots\ldots\ldots\ldots (4)$$

$$\lambda_c = 0.072e^{0.00125\rho} \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The calculations details for U-values of CMUs type I and type II are listed in Tables (9) and (10) respectively. The results show that the U-value of CMU affected by both concrete density and unit geometry. The reduction in concrete density reduces the concrete thermal conductivity which leads to a reduction in U-value of CMU.

The U-value for CMUs is more affected by cavities sizes and arrangements than concrete density. Air in small size cavities transfer less heat than that in large cavities due to reduction in the space available for convection currents. The separated cavities reduce U-value due to increase the obstructions in heat flow path. Fig.(4) shows the effect of concrete density and unit geometry on overall heat transfer coefficient of CMUs.

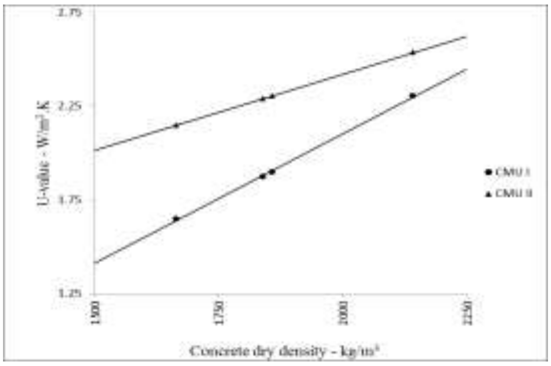

Fig.4. Effect of concrete density and unit geometry on U-value.

The highest absorption is reported for lightweight specimens due to high absorption of lightweight aggregate. The absorption of CMUs is less than the absorption of standard cubes; this is because of the difference in compaction method. The highest reduction in absorption reported for specimens containing lightweight aggregate, this is because of the effective covering of lightweight particles by low permeability cement matrix due to vibration-pressing process and the reduction in cement matrix permeability due to vibration-pressing process. Little variation in absorption is reported for CMUs in different concrete types and different geometries that lead to the following conclusion: the absorption of CMUs depends on cement matrix permeability which depends on degree of compaction. Fig. (5) shows the variation in absorption due to concrete type and specimen geometry.

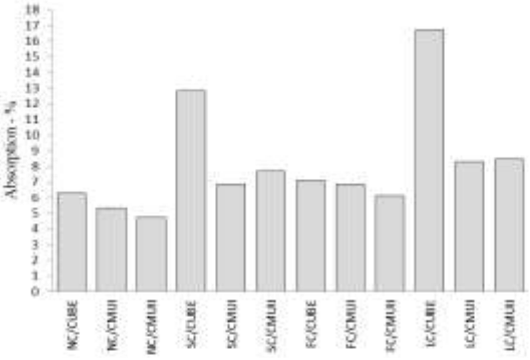

Fig.5. Effect of concrete type and specimen geometry absorption

Improving thermal insulation performance of CMUs can be achieved by reducing concrete density and/or adjustment of unit geometry.

2- The adjustment of unit geometry is more effective than the reduction in concrete density for improving thermal insulation performance of empty hollow CMUs; and the combination between them leads to the optimum thermal insulation performance.

3- The compressive strength of CMUs is less than the compressive strength of standard concrete cubes (from the same concrete mixes).

4- The absorption of CMUs is less than the absorption of standard concrete cubes.

5- Small size cavities are better than large size cavities for strength, absorption and thermal insulation of CMUs.

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Table (1) : Chemical properties of cement.

Test	Test result	Limits of IQS 5/
CaO	62.13%	-
SiO_2	20.71%	-
Al_2O_3	5.96%	-
Fe_2O_3	3.43%	
MgO	4.17%	≤ 5%
SO_3	2.14%	≤2.5%
Lose on ignition	0.88%	≤ 4%
Summation	99.42%	-
Insoluble residue	0.57%	≤1.5%
Lime saturation coefficient	0.9	0.66-1.02
Cement components according to Bogue′s equations		
C_3S	44.55%	-
C_2S	26.03%	-
C_3A	10%	-
C_4AF	10.43%	-

Table 2. Physical properties of cement.

Test	Test result	Limits of IQ.S 5/1984
Fineness (kg/m^2)	319	≥ 230
Soundness (expansion %)	0.59%	≤ 0.8%
Initial setting time (minute)	123	≥ 45
Final setting time (hours)	3:12	≤ 10
Compressive strength at 3 days (N/mm^2)	25.8	≥ 15
Compressive strength at 7 days (N/mm^2)	31.8	≥ 23

Table 3. Properties of natural gravel.

Test		Test result	Limits of IQS 45/1984
Grading	Sieve size	Percentage of materials passing through sieve.	
14mm		100	100
10mm		89.12	85-100
5mm		8.137	0-25
2.36mm		1.142	0-5
Materials passing sieve 75μm		0.173	≤ 3%
SO_3 content		0.038%	≤ 0.1%
Absorption (%)		0.81	-
Specific gravity:			
SSD		2.599	
Bulk		2.578	-
Apparent		2.633	
Bulk density (kg/m^3)		1612.4	-

Table (4): Properties of natural sand.

Test		**Test result**	**Limits of IQ.S 45/1984**
Grading	Sieve size	Percentage of materials passing through sieve	
	10.0mm	100	100
	4.75mm	98.541	90-100
	2.36mm	94.211	85-100
	1.18mm	83.396	75-100
	0.60m	65.890	60-79
	0.30mm	14.494	12-40
	0.15mm	2.220	0-10
Materials passing sieve 75µm		1.026	≤ 5%
SO_3 content		0.816	≤ 1%
Absorption (%)		0.81	-

Table (5): Properties of crushed porcelinite.

Test		**Test result**	**Limits of ASTM C33-00**
Grading	Sieve size	Percentage of materials passing through sieve	
	12.5mm	100	100
	9.50mm	99.824	90-100
	4.75mm	83.098	65-90
	2.36mm	52.407	35-65
	0.30mm	12.532	10-25
	0.15mm	6.332	5-15
Organic impurities		0.47%	-
Loss on ignition		12.83%	≤5%
Bulk density (kg/m^3)		1031.4	≤1040
Absorption (%)		46.249	-
Specific gravity (SSD)		2.316	-
SO_3 content		0.4%	-

Table 6. Mix proportions for different concrete mixes.

Mix proportions / **Concrete type**	**NC**	**SC**	**FC**	**LC**
Volume of cement (V_{cement})	1	1	1	1
Volume of sand (V_{sand})	3.5	3.5	-	-
Volume of gravel (V_{gravel})	1.75	-	5.0	-
Volume of porcelinite ($V_{porcelinite}$)	-	1.75	-	5.25
w/c	0.65	1.23	0.42	1.3
Cement content (kg/m^3)	350	350	250	350

Table 7. Properties of concrete mixes

Properties / **Concrete type**	NC	SC	FC	LC
f_{cu} (MPa)	15.7	14.2	5.3	10.6
ρ_s (kg/m^3)	2276	2096	1969.7	1941.9
ρ (kg/m^3)	2141.6	1858.5	1839.4	1664.2
Absorption%	6.3	12.8	7.1	16.7
λ_c (W/m.K)	1.047	0.735	0.718	0.576

Table 8. Properties of CMUs

	CMU type I			
Properties / Concrete type	**NC***	**SC***	**FC****	**LC*****
f_{gross}MPa	7.55	5.68	3.65	4.06
f_{net}MPa	12.7	9.56	6.15	6.83
f_{gross}/f_{net}	0.594	0.594	0.594	0.594
f_{gross}/f_{cu}	0.481	0.4	0.689	0.383
f_{net}/f_{cu}	0.809	0.673	1.16	0.644
Absorption%	5.35	6.87	6.87	8.29
$Absorption_{CMU}/Absorption_{cube}$	0.849	0.537	0.968	0.496

Table (9): Calculations of U-value for CMU type I.

Calculations **Concrete type**	**NC**	**SC**	**FC**	**LC**
ρ	2141.6	1858.5	1839.4	1664.2
$\lambda_c = 0.072 e^{0.00125\,\rho}$	1.047	0.735	0.718	0.576
R_{es}	0.04	0.04	0.04	0.04
$R_c = n \times \left(\frac{t_c}{\lambda_c}\right) = 4 \times (\frac{0.02}{\lambda_c})$	0.076	0.1088	0.111	0.1389
t_{c1} (thickness of concrete -m)	0.04	0.04	0.04	0.04
A_{v1}= cavities area / area of thermal layer	0.558	0.558	0.558	0.558
$A_{c1} = 1- A_{v1}$	0.442	0.442	0.442	0.442
$R_1 = n \times [(A_{v1}/R_{air}) + A_{c1}/({}^{t_{c1}}/_{\lambda_c})]^{-1}$ $= 2 \times (\frac{0.558}{0.18} + 0.442/\frac{0.04}{\lambda_c})^{-1}$	0.136	0.178	0.181	0.211
t_{c2} (thickness of concrete - m)	0.04	0.04	0.04	0.04
A_{v2}= cavities area / area of thermal layer	0.454	0.454	0.454	0.454
$A_{c2} = 1- A_{v2}$	0.546	0.546	0.546	0.546
$R_2 = n \times [(A_{v2}/R_{air} + A_{c2}/({}^{t_{c2}}/_{\lambda_c})]^{-1}$ $= 1 \times (\frac{0.454}{0.18} + 0.546/\frac{0.04}{\lambda_c})^{-1}$	0.059	0.079	0.081	0.096
R_{is}	0.13	0.13	0.13	0.13
$R_{T1} = \Sigma R$	0.442	0.5366	0.543	0.6165
R_T= 0.9*R_{T1}+0.1*((0.2/λ_c)+R_{es}+R_{is})	0.434	0.527	0.534	0.607
U=1/R_T	**2.304**	**1.898**	**1.873**	**1.647**

Calculations **Concrete type**	**NC**	**SC**	**FC**	**LC**
ρ	2141.6	1858.5	1839.4	1664.2
$\lambda_c = 0.072 e^{0.00125\,\rho_d}$	1.047	0.735	0.718	0.576

R_{es}	0.04	0.04	0.04	0.04
$R_c = n \times \left(\frac{t_c}{\lambda_c}\right) = 2 \times (\frac{0.03}{\lambda_c})$	0.0573	0.0816	0.0836	0.1042
t_c (thickness of concrete - m)	0.14	0.14	0.14	0.14
A_v= cavities area / area of thermal layer	0.775	0.775	0.775	0.775
$A_c = 1 - A_v$	0.225	0.225	0.225	0.225
$R_1 = n \times [(A_v/R_{air}) + A_c/(^{t_c}/_{\lambda_c})]^{-1} = 1 \times (\frac{0.775}{0.18} + 0.225/\frac{0.14}{\lambda_c})^{-1}$	0.167	0.1823	0.1832	0.1911
R_{is}	0.13	0.13	0.13	0.13
$R_T = \Sigma R$	0.3943	0.4339	0.4368	0.4653
$U = 1/R_T$	2.536	2.3047	2.2894	2.149