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A systematic review study on different kinds of interlocking concrete blocks designs and properties

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Compressive strength
Recycled aggregate
Concrete block
Interlocking

Abstract
Interlocking concrete blocks (ICBs) have been recently used worldwide to be alternative conventional blocks. ICBs are more sustainable, low involve low production cost, and environment-friendly as they emit less carbon dioxide than normal ones. ICBs have been used particularly in war zones and places affected by natural disasters where the need for quick, sustainable, low-cost buildings and earthquake-resistant buildings is indispensable. This paper provides a comprehensive literature review about different types of ICBs. It aims to demonstrate different configurations of ICBs incorporated with recycled concrete aggregate (RCA) and other additive materials used for construction. To achieve this, the compares different related studies which analyse the compressive strength results of RCA mixtures with different RCA replacements, w/c ratio, and mix proportions. Additionally, the paper discusses several techniques and methods to improve the behaviour of ICBs.

1. INTRODUCTION

Construction industries produced enormous amounts of rubbles and demolition waste; some of them are composed of original materials mixed with other wastes that are non-structural usage. Recovering construction and demolition (C&D) waste is divided into two main methods downcycling (backfilling) and upcycling, which generate new materials for construction (Ferriz-Papi & Thomas, 2020).

Rubble recycling has dramatically increased over the last several decades to produce alternative sustainable products. There are different solutions to recycle concrete waste, one of them is using recycled concrete aggregates into an innovative interlocking recycled concrete block (IRCB) to be used in a structural application instead of using conventional concrete. IRCB should be developed to be affordable for normal people live in developing countries using recycled concrete aggregate (RCA), which requires less effort and time during installation.

Generally, concrete blocks are the most common type of concrete structure in industrial construction. Researchers have developed different types of interlocking blocks by using several substitution products. Some of ICB can be built as a structural element such as retaining walls and bearing walls with reduction of mortar called; mortar-less interlocking recycled concrete block wall. IRCBs can provide good compressive strength and feasibility after adding additive materials (ADD) or by-products; and are reinforced with steel bars in the cores, which offer a great lateral, tensile, and shear strength to structures. However, several studies shed light on several structural behaviors of blocks using RCAs (Guo et al., 2018).

2. ADVANTAGES OF IRCB

IRCBs present sustainable solutions and offer several advantages, especially in disaster\war torn countries such as Syria. They are cost and time effective in various construction applications, such as pavements, temporary roads, and structural construction for both low and high-grade applications including columns, beams, and walls by developing different block patterns to be load-bearing blocks.

Some of the proven advantages of IRCB can be stated as follow:

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- Easy to install.
- Manually assembling requires no specialized masonry labor skills for wall construction.
- Used for both non-structural and structural applications such as column, wall, beam, etc...
- Used to construct single or multi-story buildings. Especially, in rural areas.
- Designed to be used in both horizontal and vertical directions, which gives an aesthetic architectural view of the building.
- Dry laying without mortar, which saves a considerable amount of cement.
- Embedded holes for electrical and plumbing installations.
- Insulating both sound and heat.
- Resistant to earthquakes, especially in disaster-prone countries.

3. LITERATURE REVIEW

Deepak (2012) concentrates on a typical case of interlocking concrete blocks called Hydraform interlocking in India. This type of block was not noticed in the Indian masonry code. For earthquake-resistant buildings, Deepak (2012) argues that grooved inside blocks can be used to strengthen the blocks. The results showed compressive strength was higher than the minimum values obtained in the Indian code (IS 1905-1987) when compared to traditional burnt clay brick. Ali et al., (2012) study some of the mechanical properties of the novel interlocking blocks (top, bottom, standard, and a half) such as shear and compressive strength, which were made of coconut fibre and reinforced concrete. Their study tests several mixed design percentages. The experimental results point that the compressive strength of many blocks is lower than an individual one, and the bottom block's compressive strength, as well as the total compressive toughness, are higher than others. Furthermore, shear strength (out-of-plane) is 25 per cent greater than in the in-plane one. Meanwhile, Sabai et al., (2013) investigate whether recycled aggregates (cementation rubble) could be used like concrete blocks for building construction in Tanzania. They used 100 per cent of recycled aggregate and tested their mechanical, physical, and chemical properties. The results showed the strength of recycled aggregate is weaker than that one made from the natural aggregate, which was the same in Hong Kong. In addition, 85 per cent of concrete block specimens have attained more than 7 N/mm^2 in the compressive strength test, which refers to the possibility to use the rubbles in building construction. Kumar & Vigneshvar (2014) focus on the design of innovative interlocking masonry blocks, which consist of two parts. The first part includes the tongue and groove parts. The second one is projection. These parts can fit each other to align perfectly. However, they have partially substituted fly ash with cement in blocks' production. This particular study aims to build mortar-free structures, which will be earthquake resistant, saving 65 per cent of time and cost, and reducing labor and materials needed for construction. Onyeakpa & Onundi, (2014) refer to the production of a new pattern of interlocking masonry blocks for sustainable construction by using local materials in both urban and rural areas; such as portland cement, water and eliminating of use mortar in construction. The block production was made in different dimensions and shapes (top, bottom, and toe shape) for wall construction and this was produced by standard dual mould. The compressive strength and compaction effort of interlocking concrete blocks are 4.80 (N/mm^2) and 3.687 (KJ/m^3), respectively. Watile et al. (2014) investigate the feasibility of using interlocking blocks incorporation with different additives materials such as sand, fly ash, and stone dust as well as reinforcing manmade fibre material as GFRP (Glass Fibre Reinforce Polymer). According to test results, increasing fly ash content leads to increasing compressive strength of interlocking blocks, absorption as well as density. Water absorption of interlocking blocks without GFRP material was ranged between 6.42 and 12.4 per cent. Meanwhile, the absorption percentage should not be more than 20 per cent in ordinary burnt clay bricks. Thus, using additives materials in interlocking blocks consumes less mortar and achieves better tolerances and efficiency in laying. Sarath et al., (2015a) create a new hollow in an interlocking concrete block that can be reinforced by steel fibres. The block's compressive strength was 6.05 N/mm^2, which was 68 per cent and 14 per cent greater than local ones, respectively. This new pattern of hollow block decreased the dead load by 28 per cent and 11 per cent compared to the local one. Interlocking blocks failures and cracks were developed through face shells, whereas the failures of solid and hollow blocks were developed due to crashing and splitting webs, respectively through the center of the block. Sarath et al. (2015a) investigate a new design of a hollow interlocking concrete block with a proper finish to construct a load-bearing wall that was reinforced with steel fibre. This kind of block has been studied to explore the failure patterns of the masonry wall and comparing the load capacity and the failure patterns to the local solid and hallow ones. The local capacity of the hallow interlocking wall was greater than in local solid and hollow block wall by 12 per cent and 22 per cent respectively. In addition, the steel fibre decreased the dead load by 28 per cent and 11 per cent as opposed to the local one. However, the failure of the interlocking hollow concrete wall was developed from detached face shells, whereas the failure in local ones was failed from joints. Ganesh & Lokeshwaran (2017) reveal the possibility of designing a new interlocking concrete block pattern used in load-bearing and building walls. The experiment was conducted by applying two types of loading on interlocking concrete block walls, compressive strength load, and axial load (uniform distributed load). Results show that the new pattern of interlocking blocks can act as a concrete wall structure and be used in ordinary load-bearing walls, in which the curves show that the block wall failure at maximum load of axial load. Lee et al., (2017) investigate how an innovation reinforced interlocking blocks could be developed to be a structural element and assembled as columns, which could be a replacement for conventional concrete construction. Columns have been tested under axial loads. Researches have conducted a comparison between experimental results and different code design specifications, such as MSJC code and Eurocode design. They used two types of infills materials grout and concrete. Results have shown that the infills significant connection with column compressive strength by using Pearson and partial correlation analysis, where the differences were between 0.65 – 1.85. The study conducted by Lee et al. (2017) recommended that the height of the reinforcement bar should not exceed 30 mm, and the infill materials' strength should be limited to 50 MPa. In their experiment, Guo et al. (2018) have used 75 per cent recycled concrete aggregate to produce building concrete blocks. The experiment investigated the durability and mechanical properties of these blocks through series of tests. It also compared RCA blocks to conventional blocks in compressive and shear capacity. The experimental results have revealed that concrete blocks incorporation with 75 per cent RCAs weaken the mechanical properties of blocks. Nevertheless, the compressive & shear performance and other mechanical properties such as normal building concrete blocks and the RCA blocks have less environmental impact than conventional ones. The study had indicated that RCA blocks are suitabe and viable to use in multi-story building construction. Safiee et al. (2018) have studied 5 full-scale interlocking masonry walls to investigate their behavior under two combined loads, in-plane lateral load and pre-compressive vertical load. These walls were constructed by using an interlocking mortar-less system. Results have shown that when the pre-compressive load has increased, the lateral load capacity of walls increased. Because of moderate toe crashing or /and diagonal shear failure, walls have failed. However, the developed tie and strut models have a role to give the logical predictions of interlocking wall tested.

Wani & Kumar (2018) have developed a simple kind of interlocking masonry block and discussed the compressive strength result, which is 5.6 – 9.46 as compared to the ordinary one which is 5.4 – 7.54 MPa. The results of this experiment have shown a reduction of up to 80 % in labour cost and quicker in construction. Besides, the experiment eliminated bed mortar and thereby it led to removing biaxial lateral tensile stresses in masonry units. Pavlu et al. (2019) have developed concrete mixtures incorporation with different substitutional materials. They have replaced quantities of two materials for building mortar-less masonry walls; the first material was recycled concrete aggregate RCA and the second one was recycled expanded polystyrene EPS. They have applied several tests on ten concrete mixtures and investigated their mechanical and thermal properties. Results have shown that by using recycled aggregate in place of natural aggregate, the thermal conductivity of concrete will increase; (almost 70 per cent lower than what was founded in ordinary concrete), but influenced negatively on the mechanical properties (e.g. the compressive strength has declined between 30 per cent to 75 per cent depending on the replacement rates).

4. REVIEW OF DIFFERENT DESIGN OF INTERLOCKING BLOCK

- **CFRC interlocking block**

- Dimention: standard block (400 × 200 × 195) mm.
- Using coconut fiber reinforced concrete for load-bearing and earthquake-resistant structures.
- Average compressive strength (MPa) of (standard, top, bottom and half) blocks is 16.48, 17.02, 7.73, and 8.66, respectively.
- Average compressive strength (MPa) of stacked standared blocks is 15.78.
- Reference: (Ali et al., 2012)

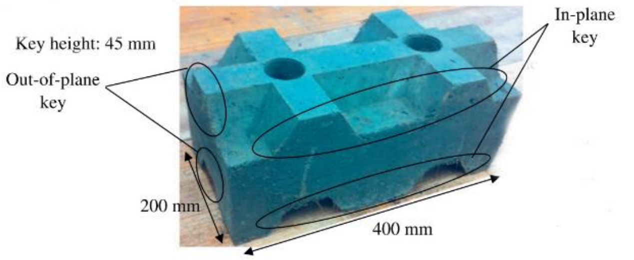

Figure 1. Coconut fiber reinforced concrete intrlockimg block

- **Interlocking lightweight cement block**

- Dimension: (600 x 200 x 200) mm.
- Using expanded polystyrene beads to reduce the self-weight.
- Designing for load-bearing masonry walls.
- Average compressive strength (MPa) of block and Wall panel strength is 4.91 and 2.13 Mpa, respectively.
- Reference: (Sayanthan et al., 2013)

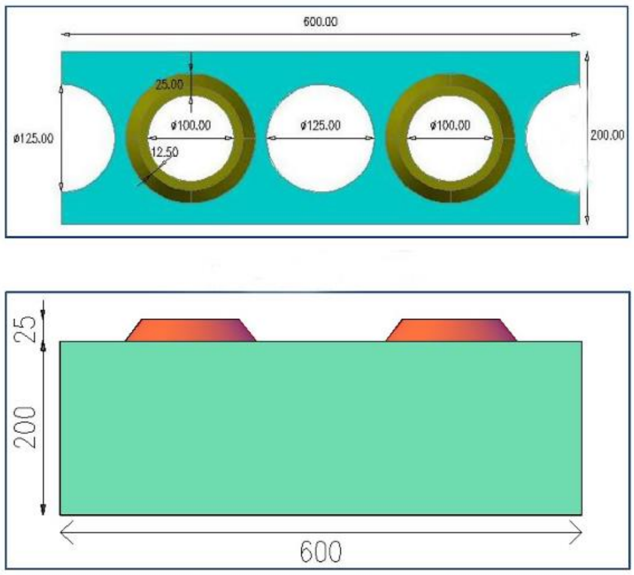

Figure 2. Interlocking lightweight cement block

- **Haener block** (U.S and Canada)

- Dimension: standard block (406.4 x 203.2 x 203.2) mm.
- Haener is a Mortarless interlocking block system.
- The main Block has three cavities, and it can be designed with only one cavity for insulation purposes.

- using Haener's two-block system to build walls and columns as well.
- Reference: (Haener, 2005)

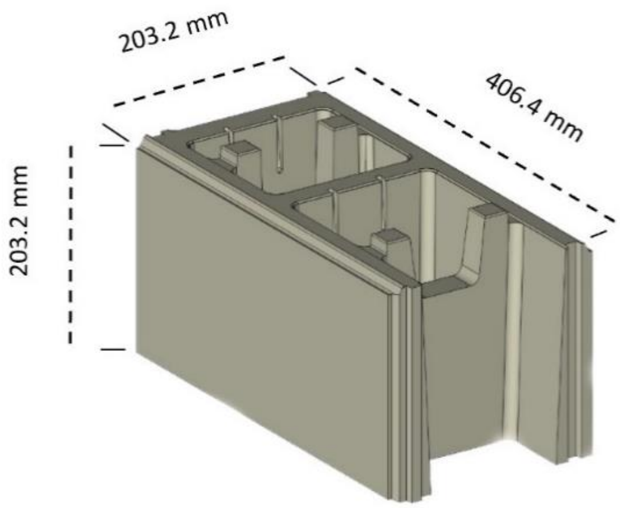

Figure 3. Haener block

- **Thai interlocking brick** (Bangkok)

- Dimension: (300 x 150 x 100) mm.
- It has vertical grooves and holes to reduce the weight that can reinforce to increase wall stability and can be used for electrical conduits.
- Reference: (Kintingu, 2009)

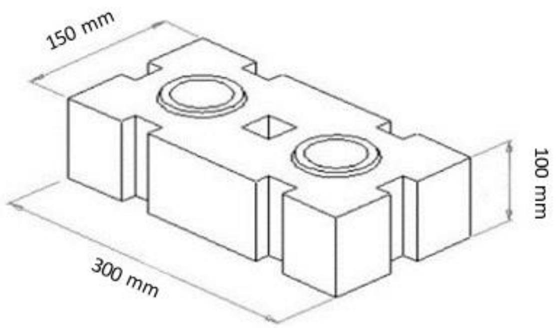

Figure 4. Thai interlocking brick

- **Putra block** (Malaysia)

- Stretcher block dimension: (300×200×150) mm.
- Average compressive strength (MPa) of (stretcher, half, and corner) blocks are 22.85, 22.02, and 23.67, respectively.
- Putra blocks were designed to explore the structural behavior of Putra block wall under out-of-plane load.
- Reference: (Safiee et al., 2018)

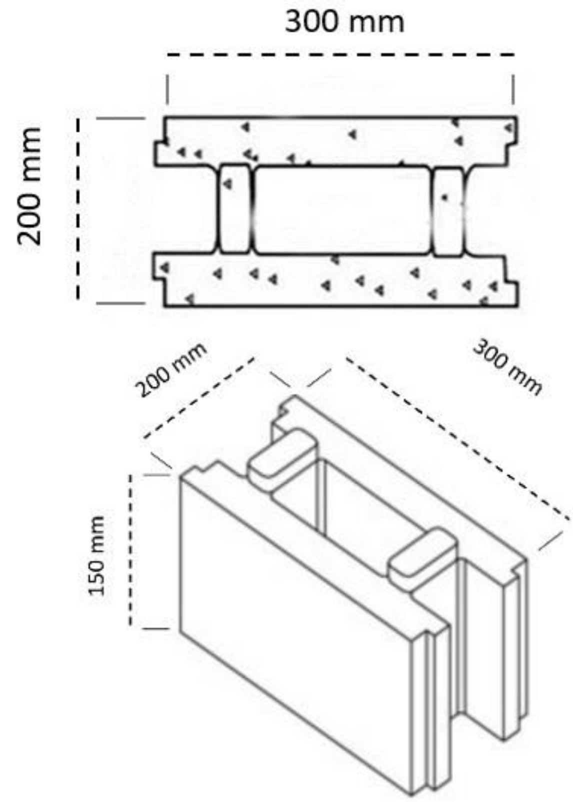

Figure 5. Putra block

- **Steel fibre reinforced concrete hollow block**

- Dimension: (600 × 200 × 300) mm.
- Using hooked end steel fibers in casting hallow blocks as a load-bearing wall.
- Using concrete cube of M10 grade (150 x 150 x 150) mm.
- After 28 days, the block's compressive strength is 6.05 Mpa.
- Reference: (Sarath et al., 2015b)

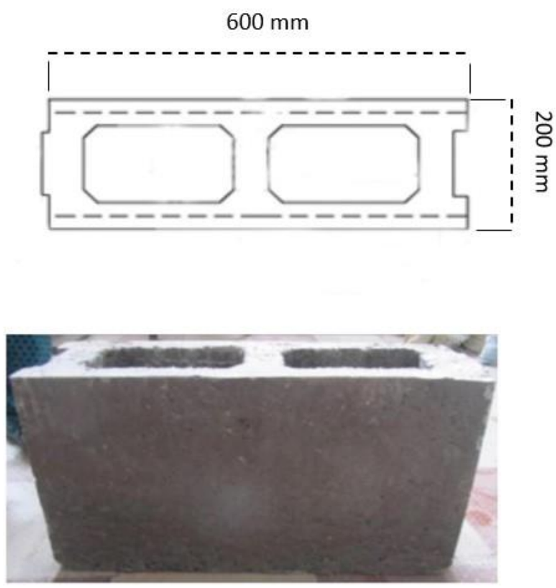

Figure 6. Steel fibre reinforced concrete hollow block

- **Interlocking concrete block**

- Dimension: (400 × 200 × 200) mm.
- Designing for a load-bearing wall (shear wall).
- Using concrete cube of M40 grade (150 x 150 x 150) mm.
- After 28 days, the block's compressive strength is 52.15 Mpa.
- Reference: (S. Jai Ganesh & Lokeshwaran, 2017)

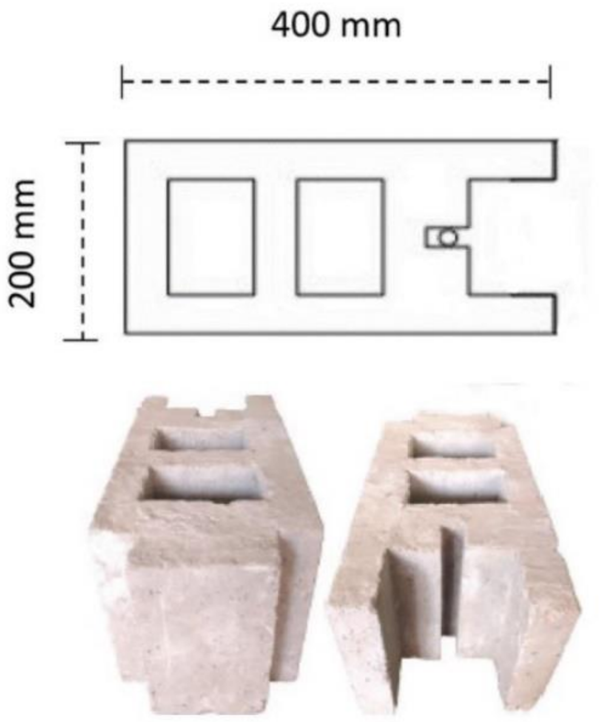

Figure 7. Interlocking concrete block

- **Tanzanian interlocking brick (TIB)**

- Dimension: full brick (300 x 150 x 100) mm.
- The key locking knops & depression are two and they are in pyramids shape with holes.
- Reference: (Kintingu, 2009)

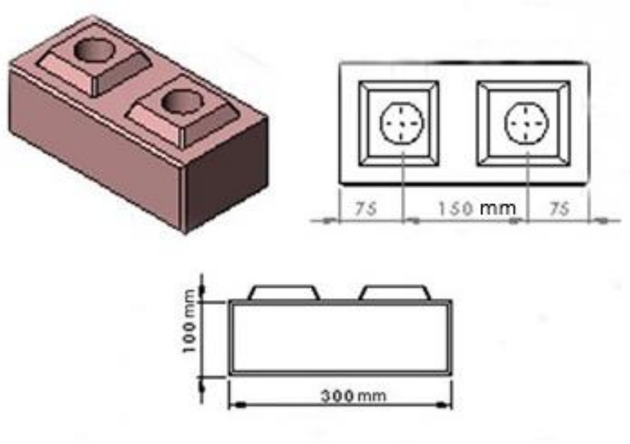

Figure 8. Tanzanian Interlocking Brick

- **Interlocking brick system**

- Dimension: standard (250 x 125 x 100) mm
- Aiming to reduce using more structural reinforced concrete reinforced elements.
- U-shape used as a supporting element of wall construction.
- Grade of mixing concrete design 35
- Compressive strength at 28 d: 35 Mpa.
- Reference: (Mirasa & Chong, 2020)

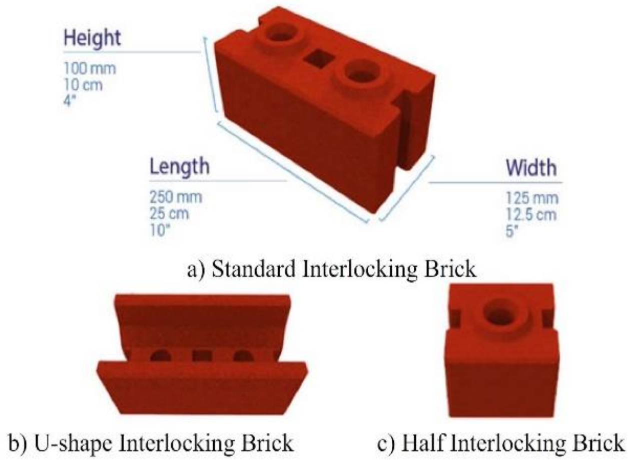

Figure 9. Interlocking brick system

- **Hollow concrete interlocking blocks**

- Dimension: full block (400 x 190 x 200) mm.
- Mortarless masonry system: MMS compressive Strength data:
 *Average strength unit: 40 Mpa.
 *Average strength masonry: 30.67 Mpa.
- Reference: (Zahra & Dhanasekar, 2018)

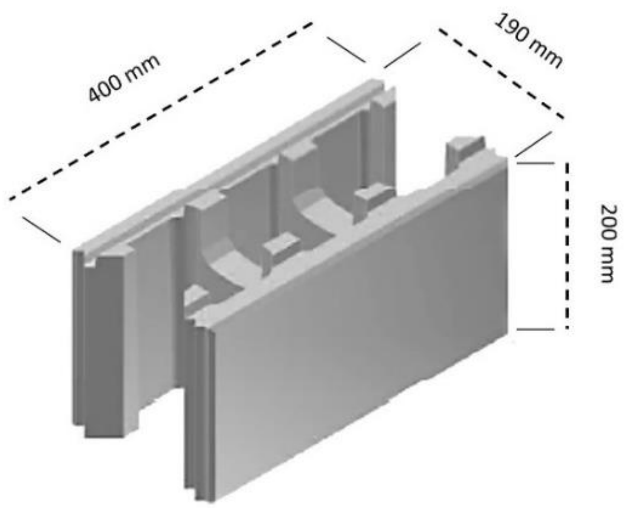

Figure 4. Hollow concrete interlocking block

5. REVIEW OF (RAC) MIXTURES

Table 1. Review of various RAC mixtures

Reference	Mix proportion			Specimens	Mould Type	Curing (Day)
	Concrete Class	W\C Ratio	RCA Replacement %			
(Opara et al., 2016)	\	0.5	(0 -100)	12 specimens for each replacement rate	Cube (150x150x150 mm)	28
(Abdel-Hay, 2017)	\	0.55	(0-25-50-100)	3 specimens for each test	Cube (150x150x150 mm) for C.S[1]	28
(Hamad & Dawi, 2017)	C28 C60	0.57 0.33	(0-20-40-60-80-100)	6 for each concrete strength type.	Cylinder 150 ×300 mm	28
(Ozalp et al., 2017)	C25\30 C30\37	\	(10-15-20) for each series	Two series, each one has three specimens	Cube (150x150x150 mm)	28
(Taffese, 2018)	C25/35 C35/45	0.61 0.55	(0-10-20) for each group	Two groups, each group has three mixes	Cylinder 150x300 mm for C.S	28
(Zheng et al., 2018)	C25 C50	0.55 0.35	(0-25 -50 -75-100) for each concrete grade	6 for each mix	Cube (100x100x100 mm)	28
(Ozbakkaloglu et al., 2018)	C40 C80	0.62 0.36	(0-25-50-100)	14 batches, 3 specimens for each mix and test	Cylinder (100x200) mm for C.S	28
(Pavan et al., 2018)	M20	0.5	(0-25 -50 -75-100) for each mould type	6 for two concrete strength type	Cube & Cylinder	28
(Pacheco & de Brito, 2019)	C25 C50 C100	0.535 0.538 0.544	(0-25-50-100)	39 specimens	Standard Cube	28
(Ajmani et al., 2019)	\	0.31	(20-50-80)	36 cube SP. for C.S,	Cube	28

[1] Compressive strength

6. COMPRESSIVE STRENGTH OF MIXTURES AND INTERLOCKING CONCRETE BLOCKS

Table 2. Review of compressive strength of mixtures

Reference number	Reference	25%	30%	40%	50%	60%
Compressive strength of Mixtures containing RCA (Mpa)						
1	(Pavan et al., 2018)	25.5			27.8	
2	(Abdel-Hay, 2017)	28.1			30	
3	(Zheng et al., 2018)	24.9			23.7	
4	(Nagaraja et al., 2017)	26.55	21.1		18.66	
5	(Manasa et al., 2019)	29.2			27.98	
6	(Hamad & Dawi, 2017)			31.4		31.6
Compressive strength of Mixtures containing RCA and ADD (Mpa)						
Reference number	Reference	25%	30%	40%	50%	60%
7	(Ozbakkaloglu et al., 2018)	41			40.5	
8	(Pacheco & de Brito, 2019)	51.1			48.2	
9	(Nagaraja et al., 2017)	26.89			22.44	
10	(Tembhurne et al., 2018)			46.7		42.7
11	(Pavlu et al., 2019)					
12	(Pavlu et al., 2019)					
13	(Akhtar & Sarmah, 2018)		46.9		33.2	
14	(Akhtar & Sarmah, 2018)				44.1	

Table 3. Review of compressive strength for interlocking concrete blocks

Compressive strength of ICB containing NCA (Mpa)			Compressive strength of ICB containing ADD (Mpa)			
Reference number	Reference	25%	Reference number	Reference	30%	40%
15	(Safiee et al., 2018)	22.85	20	(Sabai et al., 2013)	9.4	
16	(Ali et al., 2012)	16.48	21	(Guo et al., 2018)	9.38	
17	(Lee et al., 2017)	14.28	22	(Sarath et al., 2015a)		6.05
18	(Sabai et al., 2013)	14.2	23	(Sayanthan et al., 2013)		4.91
19	(Guo et al., 2018)	9.86				

6.1 RESULTS and DISCUSSION

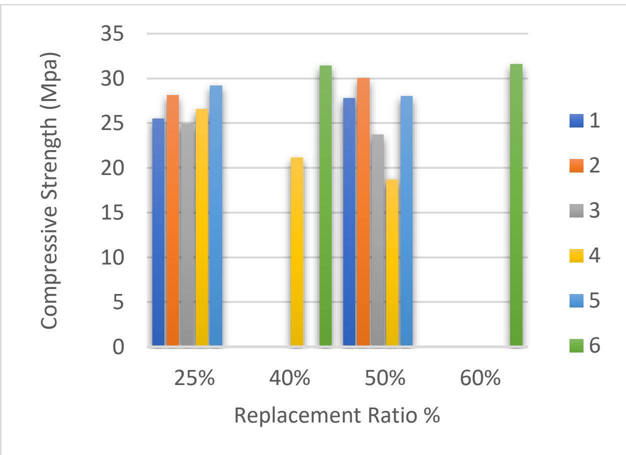

Figure 5. Compressive strength of mixtures containing RCAs

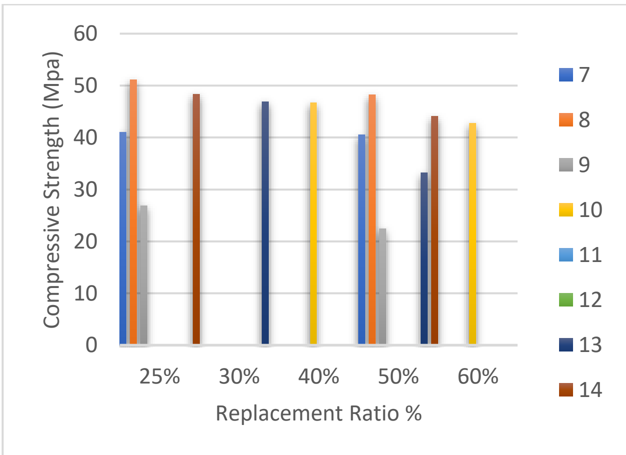

Figure 6. Compressive strength of mixtures containing NCA

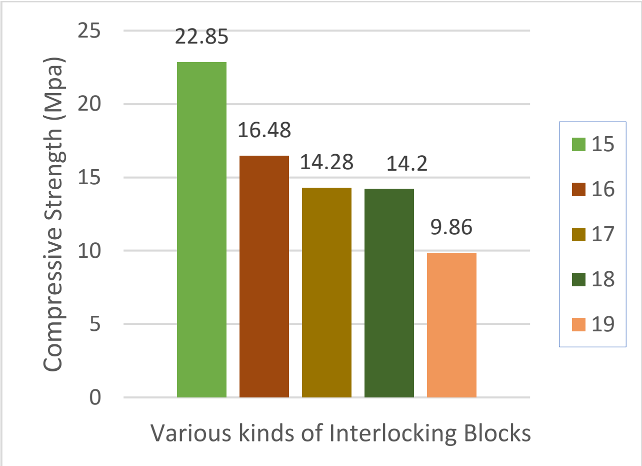

Figure 7. Compressive strength of ICBs containing RCAs & Additives

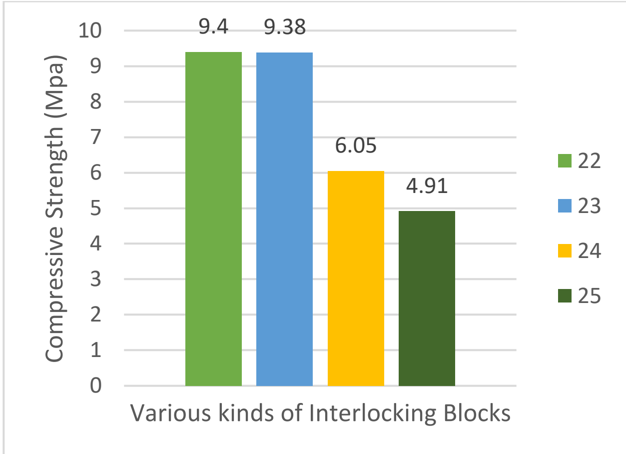

Figure 8. Compressive strength of ICBs containing RCA & Additives

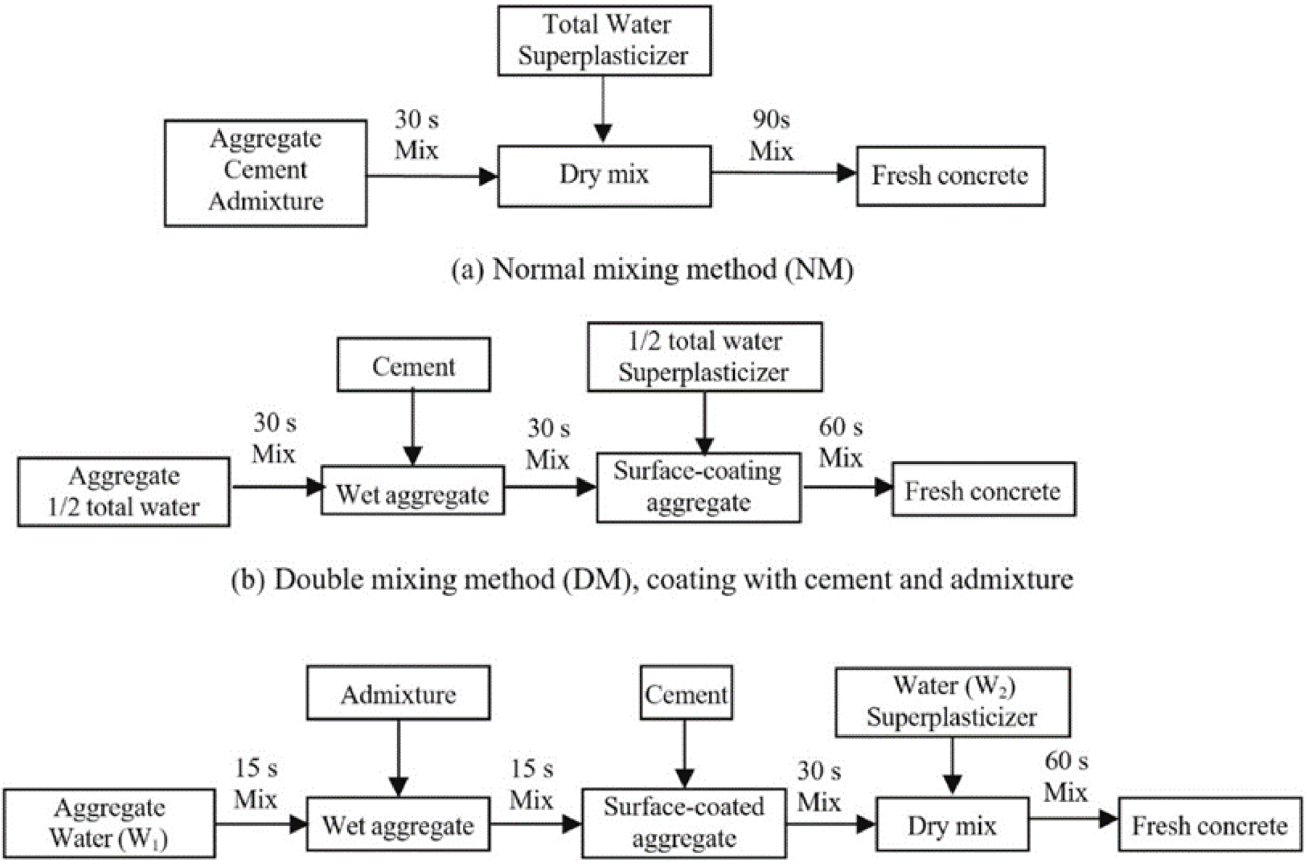

Figure 9. Double and Triple mixing methods of NAC and RAC (Kong et al., 2010)

Results in figures [14,15] show the compressive strength of mixtures containing RCA with NCA. They are ranged between 20 to 35 per cent, but they increased when adding additive materials to RCA which ranged between 25 to 50 per cent.

The bar graphs in the figures [16,17] show the changes in compressive strength by adding RCAs alone and additive materials. They demonstrate that compressive strength is increasing gradually according to the design of block pattern and the source of RCA & additive materials.

Based on previous test results, the compressive strength of interlocking concrete blocks containing RACs & additives decreased approximately between 10 to 25 per cent compared to ICB & NAC. However, researchers point out different methods to improve the strength of RAC. There are techniques classified into 2 main categories according to Purushothaman et al. (2015) and Shaban et al. (2019), the first one is eliminating adhered mortar and the second one is improving the quality of adhered mortar:

1- Eliminating adhered mortar

- Physical treatment: containing several treatments as thermal, mechanical, and thermal/mechanical.
- Chemical treatment: containing different treatments such as acid soaking.

2- Improving the quality of adhered mortar

- Physical treatment

- Polymer treatment has different solutions such as polyvinyl alcohol solution and repelled water absorbed).
- Calcium carbonate bio deposition.

- Chemical treatment

- Pozzolanic and cementitious materials such as granulated blast, furnace slag, silica fume, natural pozzolan, and metakaolin. Some of these can increase the strength between 5 to 15 per cent.
- Carbonation.
- Sodium silicate.
- Polymer treatment.

Besides, other additive materials could be used in treatments:

- limestone filler and recycled masonry aggregate.
- Steel fibres.

Furthermore, there are other techniques to enhance strength of concrete mixture such as mixing techniques:

❖ Normal, double, and triple mixing methods:
❖ Packing density mix method:

"The packing density of the aggregate mixture is defined as the solid volume in a unit total volume. The aim of obtaining packing density is to predict the number of aggregates used in the mixture and to minimize porosity and reduce the amount of cement used in the concrete" (Huang et al., 2017).

7. CONCLUSION

This review paper has discussed multiple points based on different design patterns of ICB as well as reviewing more than 40 journal papers that are related to the study. According to previous papers, the compressive strength of ICB is affected by several factors:

- RCA replacement ratio: the higher percentage of RCA leads to the lower compressive strength of RAC because the link between old mortars and new ones was weak.
- W/C ratio: RAC compressive strength has decreased when the w/c ratio increased.
- Age and Source of RCA.
- Type of additive material, replacement ratio of additive material, and ICB design as well.

These experimental studies clearly illustrate that first the appropriate replacement ratio of RCA has an efficient role in increasing the strength, which ranges between 20 to 35 per cent of concrete mixture for structural applications. Second, adding additives such as pozzolanic materials especially those materials containing silica to the RAC mixture at 28 days will improve ompressive strength by 23 per cent.

Third, different kinds of treatments such as calcium carbonate bio deposition could make improvement up to 40 % , but it will take more cost and time, and it won't be applicable for large scale according to (Shaban et al., 2019).

8. FUTURE STUDY

The review study is the first step towards the design and experiments of interlocking block dry-stack wall system with RCA from debris. The aim is to check the possibility for its structural use in post-war/disaster reconstruction processes.

An interlocking dry-stack block system can be used with a minimal amount of mortar. The interlocking mechanism allows blocks to lay on cement slurry not on mortar to provide resistance to different loads; ICBW can be assembled at least three times faster than an ordinary block wall (Guo et al., 2018). Masonry dry-stack system based on blocks that interlock with grooves and tongues to provide appropriate alignment in construction. This wall system will be resistant to several external forces, especially when it is reinforced by steel rods through holes. A dry-stacking wall system would allow eliminating the cracks of shrinkage issues on a concrete wall (Zahra, 2017).

Design:

This system has different block configurations. Each block has an interlocking key at its both top and sides in the long direction:

- Standard block (Dim: 400 x 200 x 200 mm).
- Half stretcher block is used for special situations that will arise in the field.
- Right & left corner block is used for corners.
- Quarter block is used when the wall needs to end correctly.
    - The bottom U-shape block like a channel is used as a supporting element for the wall, which has the same shape and holes as the standard one.

Experimental process:

The experimental study will focus on the structural behaviour for both individual blocks and the block wall. The compressive strength, shear strength, flexural strength of RAC interlocking block, and wall will be tested to investigate the failure mode, load-bearing, damage process, and deformation shape on ICB and ICB walls.

It will be 3 series of groups; each group has three types of concrete mixtures that will be tested with different replacement ratios of NCA:

- Replacement ratios suggestions:

30 % RM (25% RCA + 5% ADD) + 70 NCA
40 % RM (30% RCA + 10% ADD) + 60 NCA
50 % RM (35% RCA + 15% ADD) + 50 NCA

- W/C ratio: 0.5 for concrete grade C25

Finally, this wall system could be provided with an insulation material for exterior and interior sides as expanded polystyrene.

Abbreviations

- NCA: Natural concrete aggregate
- RCA: Recycled concrete aggregate
- RAC: Recycled aggregate concrete
- ADD: Additive material
- ICB: Interlocking concrete block
- IRCB: interlocking recycled concrete block
- W/C: water-cement ratio
- C&D: Construction and demolition
- STS: splitting tensile strength
- CS: Compressive strength
- Ref: Reference
- RM: Recycled materials

Author contributions

Ahmad Aswad: Draft preparation, Investigation, Visualization, Writing. **Mahmut Cem Yılmaz:** Conceptualization, planning, literature review, Editing, **Salah Hajismail:** Methodology, Data curation, Review, proof reading.

Conflicts of interest

The authors declare no conflicts of interest.

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