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EVALUATING THE PERFORMANCE OF SUSTAINABLE INTERLOCKING CONCRETE BLOCKS MANUFACTURED FROM RECYCLED CONCRETE AGGREGATE

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Abstract: This paper aims to investigate the possibility of using construction and demolition concrete wastes (C&D) in the production of recycled aggregate, which in turns will be used in the production of interlocking concrete blocks. Five groups of concrete mixtures have been prepared and tested with different proportions of recycled aggregates (0%, 25%, 50%, 75% and 100%). A series of tests (density, compressive strength, flexural strength and ultrasonic test) conducted on concrete cubes and concrete blocks to select best proportion of recycling concrete aggregate (RCA) to produce recycled aggregate concrete. The best proportion of RCA was 25%. This proportion was selected to evaluate the performance of interlocking concrete blocks pavement through studying the influence of block shape, thickness, laying pattern and jointing sand based on static plate loading test. The effect of load on the tested block pavement behavior was discussed. This behavior was characterized by deflection. It is found that shape and thickness of blocks have a significant influence on the behavior of interlocking concrete blocks pavement.

Keywords: *Concrete, Blocks, Recycling, Aggregate, Deflection, Density.*

تقييم اداء البلاطات الخرسانية المتداخلة المستدامة المصنعة من الركام الخرساني المعاد تدويره

الخلاصة: تهدف هذه الدراسة إلى إمكانية استخدام مخلفات الخرسانة الانشائية المتهدمة في إنتاج الركام المعاد تدويره والذي بدوره سيستخدم في إنتاج البلاطات الخرسانية المتداخلة. تم تحضير خمسة مجاميع من الخلطات الخرسانية بنسب مختلفة من الركام المعاد تدويره (0%، 25%، 50%، 75% و 100%). تم اجراء عدة فحوصات (الكثافة، مقاومة الانضغاط، فحص الانثناء بالإضافة الى الفحص اللااتلافي) على المكعبات والبلاطات الخرسانية لاختيار افضل نسبة من الركام المعاد تدويره لإنتاج الخرسانة ذات الركام المعاد تدويره. ان افضل نسبة للركام المعاد تدويره كانت 25%. وهذه النسبة تم اختيارها لفحص اداء التبليط بالبلاطات الخرسانية المتداخلة من خلال دراسة تأثير شكل وسماكة وطريقة رصف البلاط الخرساني بالإضافة الى تأثير المفاصل الرملية بالاعتماد على فحص التحميل الاستاتيكي. تم مناقشة تأثير الحمل المسلط على سلوك التبليط بالبلاطات التي تم فحصها. وهذا السلوك تم وصفه بواسطة الهطول. لقد وجد ان شكل وسماكة الكتل الخرسانية لها تأثير مهم على سلوك التبليط بالبلاطات الخرسانية المتداخلة.

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1. Introduction

Construction and demolition (C&D) waste materials can be recovered and re-used in new construction process. This depends on many factors including type of project, cost effectiveness of recycling, project timeline, and experience of contractor [1]. The total amount of waste in the world is 1.8 billion tons, while only 5% of these materials are reusable. Statistics showed that, 68% of recycled aggregates are used as a subbase, about 6% are used in the production of concrete, and 9% are used in the production of hot asphalt mixtures [2].

Iraq has a huge amount of concrete wastes and high consumption rate of natural aggregates. For this reason, it is necessary to provide solutions for the use of C&D waste materials in new concrete production such as their use in manufacturing of interlocking concrete block pavement. The reasons for having large amounts of C&D wastes in Iraq are as follows:

1. The demolition of residential, official and commercial buildings due to war operations during the last decades.
2. Wastes resulting from the demolition of old buildings and infrastructure.

Several researchers in Iraq and the Middle East carried out research on the use of recycled aggregates. Abbas [3] proved that the compressive strength of recycled concrete increases with increasing recycled aggregates in the mix as the flexural strength decreases with the increase in proportion of recycled aggregates. Recycled concrete density decreases with the increase the proportion of recycled rubble while in contrary to compressive strength [4].

The speed of the wave decreases with the increase in the proportion of recycled aggregates [5]. Wave speed increases with compressive strength and the relationship is non-linear [6]. El-Ariss [7] proved that the use of ordinary cement with additives is the best in comparison with the rest of other types of cements and depending on the chemical properties of the concrete action therefore, preliminary tests for other types of cement are necessary.

Recycled rubbles tests display high absorption ability that arrives to 5.9 %. These high results can be cured by soaking recycle aggregate in water before manufacturing process. Comparing with ordinary aggregate, recycled aggregate displays low density and specific gravity [8]. The workability of RAC mix is lower than the mix with natural aggregate, as concrete mixture with 30 % RCA has satisfied workable mix [9]. While, the superplasticiser is considered for satisfying the workability of concrete for more recycled aggregate percentages in mix [9].

An experiment was conducted in India using static plate load tests in the laboratory scale model made of steel box of 775 mm x 775 m x 450 mm to study the various parameters on the structural behavior of concrete block pavement (CBP). In this study, a 200 mm thick crushed rock was used as subbase. From the test, it was concluded that, the strength and laying pattern of block have no influence on the deflection of block pavements, and the deflection of the concrete block surface course decreases with the increase in load and number of load repetitions [10]. Muraleedharan et al. [11] conducted an experiment in a test section measured 6 m x 3.75 m in the laboratory of Central Road Researchers Institute. Researchers carried out static test using rigid plate and dynamic load test using falling weight deflectometer (FWD) on pavement with 60 mm unipave block on bound (lean concrete) and unbound Water Bound Macadam (WBM) base courses. From the study, they concluded that, for the same applied pressure, the lean concrete base course exhibits a deflection twice that obtained under WBM base course.

A static plate load test was also performed on CBP to study the effect of thickness of subbase material constructed with WBM and Wet Mix Macadam (WMM). From the study, the researcher concluded that, the increase in thickness of subbase from 150 mm to 300 mm reduces the deflection of the CBP, and the WBM had a higher strength as compared to the WMM subbase [12]. To evaluate the CBP, plate load test and accelerated traffic test were carried by Teiborlang et al., 2006 [13]. From this research, it is concluded that, the equivalent elastic modulus of concrete block layer has been increased with the increase in subbase thickness, and modulus varied from 700 MPa to 3000 MPa. A test on laboratory scale model on ICBP inside a tank of 1m x1m x 1m was performed and from this, it was reported that aggregate base course layer had more load spreading ability due to interlocking action of aggregate particle [14].

2. Objectives of This Study

This research is carried out to accomplish the following objectives:

1. To study the possibility of using recycled concrete wastes as aggregate in new concrete by evaluating the physical and mechanical properties of the recycled aggregate and the produced concrete.
2. To determine the optimum ratio of recycled aggregates to natural aggregates to be used as a replacement in the produced concrete.
3. To manufacture different shapes and dimensions of interlocking concrete blocks similar to those used locally using concrete with recycled aggregate and to evaluate the physical and mechanical properties of the manufactured concrete blocks.
4. Evaluating the performance of interlocking concrete block pavement by a series of static plate load tests on a laboratory setup. These tests conducted to assess the influences of block shape, thickness, laying patterns and jointing sand on the overall pavement performance.
5. The behavior of interlocking concrete blocks under static load test is characterized in term of deflections. The data of deflections have been back calculated using the computer program winjulea to find the elastic modulus of subgrade soil, subbase and concrete block layer.

3. Types of Aggregates in Concrete Mixes

3.1. *Natural Aggregate (Coarse and Fine)*

The nominal maximum size of the crushed natural coarse aggregate (CNCA) which has been used in this study is 19 mm and the minimum size is 2.63 mm. The physical properties and sieve analysis of this aggregate are shown in Table 1 and Fig. 1, respectively. Physical properties and sieve analysis of the crushed natural fine aggregate (CNFA) are shown in Table 2 and Fig. 2, respectively.

Table 1. Physical properties of crushed natural Coarse aggregate (CNCA)

Physical Properties	Test Results	Limits%	Specifications
Gsb Dry	2.571	------	ASTM C 127 [15]
Absorption %	0.38	------	ASTM C 127 [15]
Sulfate content	0.082	$\leq$ 0.1%	AASHTO T-290 [16]
Organic impurities	0.25	< 2 %	AASHTO T-21 [17]
Gsb OD	2.537	------	ASTM C 127 [15]
Gsb SSD	2.524	------	ASTM C 127 [15]
Abrasion resistance %	12	Less than 35%	ASTM C 131[18]
Dry unit weight (g/cm^3)	1.600	-------	ASTM C 29 [19]

* Tests were carried out by National Center for Construction laboratories and Research (NCCLR)

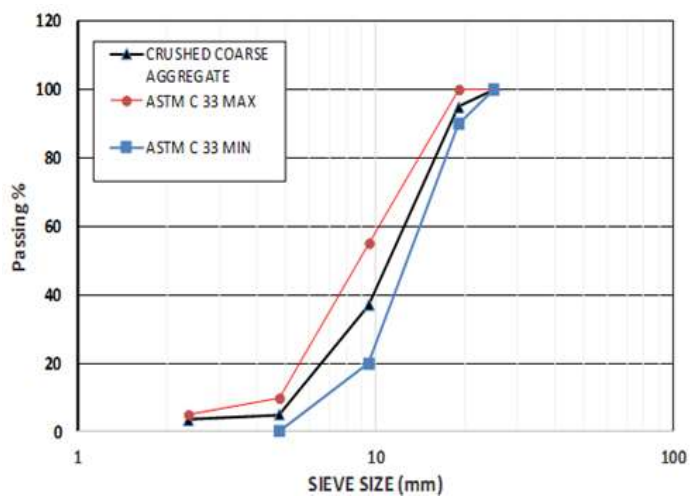

Figure 1. Sieve size analysis of crushed natural aggregate (CNCA)

Table 2. Physical properties of natural fine aggregate

Physical Properties	Test Results	Limits	Specifications
Gsb dry	2.672	---------	ASTM C 128 [20]
Absorption %	0.53	-------------	ASTM C 128 [20]
Fineness Modulus (F.M)	2.83	2.3-3.1	------------
Sulfate content	0.079	$\leq$ 0.5 %	-----------

* Tests were made by National Center for Construction Laboratories and Research (NCCLR)

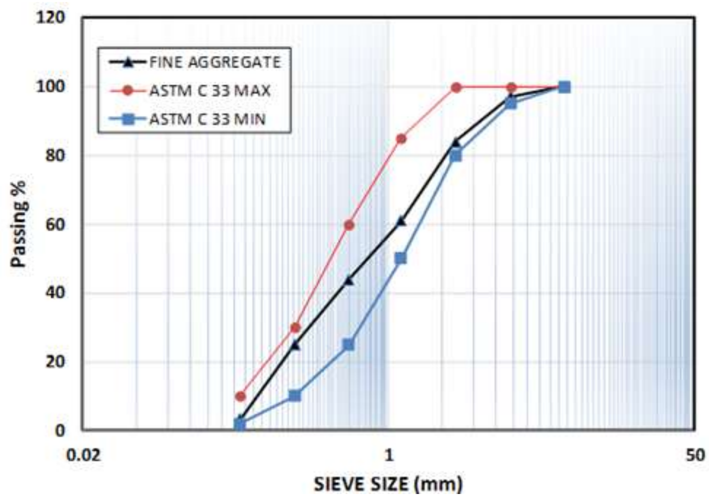

Figure 2. Sieve size analysis of natural fine aggregate

3.2. *Recycled Coarse Aggregate*

In this study, the recycled coarse aggregate (RCA) has been obtained by crushing concrete waste from Kirkuk. The concrete slab, sidewalk and curb materials have been selected as the source for RCA. The intention in this study is to prepare concrete mixes which are suitable for concrete pavements. Therefore, the maximum size of 19 mm of the RCA has been used. Any RCA over 19 mm in size contains excess interfacial transition zones (ITZ) would negatively influence the strength of the concrete. The crushing of demolished concrete was done using jaw crusher machine near Taza quarry and sieved according to the standard sieve limits of 19 mm size. Recycled Coarse Aggregate (RCA) after crushing has been divided using standard sieves into two types: recycled coarse aggregate (RCA) which passes sieve 19 mm and retains on sieve 9.5 mm, and recycled coarse aggregate (RCA) which passes sieve 9.5 mm and retains on sieve 4.75 mm. The same tests and sieve analysis for natural aggregates have been carried out on recycled coarse aggregates. The physical properties and sieve analysis are shown in Table 3 and Fig. 3.

Table 3. Physical properties of recycled coarse aggregate (RCA)

Physical Properties	Test Result	Standard
Gsb Dry	2.492	ASTM C 127 [15]
Absorption %	6	ASTM C 127 [15]
Sulfate content	0.061	
Gsb OD	2.424	ASTM C 127 [15]
Gsb SSD	2.493	ASTM C 127 [15]
Abrasion resistance %	25	ASTM C 131 [18]
Dry Unit weight (g/cm^3)	1.390	ASTM C 29 [19]

* Tests were carried out by National Center for Construction Laboratories and Research (NCCLR)

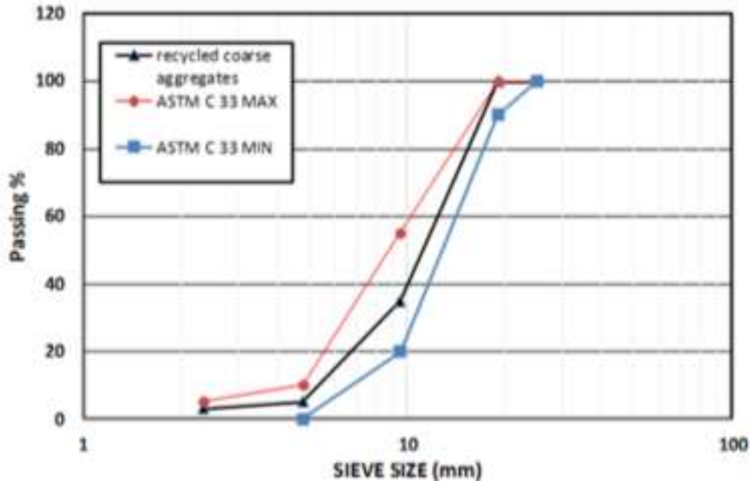

Figure 3. Sieve size analysis of recycled coarse aggregate

4. Concrete Mixes

4.1. *Groups of Mixes*

Five groups of concrete mixes have been prepared in this study with target compressive strength (f_{cu}) of 33 MPa. These groups of mixes have been prepared by weight replacement of natural coarse aggregate (NCA) by recycled coarse aggregate (RCA) as follows:

The first group : 0% replacement.
The second group: 25% replacement.
The third group : 50% replacement.
The fourth group : 75 % replacement.
The fifth group : 100% replacement.

4.2. *Samples Preparation and Planned Program for Concrete Tests*

The mixtures and samples have been prepared in the Structural and Material laboratory of the Civil Engineering department of Faculty of Engineering/Al-Mustansiriyah University to determine the properties of hardened concrete. The samples of cubes, prisms and concrete blocks were cast for each group of concrete mixes as shown in Table 4 and Table 5.

Table 4. Casting samples for concrete properties

Test	Samples	No. of samples
Compressive strength	Cubes (150×150×150) mm at 7 days age	3
	Cubes (150×150×150) mm at 28 days age	3
Flexural strength (modulus of rupture)	Prism (100×100×550) mm at 28 days age	3

Table 5. Casting samples for concrete blocks

Test	Concrete Blocks		Number of Samples
	Shape	Thickness (mm)	
Compressive Strength	I shape	80	3 for each mix (total 3x5=15)
	Octagonal	80	3 for each mix (total 3x5=15)
	Rectangular	80	3 for each mix (total 3x5=15)
	Rectangular	60	3 for each mix (total 3x5=15)
Static Plate Load	Rectangular	80	10
	Rectangular	60	10
	Octagonal	80	10
	I shape	80	10

4.3. *Mix Constitutes*

The concrete mix proportions of (1) m^3 are shown in Table 6**.** All the mixes have been designed for slump of (25-100) mm and air content of 0.015 per unit volume. The same (water/cement) ratio and Portland cement content have been used in all mixes; the only variable is the coarse aggregate type (with replacement), as shown in Table 7.

Table 6. Mix proportions for 1 m^3

Cement (kg)	Sand (kg)	Coarse aggregate (kg)	Water (Lt)	W/C Ratio
460	675	1080	192	0.42

Table 7. Mix proportions of all mixes for 1 m^3

Mix	Cement (kg)	Sand (kg)	NCA (kg)	RCA (kg)	Water (kg)
Mix A	460	675	1080	------	192
Mix B	460	675	810	270	192
Mix C	460	675	540	540	192
Mix D	460	675	270	810	192
Mix E	460	675	------	1080	192

5. Static Plate - Load Test for Interlocking Concrete Blocks

5.1. *Test Setup*

The test performed by using a laboratory scale model setup in Faculty of Engineering/ Mustansiriyah University. It consisted of a strong steel box of 450 * 450 mm in plan and 1100 mm depth. The section of interlocking concrete block pavement (ICBP) was constructed within the test box as shown in Fig.4. A hydraulic jack was fitted to the reaction frame to apply a central load to the pavement through a rigid circular plate of diameter 300 mm. This diameter corresponds to the tire contact area used in pavement analysis. A maximum load of 51 kN was applied to the pavement.

This load corresponds to half the single axle legal limit. Two gauges with an accuracy of 0.01 mm were placed on two opposite side of the plate at a distance 150 mm from the center of loading to measure the deflection of the pavement.

The average value of two deflection readings was used for comparing experimental results. In this study thickness of bedding sand and quality of sand in bed and joints were kept constant for all experiments. The loose bedding sand thickness and the compacted thickness of crushed aggregate subbase were 50 mm and 350 mm, respectively.

Figure (4) Static plate load test setup

5.2. *Preparation of Test Section*

The soil samples have been tested in the laboratory for CBR test, optimum water content, density, soil classification and other tests which are carried out by (NCCLR) as shown in Table (8**).** Subgrade was placed and compacted in 4 layers of equal thickness and its optimum moisture content was checked for its density. Load of 10 kN was applied to the surface of the subgrade through the hydraulic jack and surface deflection was noted on each side of the plate. These data was later used to determine the modulus of the subgrade. The subbase layer consists of unbound granular particles.

The CBR, optimum water content, density tests of subbase are conducted in soil laboratory, other properties tests such as chemical tests and sieve analysis have been carried out by (NCCLR), as shown in Table 9 and Fig. 5. Subbase layer of 350 mm thickness was placed and manually compacted over the subgrade layer. After the process of compaction on the subbase material is over, a load of 30 kN was applied through the hydraulic jack and deflection measurements of the surface was noted. These data were later used to determine the subbase modulus by back calculation procedure. The bedding sand is placed on the subbase layer having thickness of 50 mm. Concrete blocks are placed and compacted manually on the top of the bedding sand. When testing concrete blocks with joining sand, the same sand that was used as bedding material was made to pass through sieve of (1.18 mm) and spread on laid blocks. The sand is brushed into the joints and compacted so that the sand can fill the gaps in between blocks. More joining sand was spread on the surface and compaction was carried out until the sand refuse to go in between the concrete blocks.

Static plate - load test was applied on the block surface layer at a load of 51 kN and surface deflection was noted. These deflection data were later used to determine the concrete block modulus by back calculation procedure. The static load test was carried out on concrete blocks for all the variable parameters of this study as listed in Table 10.

Table 8. Subgrade soil laboratory test results

Tests	Test result	Specification Limits
L.L%	35	55 max
P.I %	20	30 max
Total sulfate (1:50) %	2.88	10 max
Organic substance	0.063	12 max
Soil classification	CL	---------

Table 9. Subbase materials test results

Tests	Test result	Specification limits
L.L%	None	25 max
P.I %	None	6 max
Abrasion resistance %	15	45 max
SO_3 %	2.72	5 max
Total sulfate (1:50) %	13.55	10 max
$Caso_4$, $2H_2O$ %	5.85	10.75 max
Organic substance	0.063	2 max

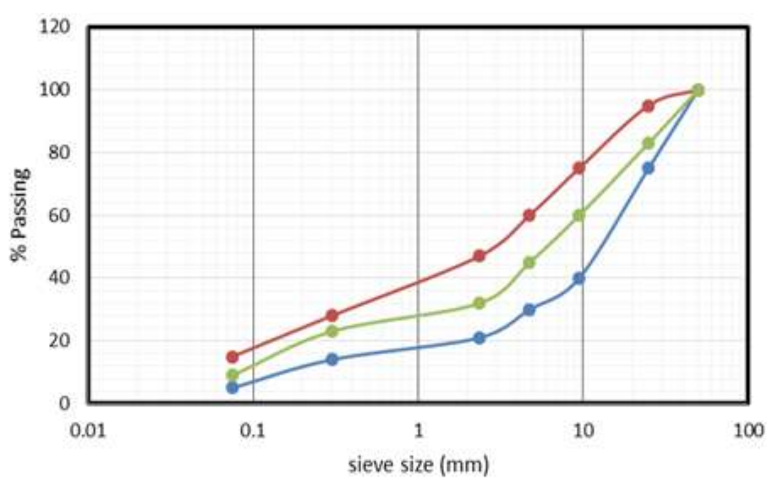

Figure 5. Sieve analysis of subbase material

Table 10. Variation of static load test for concrete blocks pavement

Test NO.	Case Study	Concrete Blocks		Laying Patterns	With / Without Joint Sand (mm)
		Shape	Thickness (mm)		
1	Effect of block shape	I shape	80	Stretcher	3
2		Rectangular	80	Stretcher	3
3		Octagonal	80	Stretcher	3
4	Effect of block thickness	Rectangular	80	Stretcher	3
5		Rectangular	60	Stretcher	3
6	Effect of jointing sand	I shape	80	Stretcher	3
7		I shape	80	Stretcher	without
8		Octagonal	80	Stretcher	3
9		Octagonal	80	Stretcher	without
10		Rectangular	80	Stretcher	3
11		Rectangular	80	Stretcher	without
12		Rectangular	60	Stretcher	3
13		Rectangular	60	Stretcher	Without
14	Effect of laying pattern	Rectangular	80	Stretcher	3
15		Rectangular	80	Herringbone	3

6. Results and Discussion

6.1. *Density*

In general, it can be said that, concrete density for cubes and concrete blocks decreases with the increase in recycled coarse aggregates replacement in the mix. This is due to the size and form of recycled aggregates as well as cement mortar attached on recycled aggregates that leads to low-density. Table 11 shows the average density for cubes and concrete blocks at 28 days.

Table 11. Average test results of hardened density of cubes and concrete blocks in kg/m^3 at 28 days with different percentage of RCA replacements to VCA

Samples	0%	25%	50%	75%	100%
Cubes	2396	2367	2345	2332	2315
Concrete blocks (Rectangular 80 mm thickness)	2393	2370	2344	2328	2317
Concrete blocks (Rectangular 60 mm thickness)	2389	2366	2349	2330	2314
Concrete blocks (I-shape 80 mm thickness)	2392	2371	2345	2334	2319
Concrete blocks (Octagonal 80 mm thickness)	2390	2367	2343	2328	2315

6.2. *Compressive Strength*

Table 12 shows the average compressive strength for cubes and concrete blocks at 28 days. It is interesting to notice that all compressive strength values are above 33 MPa and this is acceptable according to IQS 1606 [21]. At 25% percentage replacement of RCA, the compressive strength of the blocks can be produced and satisfies local requirements, while the 50% percentage replacement of RCA gives the lowest values for the compressive strength and still above the targeted value.

Table 12. Results of compression test of cubes and concrete blocks in MPa at 28 days with different percentage of RCA replacements to VCA

Samples	0%	25%	50%	75%	100%
Cubes	36.8	37.7	34.2	35.4	35.5
Concrete blocks (Rectangular 80 mm thickness)	36.5	37.8	33.9	35.1	35
Concrete blocks (Rectangular 60 mm thickness)	35.5	36.5	33.5	34.9	35.2
Concrete blocks (I-shape 80 mm thickness)	36.7	37.5	34.5	35.4	35.9
Concrete blocks (Octagonal 80 mm thickness)	36.3	36.9	33.9	35.2	35.7

6.3. *Ultrasonic Pulse Velocity Test (Pundit)*

This test has been conducted to determine important properties of concrete such as the ultrasonic pulse velocity and the dynamic modulus (E_d).

The dynamic modulus (E_d) can be obtained by standard equation using the value of ultrasonic pulse velocity of concrete measured by ultrasonic pulse device following ASTM C597-02 specifications [22].

It can be seen in Figs. 6 and 7 that, the maximum value of pulse velocity have been obtained for mix that contains 25% of recycle concrete aggregate. These results support the accuracy of both previous test results; density and compressive strength because the wave velocity depends on density and strength of the materials.

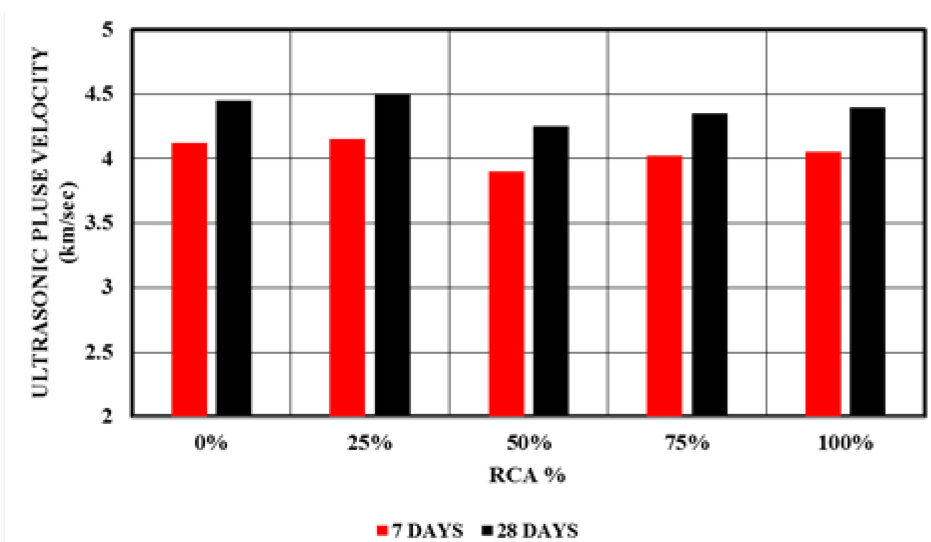

Figure 6. Ultrasonic pulse velocity (km/sec) of concrete cubes with different percentages of RCA replacement to VCA

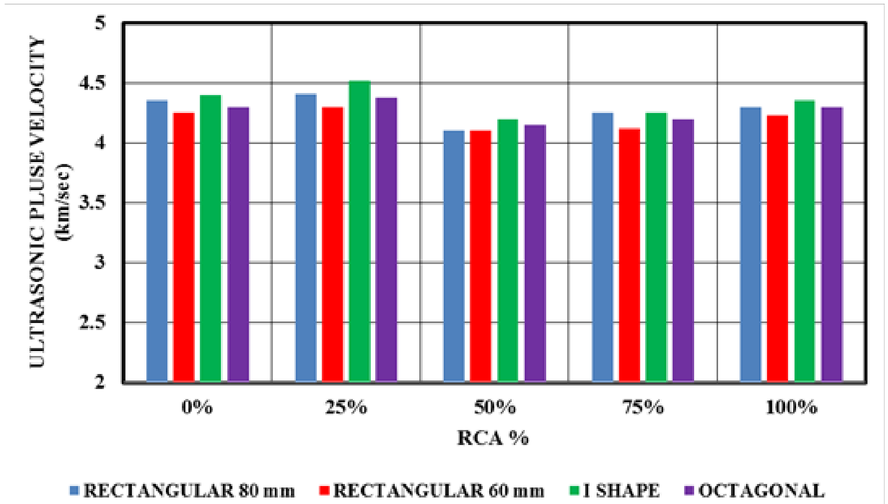

Figure 7. Ultrasonic pulse velocity (km/sec) of concrete blocks with different percentages of RCA replacement to VCA

6.4. *Workability*

High absorption rate of RCA reduces the workability of the concrete mix and as it can be noted in Table 13.This depends on several factors, including the high re-absorption of aggregate, the internal structure and the size of the voids and the size of cement mortar attached to recycled aggregates and the amount of water to be added to the RCA during mixing.

Table 13. Average slump test values of tested concrete

% RCA in mix	Slump result (mm)
0%	18
25%	16.5
50%	15
75%	12
100%	10.3

6.5. *Modulus of Elasticity*

6.5.1. Dynamic Modulus of Elasticity

The dynamic modulus of elasticity for each sample has been calculated in equation (1) according to BS1881: Part 203:1986 by using density and wave velocity values, which has been determined in the above mentioned tests

$$Ed = \rho .\ v^2 .\ [(1+\upsilon).(1-2\upsilon).(1-\upsilon)^{-1}] \qquad (1)$$

Where;

Ed is the dynamic elastic modulus (in MN/m^2);

υ is the dynamic Poisson's ratio (υ equal to 0.2 for concrete);

ρ is the density (in kg/ m^3); and

v is the compression pulse velocity (in km/s).

The behavior is similar to the performance of compressive strength test results. Again, these results support the accuracy of both previous test results; density and compressive strength because the dynamic modulus depends on wave velocity as per the equation (1) which depends on sample density and strength of the materials. It can be noticed that, the dynamic modulus of elasticity of concrete blocks is similar or lower than that of concrete cubes which is acceptable because the dynamic modulus of elasticity is a property of the material (Table 14).

6.5.2. Static modulus of elasticity

The static modulus of elasticity of concrete (Es) has been calculated using the equations presented by the ACI Code (318) [23].

$$Es = 4700. (fc)^{1/2} \quad (2)$$

Where;

Es = modulus of elasticity (MPa)

fc = compressive strength (MPa)

There is a little difference between the Static elastic modulus of cubes and the elastic modulus of block models due to the difference in mass, volume, and density of models. Table 14 show static modulus obtained. The dynamic modulus is higher than static elastic modulus by about (1.4 – 1.7) times.

Table 14. Static modulus and dynamic modulus for all samples

Concrete Cubes			
Sample	Static Modulus (MPa)	Dynamic Modulus (MPa)	Dynamic Mod./Static Mod.
0%	25829	42702	1.65
25%	26126	43139	1.65
50%	24870	38121	1.53
75%	25310	39715	1.57
100%	25310	40337	1.59
Concrete Blocks (I – Shape 80 mm Thickness)			
Sample	Static Modulus (MPa)	Dynamic Modulus (MPa)	Dynamic Mod./Static Mod.
0%	25786	41678	1.62
25%	26084	43596	1.67
50%	25003	37229	1.49
75%	25310	37942	1.5
100%	25484	39493	1.55
Concrete Blocks (Octagonal 80 mm Thickness)			

Sample	Static Modulus (MPa)	Dynamic Modulus (MPa)	Dynamic Mod./Static Mod.
0%	25700	39772	1.55
25%	25871	40869	1.58
50%	24781	36317	1.47
75%	25267	36959	1.46
100%	25441	38524	1.51
Concrete Blocks (Rectangular 80 mm Thickness)			
Sample	Static Modulus (MPa)	Dynamic Modulus (MPa)	Dynamic Mod./Static Mod.
0%	25700	40753	1.59
25%	26168	41483	1.59
50%	24781	35462	1.43
75%	25223	37845	1.5
100%	25179	38557	1.53
Concrete Blocks (Rectangular 60 mm Thickness)			
Sample	Static Modulus (MPa)	Dynamic Modulus (MPa)	Dynamic Mod./Static Mod.
0%	25354	38836	1.53
25%	25700	39373	1.53
50%	24647	35538	1.44
75%	25135	35595	1.42
100%	25267	37264	1.47

6.6. *Modulus of Rupture (MR) (Flexural Strength)*

Table 15 present comparison between the tested values of modulus of rupture (flexural strength) for different percentages of RCA and the values estimated using equation which is recommended by ACI (363 R).

$$MR = 0.94\ (fc)^{1/2} \qquad (3)$$

Where; MR is the modulus of rupture (MPa), and

fc is the compressive strength (MPa).

It can be noticed that, increasing the percentage of recycled aggregate decreases the flexural strength of the tested concrete beams.

Table 15. Average flexural strength of concrete beam samples

Test	0 % RCA	25 % RCA	50 % RCA	75 % RCA	100 % RCA
Compressive strength of cube samples (MPa) (at 28 days age)	36.8	37.7	34.2	35.4	35.5
Point load at failure (N)	10200	10800	10000	9900	9160
Tested modulus of rupture (MPa)	5.1	5.4	5	4.95	4.58
Modulus of rupture (MPa) (3)	5.2	5.2	5	5.1	5.1
Ratio of tested modulus of rupture to calculated by (3)	0.98	1.0	1.0	0.97	0.9

6.7. *Subgrade Soil and Subbase Test Results*

6.7.1. *Density test*

Optimum moisture of the subgrade soil and subbase is necessary to know the amount of water to be added to achieve the highest density at the site and to get an ideal compaction. Figs. 8 and 9 illustrate the results of these tests. Density of subgrade and subbase are 1650 kg/m^3 and 2100 kg/m^3 at optimum water content of 12% and 5% respectively.

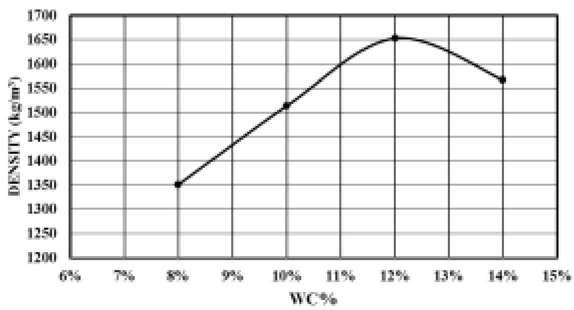

Figure 8. Relationship between moisture content and density of subgrade soil

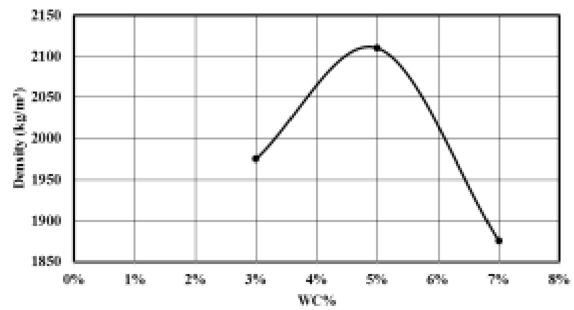

Figure 9. Relationship between moisture content and density of subbase

The values of the CBR of subgrade soil and subbase layers are (6 and 35) respectively. These values are considered within accepted limit (for Baghdad city, the CBR value for subgrade soil is within (3.5-15), while for subbase type B the minimum CBR value is 35, therefore, these materials match the required local standards (SORB) [24].

6.7.3. *Static modulus of subgrade soil and subbase*

6.7.3.1. *Static modulus of subgrade soil*

For fine-grained soils with a soaked CBR between 5 and 10, by using the following equation which correlates CBR to resilient modulus (Mr) (AASHTO 1993):

Design Mr (psi) = 1500 x CBR
= 1500 x 6
= 9000 psi = 62 MPa

This value is considered acceptable for the design of roads, according to AASHTO 1993 [16] because the typical values for fine-grained soils are 2000 to 10000 psi

6.7.3.2. *Static modulus of subbase*

To find the modulus of elasticity of the subbase materials, the scale derived by NCHRP project 128 [17] can be used. Using this scale, the modulus of elasticity of subbase can be found by entering the value of the CBR of the subbase and match it with corresponding value of the modulus of elasticity. Modulus of elasticity is 15000 psi (103 MPa) for this value of CBR is considered acceptable since the typical values for subbase modulus are 10000 to 20000 psi.

6.8. *Load - Deflection Behavior of Interlocking Concrete Block Pavement (ICBP) Layers*

In concrete block pavements, the blocks make up the wearing surface and are a major load - spreading component of the pavement. Load – deflection behavior of blocks affected by many variables such as blocks shape, thickness of blocks, laying patterns of the blocks and jointing sand.

The results of a series of static plate load tests on the concrete block layers; subgrade, subbase, and concrete blocks including all of above variables summarizes as follows:

6.8.1. *Effect of block shape*

Three shapes of concrete blocks were selected to illustrate the effect of block shape as shown in Fig. 10. The shapes were rectangular, I and octagonal. All shapes have constant thickness of 80 mm and laid in the same stretcher pattern with jointing sand. The shape of the load - deflection path is similar for three shapes.

Using the concrete blocks with I shape reduced the deflection by 20.8% as comparing with the concrete blocks with rectangular shape and 11.6% as comparing with the octagonal blocks. Octagonal blocks have the largest vertical surface area but the number of frictional faces for I shape more than the octagonal shape. Consequently, shaped blocks have larger frictional areas for load transfer to adjacent blocks.

From the results of deflection of the three shapes under investigation, it is concluded that the shape of the concrete blocks influences the performance of the block pavement under load. The effectiveness of load transfer depends on the vertical surface area and frictional faces of the blocks

6.8.2. *Effect of block thickness*

Concrete blocks with rectangular shape laid in the stretcher pattern with jointing sand were chosen for this study to illustrate the effect of block thickness as shown in Fig. 11. Two different thicknesses were selected for testing, (60 mm and 80 mm).

The shapes of load-deflection paths are similar for the two different thicknesses. The concrete blocks with 80 mm thickness reduced the deflection by 20% as comparing with those of 60 mm thickness. Thicker concrete blocks provide higher frictional area. Thus, load transfer will be higher for thicker blocks.

Also, the thrusting action between adjacent blocks at hinging points is more effective with thicker blocks. Thus, deflections are much less for thicker blocks .The combined effect of higher thrusting action for thicker concrete blocks provides more efficient load transfer.

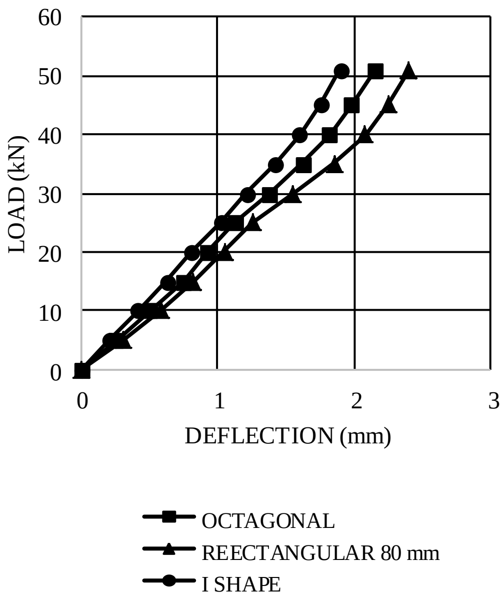

Figure 10. Behavior of load-deflection for concrete blocks: Effect of block shape

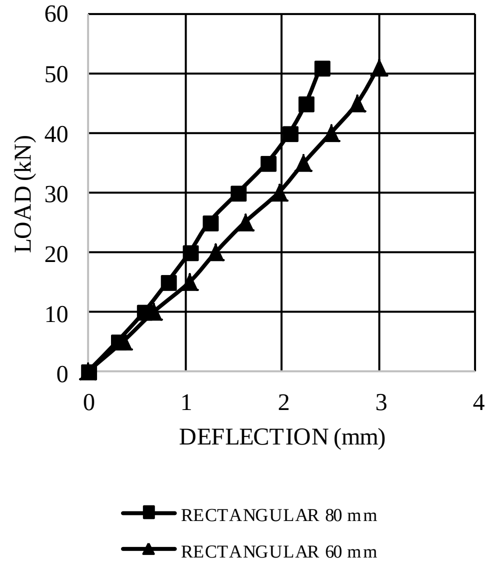

Figure 11. Behavior of load-deflection for concrete blocks: Effect of block thickness

6.8.3. *Effect of jointing sand*

Figs. 12 to 15 present the value of deflection for block pavements with and without jointing sand for all the concrete block shapes (I shape 80 mm thickness, rectangular shape 80 mm thickness, rectangular shape 60 mm thickness and octagonal shape 80 mm thickness).

The jointing sand reduced the deflection of the concrete blocks by (15.3% - 20.8%) as comparing with the concrete blocks without jointing sand. The concrete blocks in the pavement without jointing sand behave as individual units. Individual units do not transfer the load to adjacent blocks. Thus, the concrete blocks layer has little load spreading capacity. For this reason, the joints between the concrete blocks should be filled with sand.

6.8.4. *Effect of laying pattern*

There are several patterns used in this type of pavement. The patterns used in this study were herringbone and stretcher patterns with rectangular shape (80 mm thickness). As shown in Fig. 16 the deflections are almost the same with very little difference for the two laying patterns.

The friction areas and thickness of blocks used for the two laying patterns are the same. Thus, the same elastic deflections are observed.

Therefore, the deflections of block pavements are independent of the laying pattern in the pavement.

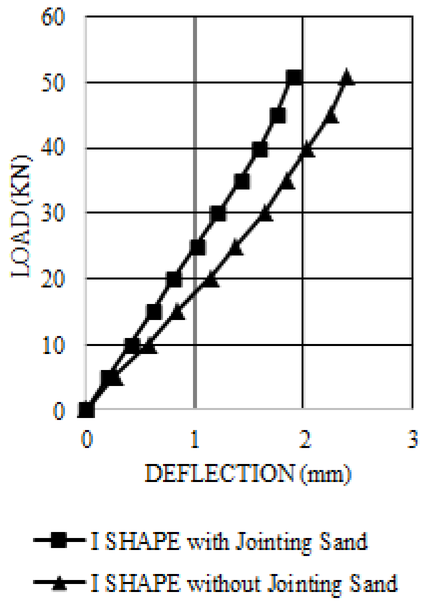

Figure 12. Behavior of load-deflection (I shape block): Effect of jointing sand

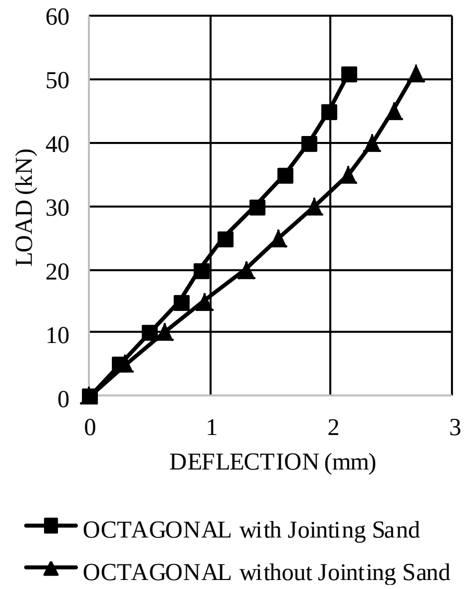

Figure 13. Behavior of load-deflection (Octagonal block): Effect of jointing sand

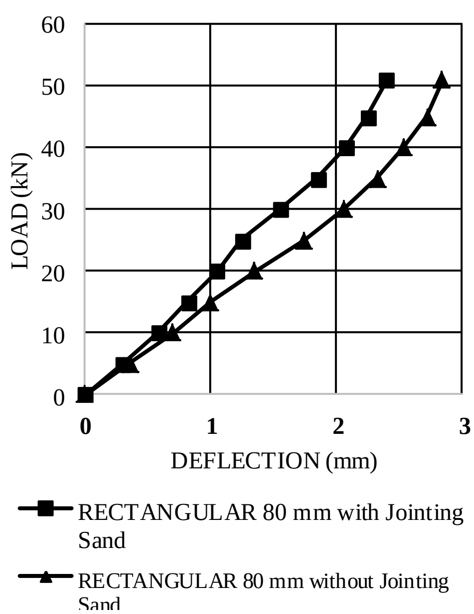

Figure 14. Behavior of load-deflection (Rectangular 80 mm): Effect of jointing sand

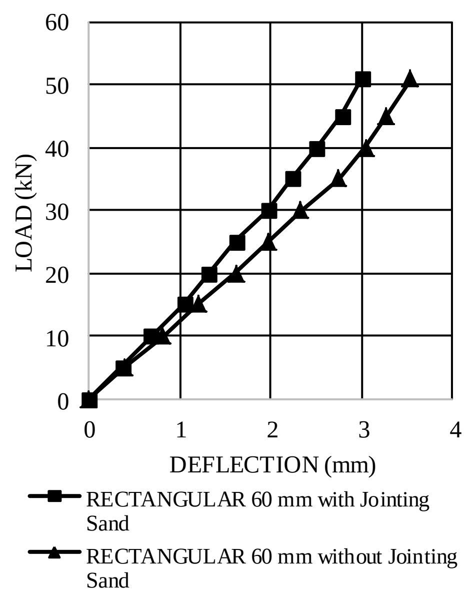

Figure 15. Behavior of load-deflection (Rectangular 60 mm): Effect of jointing sand

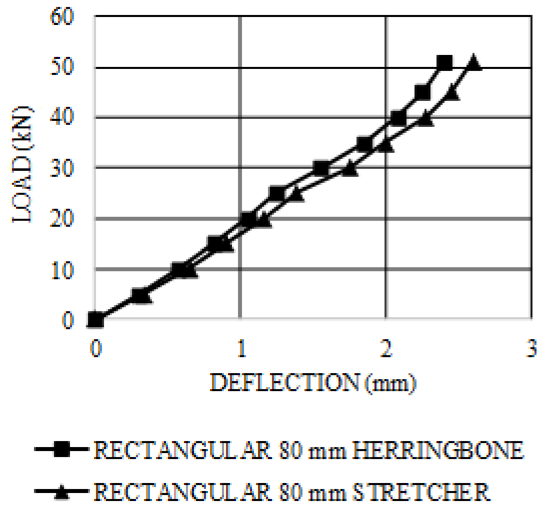

Figure 16. Behavior of load-deflection
(Rectangular block 80 mm thickness): Effect of laying pattern

6.9. *Modulus of Elasticity of ICPB Layers Using Winjulea Program for Back Calculation*

The surface deflection for all blocks was taken as inputs in winjulea program to estimate the elastic modulus of the pavement layers. This program adopted a stress analysis (called back calculation) using the multilayer elasticity theory. Table 16 shows the modulus of elasticity of different layers obtained by winjulea program.

Table 16. Modulus of elasticity of different layers using winjulea program

Layer	Modulus of Elasticity (MPa)
Subgrade layer	23
Subbase layer	80
Rectangular block 80 mm	1000
I shape blocks	2000
Octagonal blocks	1400
Rectangular block 60 mm	900

7. Conclusions

Experiments show that the using C&D wastes in producing recycled aggregate has a good potential in producing recycled concrete for most construction application. It can be used as course aggregate in manufacturing interlocking concrete blocks.

1. The gradation and sieve analysis of RCA materials match the specifications limits of local and ASTM standards for gradation and sieve analysis of aggregate materials.

2. The dry density and workability of recycled aggregate concrete are decreasing with increasing the percentage of RCA.
3. The compressive strength for mixes that contain the recycled coarse aggregate exceeds the 33 MPa target design strength and convergent with mix without RCA.
4. The tested flexural strength for 100% RCA replacement is the lowest, while the tested concrete which has 25% RCA replacement has the highest flexural strength.
5. The dynamic modulus of elasticity of concrete with RCA can be determined by nondestructive ultrasonic pulse velocity test and is higher by (1.4 – 1.7) times than static modulus.
6. Best percentage of RCA replacements with natural aggregate that achieved best performance of recycled concrete was founded at 25% of RCA.
7. I-shape blocks have been chosen as best shape in concrete blocks from points of compressive strength and density.
8. Concrete blocks shapes are used in ICBP layer effect on surface deflection as a result of load applying where the results of the tests on rectangular shape, I-shape and octagonal shape showed that the I- shape blocks exhibited better performance than the other shapes with the same thickness and laying pattern.
9. The results show that the laying patterns do not influence the surface deflection of the concrete blocks.
10. Increasing thickness of blocks has a main role in decreasing surface deflection.
11. Using jointing sand contributes to reduce the deflection of concrete blocks by (15.3% - 20.8%) as compared with the Concrete blocks without jointing sand.
12. A good edge restraint is required for effective load spreading in the concrete blocks pavement.

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