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EFFECT OF CELLULAR CONCRETE BLOCKS AND TRANSVERSE INTERNAL RIBS ON SHEAR STRENGTH OF HOLLOW REINFORCED CONCRETE BEAMS

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Abstract:
This study is devoted to investigate the structural behavior of reinforced concrete hollow beams filled with cellular concrete blocks (thermostone) under the effect of shear. The number (or location) of the thermostone blocks is the major variable adopted in this research, while, the other variables are kept constant for all tested specimens. The experimental part includes casting and test of five (200x300x1200mm) beam specimens with different locations of internal thermostone blocks. The experimental results indicated that the shear strength are increased (33%) to (70%) for beams containing internal ribs in comparison with reference beam. Also, the change of beam state from hollow section to solid section led to increase the capacity for about (100%). Comparison with ACI-318 Code empirical equation for shear is take place and the results indicated that the ultimate loads are in good agreement with the experimental results.
Keywords: *Shear Strength, Beam, Hollow, Reinforced Concrete, Thermostone, AC1-318.*

تاثير كتل الخرسانه الخلويه والاضلاع الخرسانيه الداخليه المستعرضه على مقاومة القص للعتبات الخرسانيه المسلحه المجوفه

الخلاصه:
تختص هذه الدراسة في التحري العملي و النظري للسلوك الانشائي للعتبات الخرسانية المجوفه المملؤه بكتل الخرسانه الخلويه (الثرموستون) تحت تأثير القص. ان المتغير الرئيسي المعتمد في هذا البحث هو عدد قطع كتل الخرسانه الخلويه الداخليه، بينما تم الابقاء على المتغيرات الاخرى ثابتة لكل العتبات المفحوصه. تضمن الجزء المختبري صب وفحص خمسة عتبات خرسانيه مسلحه مجوفه (او صلده) بابعاد (٢٠٠x300x1200 ملم) تحتوي على كتل الخرسانه الخلويه بمواقع مختلفة. اشارت النتائج المختبريه الى أن مقاومه القص ازدادت بمقدار (٣٣%) الى (70%) للعتبات المجوفه الحاويه على اضلاع مستعرضه مقارنة مع العتبه المرجعيه. ان تغيير حالة او نوع العتبه من المجوفه الى الصلده ادى إلى زيادة التحمل الاقصى بحدود (١٠٠%). تم اجراء مقارنه مع المعادلات التجريبيه للقص المعتمده من قبل كود معهد الخرسانه الامريكي (ACI-318) وقد اشارت النتائج أن الحمل الاقصى في توافق جيد مع النتائج المختبريه.

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1. Introduction

Hollow cross section beam mean closed thin walled section beam. A thin walled beam is characterized by relative magnitude of its dimensions; the wall thickness is small compared to the other linear dimensions of the cross section [1]. A hollow beam structure consists of top and bottom flanges connected by vertical (or inclined) webs to form a cellular section. Presence of these hollow through a solid beam eliminates a significant amount of dead space, and as a result the beam stiffness reduced and this lead to alter the simple beam behavior to a more complex one.

The reduced stiffness of the beam may also give rise to excessive deflection under service load and result in a considerable redistribution of internal forces and moments.

The main advantage of manufacturing cellular or autoclaved aerated concrete (ACC), (called thermostone blocks in Iraq) is to get high thermal insulating material with suitable density and compressive strength to be used as lightweight units in masonry works.

Several researches are interest in hollow beams under the effect of flexural, shear and torsion loads [2]. Shear behavior of reinforced self-compacting concrete deep box beams lightweight concrete infill is also studied [4].

The present research is focused on use of lightweight concrete as infill of a reinforced concrete hollow section. The produced section can be used as beam or slab, which has advantage due to its lighter weight. Shear behavior of hollow RC beams filled with cellular concrete blocks (Thermostone) will be studied as well as the effect of the number of cellular blocks which were separated transversally from each other by concrete ribs.

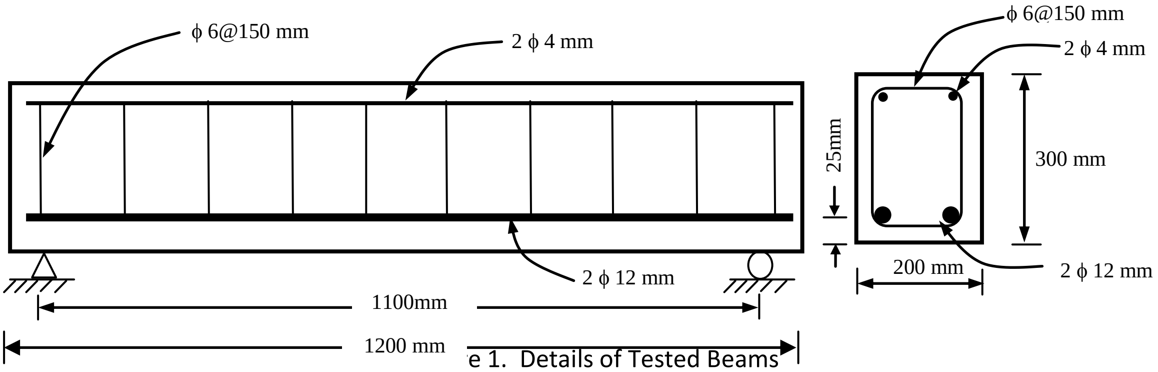
2. Experimental study

2.1. Experimental Program

Tests were carried out on five, rectangular section, simply supported beam specimens under monotonically concentrated load. The tested beams are reinforced in longitudinal direction (flexural reinforcement at the bottom), transverse direction (shear reinforcement) and have been designed to ensure failed in shear mode of failure. The number of internal cellular concrete blocks, which were separated from each other by transverse concrete ribs, is the major adopted variable. The beam length, shear span-depth ratio (a/d), longitudinal and transverse reinforcement are kept constant for all tested beams. To evaluate the compressive strength of concrete, the experimental program consists, also, cast and test of a series of control specimens (cubes).

2.2. Beam Specimens Details

The nominal dimensions and the details of tested beams are shown in Fig. 1 and Table 1. The overall length was (1200 mm), while, the overall depth and width are (300mm) and (200 mm) respectively. All beam specimens were reinforced with ($2\phi 12$ mm) deformed bars as tension (flexural) at the bottom (with clear cover of 25mm) and ($\phi 6$ mm @150mm) deformed bars as shear reinforcement (stirrups). To hold the shear reinforcement (stirrups) in place, (2 ϕ 4 mm) smooth bars at the top are used, see Fig.



e 1. Details of Tested Beams

Figure 2. Details of Reinforcement

The first beam specimen, (B-1), is poured without any cellular concrete block (hollow beam), while the beam specimens (B-2) is poured with one cellular concrete block (the block is confined totally in concrete and extended throughout an entire length). The beam specimens (B-3) and (B-4), are poured with two and four cellular concrete block (separated internally by concrete ribs) respectively. The last beam specimen, (B5), is poured without any cellular concrete block (solid). For beam specimens containing cellular concrete block, the block cross section is (100x200mm) and the thickness of concrete around block is (50mm). It may be noted that the main function of the ribs at the ends is to prevent the local failure of tested beams due to high concentration of stress near supports. While, the main function of the internal ribs is to assist or evaluate its contribution as well as cellular concrete block to increase shear strength of tested beams.

Table 1. Beams Designation and Details

Beam Designation	*Dimensions (mm)*			*Reinforcement*		**Cellular Concrete Block**
	b_w	h	l	Flexural	Shear	
(B-1)*	200	300	1200	$2\phi 12$ mm	$\phi 6$ mm @200mm	None (Hollow)
B-2						One
B-3						Two
B-4						Four
B-5						None (Solid)

*Reference Beam

Table 1 shows the details of tested beams, the locations of cellular concrete block are shown in Fig. 3 and Fig. 4.The cross section of the beam contains a cellular concrete block that blocks out the center of the beam over specified lengths. The cellular concrete block is included to add much resistance to the section and reduce the self-weight of the beam. For practical reasons, the void in the beam cross-section is obtained by a stay-in-place polystyrene block. The creation of the void through the polystyrene block makes casting the beam both time and labor intensive.

Figure 3. Details of Cellular Concrete Blocks

There were three lengths of cellular concrete block pieces as shown in Fig. 3.

1-One piece with length of (1100mm) for beam specimens (B-2), with one cellular concrete block and one concrete rib (50mm width) at each end of the beam.

2-Two cellular concrete block pieces with length of (525mm) for each one of them, separated by three concrete ribs (50mm width) (one internal and two at the ends), for beam specimen (B-3).

3-Four cellular concrete block pieces with length (237.5mm) for each one of them, separated by five concrete ribs (50mm width) (three internal and two at the ends), for beam specimens (B-4).

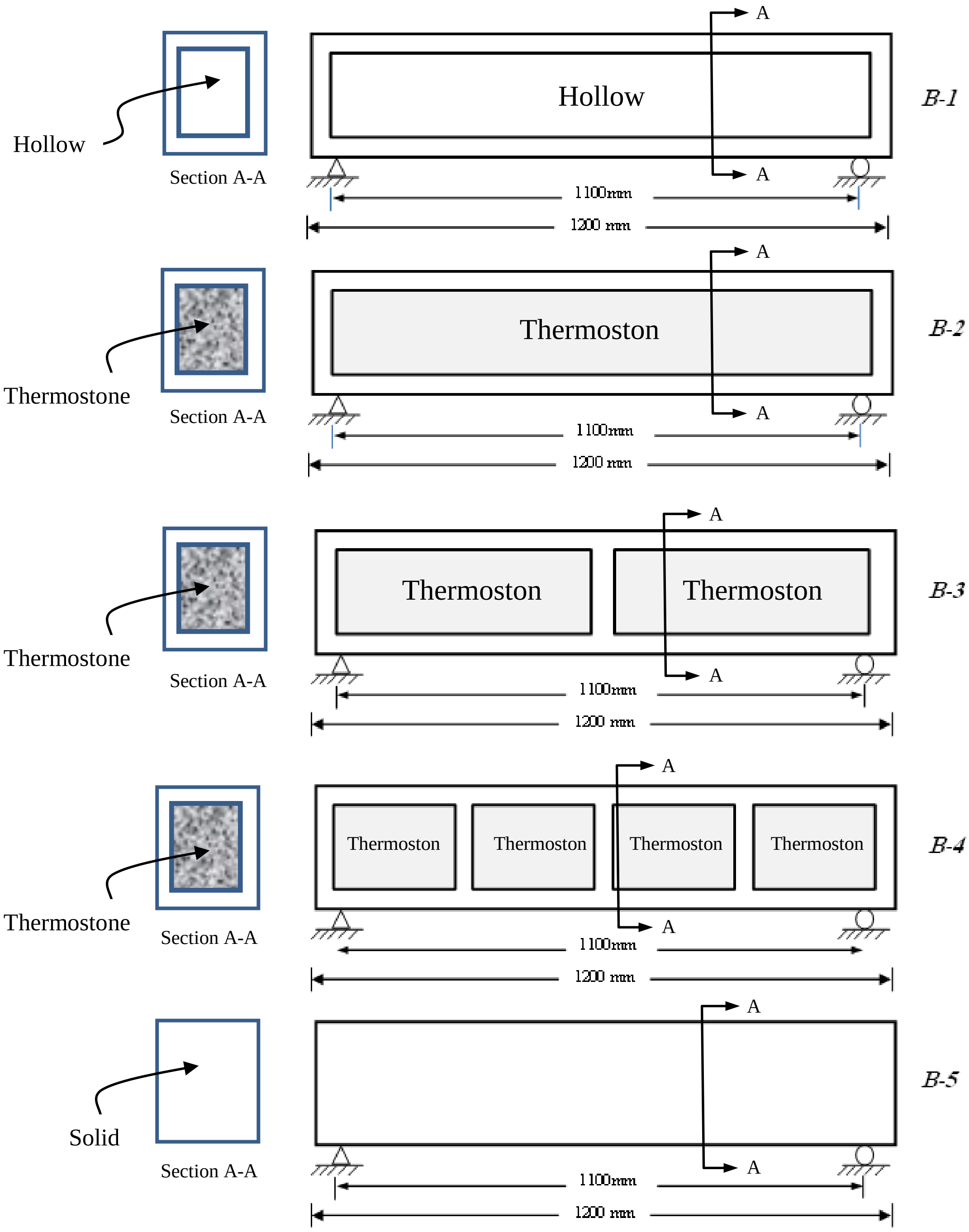


Figure 4. Locations of Cellular Concrete Blocks

2.3. Materials

In manufacturing the test specimens, the properties and description of used materials are reported and presented in Table 2.

Tensile test of steel reinforcement (manufactured in Ukraine) was carried out on (ϕ12mm) hot rolled, deformed, mild steel bar employed as tension reinforcement, and (ϕ6mm) deformed mild steel bar was used as stirrups (shear reinforcement). Also, the test included testing of (ϕ4mm) plain mild steel bar which was used to hold stirrups in place. Table 3 shows the results of tensile test for bars.

Table (2) Description of Construction Materials

Material	**Descriptions**
Cement*	Ordinary Portland Cement (Type I)
Sand**	Natural sand from Al-Ukhaider region with maximum size of (4.75mm)
Gravel**	Crushed gravel with maximum size of (12mm)
Water	Clean tap water (Used for Both Mixing and Curing)

* Conform to Iraqi specification No. 45/1989[5]. ** Conform to Iraqi specification No. 45/1984[6].

Table (3) Properties of Steel Bars

Nominal Diameter (mm)	*Bar Type*	f_y* *(MPa)*	f_u *(MPa)*	E_s** *(GPa)*	*Elongation %*
4	Plain	461	633	200	16
6	Deformed	383	545	200	11
12	Deformed	860	915	200	16

*****Each value is an average of three specimens (Each 40 cm length) **ACI 318-M08[7]

2.4. Cellular Concrete Blocks

Al-Najaf thermostone blocks are used throughout this work. The common raw materials used to manufacturing thermostone blocks are Portland cement, hydrated lime (calcium oxide), aluminum fine powder, water, and sand. The raw materials are mixed into slurry by a special machine and then poured into molds. Mechanical properties of cellular concrete block are presented in Table 4. The used blocks conforms to ASTM-C1386-07 [8], class (70). Modulus of rupture (f_r) of thermostone blocks can be roughly estimated according to the Equation (1) [9]:-

$$f_r = 0.27+0.21f_c \quad \ldots\ldots\ldots\ldots\ldots(1)$$

While, the splitting tensile strength can be estimated according to the Equation (2) [10]:-

$$f_t = 0.2\sqrt{f_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where, (f_c) is the compressive strength in MPa.

Poisson's ratio of thermostone blocks can be considered same as the traditional concrete [11].

Table 4. Properties of Cellular Concrete Block*

Strength Class	*Density (kg/m^3)*	*Average Compressive Strength (N/mm^2)*	*Modulus of Elasticity (N/mm^2)*	*Thermal Conductivity (W/mk)*
C 40	400	2.4	180-1170	0.12
C 50	500	3.2	1240-1840	0.13
C 60	600	3.5	1760-2640	0.16
C 70	700	5.0	2420-3580	0.17

*According to ASTM-C1386

2.5. Concrete Mix design

One concrete mix was used in this work; the concrete mix proportions are reported and presented in Table 5. It was found that the used mix produces good workability and uniform mixing of concrete without segregation.

Table 5. Proportions of Concrete Mix

Parameter	**Quantity**
Water/cement ratio	0.45
Water (Liter)	168
Cement (kg/m^3)	420
Fine Aggregate (kg/m^3)	600
Coarse Aggregate (kg/m^3)	1200

2.6. Molds

One wooden mold containing four boxes, (200x300x1200mm) dimensions are used to poured beam specimens, see Fig. 3. The molds were manufactured with (18mm) thick plywood base and seven movable sides. The sides were fixed to the base by screws. When the mixing process was completed, the beam and control specimens were then cast in three layers and compacted by a table vibrator (external vibrator) to shake the mix and consolidate it into the molds. The surface of the concrete (top face of control specimen and side face of beam specimens) was leveled off and finished with a trowel. Then, the specimens were covered with a nylon sheet to prevent evaporation of water. It may be noted that, to ensure that it would be easy to remove the samples when the concrete hardened, the inner faces of molds was oiled.

2.7. Test Measurements and Instrumentation

Hydraulic universal testing machine (MFL system) was used to test the beams specimens as well as control specimens. Central deflection has been measured by means of (0.01mm) accuracy dial gauge (ELE type) and (30mm) capacity. The dial gauges were placed underneath the bottom face of each span at mid.

2.8. Concrete Mixing and Placing (Pouring)

2.8.1. Concrete Mixer and Vibrating Table

The concrete was mixed by using a horizontal rotary mixer with (0.19 m3) capacity. While, vibrating table are used to vibrate the concrete of specimens (beams and control specimens). The vibrating table consists of (1.0x1.5m) table made of (10mm) thick steel plate. The source of vibration was a rapidly rotating eccentric weight which makes the table vibrates with a simple harmonic motion. The vibrator was manufactured by Marui Company, Japan. The frequency of vibration was (7000rpm).

2.8.2. Curing and Age of testing

After (24) hours, the beam specimens and control specimens were stripped from the molds and cured (kept) in water bath for (28) days with almost constant laboratory temperature. Before (24) hours from the date of testing, they were taken out of the water bath and tested in accordance with the standard specifications.

2.9. Test Results of Control Specimens

Test results of mechanical properties of control specimens (compressive strength) are summarized in Table 6. Compressive strength for cubes (f_{cu}) was carried out on concrete in accordance with BSI 881-116 [12] with standard cubes (150x150x150 mm). The cubes were loaded uniaxially by the universal compressive machine up to failure.

Table 6. Mechanical Properties of Concrete

Property (MPa)	Value (MPa)
Cube compressive strength (f_{cu}) *	30
Cylinder compressive strength ($f_c^{'}$)**	25.5

*Average of three samples. ** $f_c^{'}$ =0.85 f_{cu}

2.10. Test Procedure

All beam specimens were tested using universal testing machine (MFL system) with monotonic loading to ultimate states. The tested beams were simply supported over an effective span of (1100mm) and loaded with a single-point load; Fig. 5 shows the setup of beam specimens. The beams have been tested at ages of (28) days. The beam specimens were placed on the testing machine and adjusted so that the centerline, supports, point load and dial gauge were in their correct or best locations.

Loading was applied slowly in successive increments. At the end of each load increment, observations and measurements were recorded for the mid-span deflection and crack development and propagation on the beam surface. When the beams reached advanced stage of loading, smaller increments were applied until failure. They fail abruptly without warning (sudden failure) and the diagonal cracks that develop becomes wider and as a result, the load indicator stopped recording anymore and the deflections increased very fast without any increase in applied load. The developments of cracks (crack pattern) were marked with a pencil at each load increment.

Figure 5. Beam Specimen Setup

3. Results and Discussion

As mentioned before, the main objectives of this study are to examine or assess the effect or contribution of internal thermostone blocks on shear behavior of hollow reinforced concrete beams.

During the experimental work, ultimate loads, load versus deflection at mid-span for each beam were recorded. Photographs for the tested beams are taken to show the crack pattern and some other details. The recorded data, general behavior and test observations are reported to analyze and understand the effects of adopted parameters on the shear behavior.

3.1. General Behavior

Photographs of the tested beams are shown in Fig. 6 and test results are given in Table 7. All beams were designed to fail in shear, which was characterized by sudden failure and diagonal wide cracks which extended from supports towards the load or openings locations.

The general behavior of the tested beams can be described as follows; at early stages of loading, small vertical deflection initiated in the mid span of tested beams, with further loading, diagonal cracks extended upwards and became wider in shear span. One or more cracks propagated faster than the others and extend through weak locations in the beam (hollow zones) and reached the compression face (near applied load), where crushing of the concrete near the positions of applied loads had occurred due to high concentrated stresses under load.

Figure 6. Crack Patterns Tested Beams

3.2. Mode of Failure

The appearance of the cracks reflects the failure mode for the tested beams. The experimental evidences show that the diagonal cracks extended horizontally along the tension reinforcement and eventually, the failure take place due to diagonal tension cracks were formed diagonally and moved up and towards the position of load, this crack is associated with crushing of the concrete near the positions of applied loads, this mode of failure is called “Shear-Compression” failure, as shown in Fig. 6.

The recorded ultimate loads of the tested beams are presented in Table 7. As expected, test results show that the reference beam (B-1) has the minimum ultimate strength in comparison with the rest beams. This may be due to absent of any internal ribs (or thermostone blocks) in the section (in shear span).

Table 7. Ultimate Shear Strength of Tested Beams

Beam Designation	P_u *(kN)*	P_c *(kN)*	V_u *(kN)***	$(V_u)_i/(V_u)_R$ *(%)*	**Mode of Failure**
(B-1)*	90	15	45	1.0	Shear-Compression
B-2	120	20	60	1.33	Shear-Compression
B-3	140	24	70	1.6	Shear-Compression
B-4	150	24	75	1.7	Shear-Compression
B-5	180	25	90	2.0	Shear-Compression

*Reference Beam **$V_u = P_u/2$

As shown in Table 7, relatively, the ultimate shear strength increased when the number of concrete blocks increased (in shear span) and when we moved toward of and closes up to the support. For the tested beam (B-5), which have made fully without hollows, the ultimate shear strength increased by (100%) in comparison with reference beam, this clearly due to concrete contribution to resist shear stress.

The ultimate shear strength increased about (33%) to (70%) for the tested beams (B-2), (B-3) and (B-4) respectively, the presence of internal ribs led to increase resistant area of concrete and as a results, the shear strength increased significantly.

3.4. Deflections

Load-deflection curves of the tested beams at mid-span at all stages of loading up to failure are constructed and shown in Fig. 7.

As shown in Fig. 7, at the beginning, all curves were identical and the tested beams exhibited linear behavior and the initial change of slope of the load-deflection curves occurred between (10 kN to 30kN), which may be indicated the first crack loads. Beyond the first crack loading, each beam behaved in a certain manner.

Behavior of reference Beam (B-5) exhibited greater loads and smaller deflections in comparison with the other beams. This beam had the greatest stiffness due to absent of any hollows. For tested beams (B-2), (B-3) and (B-4), presence of thermostone blocks as well as the internal ribs in hollow section leads to increases the stiffness of tested beams due to concrete contribution, and this leads to increase in carrying capacity and reduce in corresponding deflection.

In other words, due to abrupt changes in the sectional configuration (from solid to hollow), for beam specimen (B-1), reduction in stiffness of the tested beams is occurred, as a results, the hollow beam corners, closed thin webs and flanges are subject to high stress concentration and produced cracking and excessive deflection.

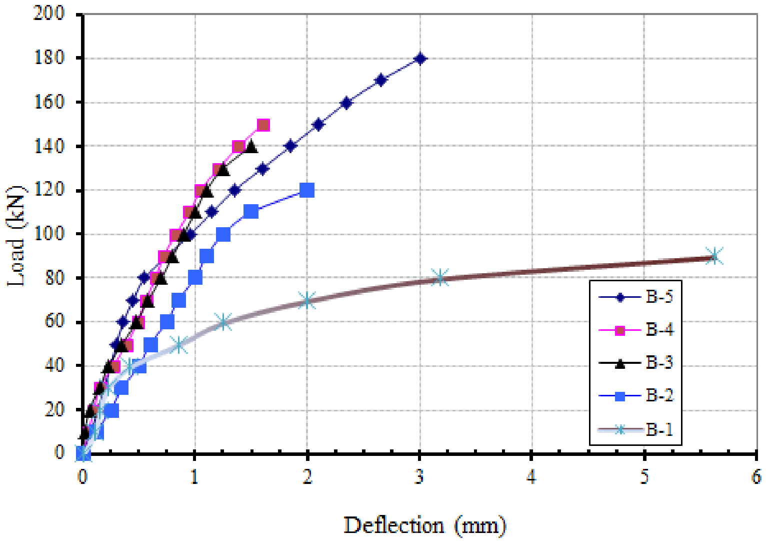


Figure 7. Load-Deflection Relationship of tested Beams

3.5. Comparison between Experimental Results and ACI-318

The ACI-318 empirical equation can be used directly to calculate shear strength of solid or hollow sections, see (Appendix-A). For hollow sections containing thermostone blocks and internal ribs, (B-2, B-2 and B-4), the shear strength estimated by ACI-318 empirical equation agree well with the experimental results.

Comparison between experimental results and ACI-318 are reported and presented in Table (8). The analytical results indicated that the ultimate loads are in good agreement with the experimental results. It may be noted that the contribution of transverse reinforcement is taken into account to evaluate shear strength as well as the contribution of concrete.

Table (8) Experimental and Calculated Shear Strength

Beam Designation	*V_u (kN)*		**$(V_u)_{Exp.}$/ $(V_u)_{ACI}$**
	Exp. *	ACI-318**	**(%)**
B-1	45	66.67	0.67
B-2	60	72.3	0.83
B-3	72	72.3	1.0
B-4	7٥	72.3	1.04
B-5	90	89.8	1.0

*Table (7) **Appendix-A-

3.6. Contribution of Thermostone Blocks

Presence of thermostone blocks leads to increases the stiffness of tested beams due to blocks contribution, and this leads to increase in carrying capacity. Experimentally, the contribution of thermostone blocks is the difference between the capacities of hollow beam specimen, (B-

1), and beam specimen, (B-2), which filled fully with thermostone blocks. As shown in Table 8, the increased in ultimate capacity is for about (33%).

3.7. Contribution of Transverse Internal Ribs

As shown in Table 8, presence of thermostone blocks as well as the internal ribs in hollow section leads to increases the stiffness of tested beams due to concrete contribution, and this leads to increase in carrying capacity. Experimentally, the contribution of transverse internal ribs is the difference between the capacities of beam specimen, (B-2), which filled fully with thermostone blocks and beam specimens (B-3) and (B-4), which contents one and three transverse internal ribs respectively. As shown in Table 8, the increased in ultimate capacity is for about (17%) and (25%). This means that the presence of internal ribs affected significantly on ultimate capacity of tested beams.

4. Conclusions

Based on the results obtained from the experimental and theoretical work, the following conclusions are obtained:-

1- Presence of thermostone blocks and internal ribs in hollow sections lead to increase shear strength in a certain degree. The shear strength is increased (33%) to (70%) for beams filled with thermostone blocks and containing internal ribs in comparison with reference beam.

2- The contribution of thermostone blocks to increase shear capacity was (33%), for beam specimens filled fully by thermostone blocks, while the contribution of transverse internal ribs were (17%) and (25%) for beam specimens contains one and three transverse internal ribs respectively.

3-The change of beam state from hollow section to solid section led to increase the capacity for about (١٠٠%).

4- The ACI-318 empirical equations can be used directly to calculate shear strength of solid or hollow sections, but, for hollow sections containing internal ribs, and to take into account presence of these ribs, modification for ACI-318 is required.

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Appendix-A-

Shear Strength of RC Sections Based on ACI-318 Code

According to ACI-318 Code, the nominal shear strength of RC members can be calculated by using the following equation:- $V_n=V_u/\phi=V_c+V_s$ ……………..(A-1)

To take into account the contribution of thermostone blocks to resist shear strength, the above equation can be rewrite as follows:- $V_n=V_u/\phi=V_c+V_s+V_{Th.}$ ……….(A-2)

Where,

V_u = ultimate shear strength.

V_c= shear strength of concrete.

V_s= shear strength of transverse reinforcement.

V_{Th}= shear strength of thermostone

ϕ = shear reduction factor

1-Shear Strength of Concrete Solid Sections (V_c)

According to ACI-318 Code, the shear strength of solid concrete member can be calculated by using the following equation:- $V\mathrm{c} = \lambda \frac{1}{6}\sqrt{f_c'}\, bw.d$ ……………...(A-3)

Where:

f_c' = Cylinder Compressive Strength of Concrete=25.6MPa (see Table 5)

b_w = Beam Width=200mm

d = Effective depth of Beam=275mm

λ = Modification factor

=1.0 (For normal strength concrete)

=0.85 (For sand lightweight concrete)

=0.75 (For lightweight concrete)

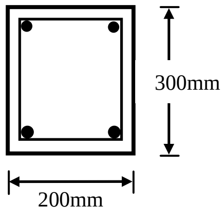


Fig. A-1 Solid Section

$$Vc = (1) * \frac{1}{6}\sqrt{25.5}\,(200)(275) * 10^{-3} = 46.3kN$$

<u>2-Shear Strength of Concrete Hollow Sections(</u>V_c<u>)</u>

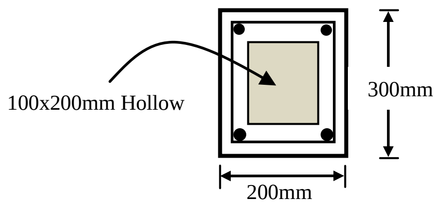
According to ACI-318 Code, the shear strength of hollow concrete member can be calculated by using the following equation:- $Vc = \lambda \frac{1}{6}\sqrt{f_c'}\ bw.d$……………...(A-4)

Where:

f_c' = Cylinder Compressive Strength of Concrete=25.5MPa (see Table 5)

b_w = Total Width of Vertical Thin Walls of Hollow Section=(50+50)mm=100mm

d = Effective depth of Beam=275mm



$$Vc = (1) * \frac{1}{6}\sqrt{25.5}\,(100)(275) * 10^{-3} = 23.15kN$$

Fig. A-2 Hollow Section

<u>3-Shear Strength of Transverse Reinforcement (Stirrups) (</u>V_s<u>)</u>

According to ACI-318 Code, the shear strength of transverse reinforcement can be calculated by using the following equation:- $Vs = \frac{A_v * f_y * d}{s}$……………...(A-5)

Where:

A_v=Area of transverse reinforcement (area of legs)=2*π/4*(d_b)^2=2*π/4*(6)^2=56.55mm^2

f_y=Yield tensile strength of steel bars=420MPa

d= Effective depth of Beam =275mm

S= spacing between stirrups=150mm

$$Vs = \frac{(56.55) * (420) * (275)}{150} * 10^{-3} = 43.5\ kN$$

4- Shear strength of Thermostone block (V_{Th})

Shear strength of Thermostone block by using the following equation:-

$$V_{Th.} = \lambda \frac{1}{6}\sqrt{f_c'}\ A_{Th.} \qquad \text{(A-6)}$$

Where:

f_c' = Compressive Strength of Thermostone =5.0 MPa (see Table 4)

$A_{Th}.$ = Area of Thermostone section=100x200mm

λ=0.75

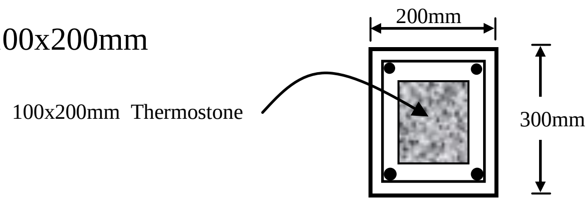


Fig. A-3 Hollow Section filled with Thermostone

$$V_{Th.} = (0.75) * \frac{1}{6}\sqrt{5}\ (100)(200) * 10^{-3} = 5.63kN$$

So, the nominal shear strength of RC solid member is:-

V_n=46.3+43.5 = 89.8 kN

While, the nominal shear strength of RC hollow member is:-

V_n=23.15+43.5= 66.65 kN

Also, the nominal shear strength of RC hollow member containing thermostone blocks is:-

V_n=23.15+43.5+5.63= 72.3 kN