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Feasibility of concrete mixtures containing coarse and/or fine recycled brick aggregates

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Abstract. This paper assesses the feasibility of concrete mixtures containing high replacement rates of fine and/or coarse waste brick aggregates. Three mixture series prepared with different water-to-cement ratios are tested for workability, compressive strength, split tensile strength, modulus of elasticity, water permeability (by capillary or under pressure), and drying shrinkage. Test results showed that the concrete properties remarkably degrade when the coarse natural aggregate fraction (i.e., retained on sieve No. 4) is fully replaced by recycled waste bricks, given their increased porosity that reduces the concrete density and weakens its skeleton. In contrast, the strength and durability remained almost unaltered when the fine natural aggregate fraction was replaced by 50 % recycled waste bricks, and considerably better than equivalent mixtures made using the same amount of recycled fine aggregates derived from hardened waste concrete.

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1. Introduction

The recycling of construction and demolition wastes (CDW) in infrastructure engineering works considerably increased in the past few years. Such practice proved efficient to preserve natural resources, almost proportionally to the replacement rate, while reducing the landfill debris and mitigating the carbon dioxide (CO_2) emissions [1–3]. Also, this is in line with many regulation guidelines (such as Directive 2008/98/EC) and sustainable strategies established to valorize the CDW including their life cycle management and environmental impacts.

The waste concrete constitutes by far the biggest component of CDW which, after crushing, leads to the production of recycled concrete coarse aggregate (rCCA) typically larger than 5 mm size (i.e., retained on sieve No. 4) and recycled concrete fine aggregate (rCFA). The rCCA is composed of natural coarse aggregates with about 30–40 % adhered cement paste that alters the material's texture and increases water absorption [1, 2, 4]. The valorization of rCCA by partial or complete replacement of coarse aggregates in concrete works is well documented in previous studies [1–4]. The curtail in the concrete mechanical properties encountered due to rCCA additions can be mitigated by different methods such as reducing the free mixing water or incorporating supplementary cementitious materials, fibers, and polymers [5–8]. Unlike rCCA, the rCFA is generally considered as unwanted by-product generated from the CDW crushing process. This aggregate fraction is rich with hydrated cement compounds, albeit their re-hydration remains weaker than ordinary cement because of reduced compacity and crystallization degree of the new hydrates [9, 10]. The difficulty to control the poor physical properties (mostly the water absorption and contaminants) are among the main reasons that limited the use of rCFA in new construction and building materials. Several countries and standard regulations restricted the use of rCFA to mortars intended for masonry and rendering works, applications located in non-aggressive environments, and within limited replacement rates in low-strength concrete grades [11–13].

Bricks are the second most abundant CDW component [14, 15]. Depending on the vitrification process, these are broadly divided into two categories including (1) the semipermeable ones used for ceramic stoneware and tiles having high hardness and low water absorption (i.e., 5 to 8 %) and (2) those used as building stones and roof tiles with relatively higher water absorption (i.e., 12 to 18 %) [16]. Huge amounts of waste bricks are generated each year, which represented in 2018 about 33 % of all CDW produced in Brazil and 54 % in Spain [17]. The manufacture of ceramics also generates large amounts of wastes estimated to be about 19 kg/m^2 of tiling product, which is equivalent to about 30 % of daily production [18]. In 2018, India produced 650 million m^2 of sanitary and tiling products, which generated about 12 billion tons of waste bricks [19].

Just like the waste concrete, waste bricks are generally crushed and sieved to produce recycled brick coarse aggregate (rBCA) larger than 5 mm size and recycled brick fine aggregate (rBFA). Current literature converges that the concrete strength and durability degrade with rBCA, mostly depending on the addition rates and inherent aggregate characteristics such as the hardness and porosity levels [14, 16, 20]. Cachim [21] reported that the concrete compressive strength (f'_c) remains practically invariable when the natural coarse aggregate replacement rate by rBCA is less than 15 %. At higher rates, the drop in f'_c could reach 20 % depending on the brick types. Zhang and Zong [22] suggested that 30 % was an appropriate replacement rate, while Zhu and Zhu [16] found that f'_c could drop by 45 % when the coarse aggregate fraction is fully replaced by rBCA. Many scholars reported that the mixed use of rBCA and rBFA could improve the concrete strength, given the creation of a denser interfacial transition zone (ITZ) between the mortar and aggregate rough surface [23, 24]. Additionally, the strength gain could be attributed to pozzolanic reactions owing to the rich brick silicon dioxide (SiO_2) content that promotes the calcium silicate hydrate (C-S-H) development and refines the microstructure. Toledo et al. [25] showed that the f'_c and modulus of elasticity remain almost unaffected as long as the natural sand replacement by rBFA is less than 20 %. Naceri and Hamina [26] found that finely ground waste bricks having a mean particle diameter smaller than 30 μm can be used up to 30 % cement replacement without detrimental effects on mechanical properties.

The durability of concrete mixtures containing waste bricks is of prime importance, especially knowing the inherent porous nature of such additions. Earlier studies showed that the transfer properties such as the resistance to water permeability and ingress of chloride/sulphate ions could substantially decrease when the natural coarse aggregates are replaced by rBCA [14, 16, 17]. Such phenomenon becomes however less pronounced with the use of rBFA at low replacement rates (i.e., less than 20 %), which may be attributed to the refined porous structure and pozzolanic reactions [16, 23]. Nevertheless, some scholars reported that the brick porosity might be beneficial to promote internal curing with direct consequences on hydration reactions and strength development. For instance, Khatib [27] observed that drying shrinkage could increase by only 10 % when natural sand is fully replaced by rBFA. Other studies showed that shrinkage may be twice to six times higher, due to lower restraining effect and reduced brick modulus of elasticity compared to natural aggregate [21–23]. Bravo et al. [28] noticed that durability properties such as shrinkage, sorptivity, and carbonation could be improved when reducing the mixing water added to compensate the water absorption resulting from the bricks. The resistance against freeze-thaw cycles and thermal conductivity improved due to the increased global porosity of concrete containing waste bricks [28–30].

Limited comparative investigations were carried out to evaluate the effect of waste concrete or brick aggregates on concrete properties and durability. Such studies can be relevant to ascertain the extent of natural aggregate replacement rates that can be incorporated for a specific application, including the benefits and limitations of each kind of recycled aggregate on concrete performance. Zheng et al. [31] are among the few researchers who compared the effect rCCA and rBCA on f'_c of concrete having 25 and 50 MPa strength grades (i.e., C25 and C50). At 100 % aggregate replacement rate, the f'_c dropped by 7.2 % and 9.6 % for C25 and C50 mixtures containing rCCA, while this reached 11 % and 13 % for C25 and C50 mixtures prepared with rBCA. However, no information was given regarding the origin and source of parent concrete and brick demolished structures. Khatib [27] observed that the strength decreased by 10 % when the natural sand is replaced by rBFA, while this reached 30% for rCFA. Similar losses were also found by Mobili et al. [32], albeit a slight improvement in mechanical properties was observed in the case of fine waste bricks.

This paper is part of a comprehensive research program undertaken to evaluate the effect of recycled waste bricks on concrete properties including the structural behavior of reinforced concrete members. The waste bricks were crushed and sieved to secure rBFA and rBCA fractions meeting ASTM C33 gradations, which were incorporated at the highest feasible replacement rates of 50 % to 100 %, as will be discussed later. Three mixture series prepared with different water-to-cement ratio (w/c) are tested, while the evaluated properties included workability, f'_c, split tensile strength, modulus of elasticity, water permeability (by capillary or under pressure), and drying shrinkage. Special emphasis was placed to compare the hardened properties of concrete mixtures prepared with recycled aggregates derived from waste bricks to those derived from waste concrete. The structural properties determined using 2.2 m long reinforced concrete beams are presented in a follow-up paper. Such data can be useful to contractors, municipalities, and environmental activists to valorize the brick component in CDW during civil and engineering construction works.

2. Methods

2.1. Materials

CEM III 32,5 N Portland cement complying with BS EN 197-1 [33] was used; its chemical composition (along with the brick wastes) is given in Table 1. Continuously graded siliceous natural coarse aggregate (NCA) and siliceous natural fine aggregate (NFA) were employed; their particle gradations varied respectively from 4.75 to 16 mm and from 0 to 4.75 mm, in accordance with ASTM C33 requirements [34]. A polycarboxylate-based high-range water reducer (HRWR) complying with EN 934-2 [35] was employed; its solid content, specific gravity, and maximum recommended dosage rate are 32 %, 1.07, and 4 % of cement mass, respectively.

Table 1. Chemical composition for the cement and waste brick.

	Cement	Brick
SiO_2, %	25.53	58.67
Al_2O_3, %	6.3	13.08
Fe_2O_3, %	2.29	0.84
CaO, %	55.59	4.51
MgO, %	4.05	1.32
SO_3, %	2.34	0.89
K_2O, %	0.78	2.55
TiO_2, %	0.28	–
LOI, %	2.15	2.81

Two types of fine and coarse recycled aggregates sourced from waste concrete or brick structures are investigated. A laboratory jaw crusher was used to crush the wastes, which then were carefully sieved to produce similar gradations as the natural fine and coarse aggregate fractions. Typical grading curves are presented in Fig. 1, while the aggregate physical properties are summarized in Table 2. The parent concrete from which the rCCA and rCFA were derived had a compressive strength varying from 35 to 42 MPa [11]. The adhered mortar content determined using a sodium sulphate solution by the freeze-thaw test method was 39% ±2.5 % [11, 18].

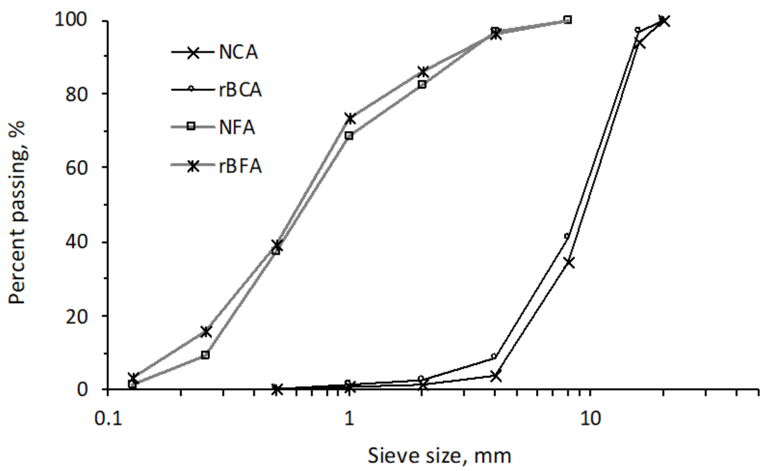

Figure 1. Particle size distribution curves for NCA, NFA, rBCA, and rBFA.

Table 2. Physical properties for the coarse and fine aggregate fractions.

	Coarse aggregate fraction			Fine aggregate fraction		
	NCA	rBCA	rCCA	NFA	rBFA	rCFA
Specific gravity	2.65	2.13	2.43	2.61	2.1	2.37
Fineness modulus	7.45	6.79	6.77	3.05	2.85	3.1
Water absorption, %	2.1	9.96	7.04	1.31	12.94	9.25
Los Angeles abrasion, %	26.5	31.4	32.6	–	–	–
Material finer than 75-µm, %	–	–	–	0.44	6.4	5.8

Stones of fired clay brick wastes having 215×102.5×65 mm size were collected from demolition sites and crushed to produce the rBCA and rBFA. The compressive strength of the brick blocks was 38 ±3 MPa. It is to be noted that several brick samples were ground finer than 100-µm sieve, and incorporated at 20 %, 40 %, and 60 % replacement rates by cement mass in order to determine the strength activity index (SAI), as per ASTM C311 [36]. The cement-sand-water ratio used for mortar batching was set at 1:2.75:0.5. As shown in Fig. 2, the SAI at 20 % replacement rate was higher than 80 % (reaching 104 % at 56 days), reflecting moderate pozzolanic reactivity equivalent to ASTM C989 Grade 100 pozzolan [37]. The SAI reached 76 % and 58 % at 56 days, despite the relatively high cement replacement rates of 40 % and 60 %, respectively.

The NCA specific gravity was 2.65, while remarkably decreased to 2.13 for rBCA because of increased porosity (Table 2), making this kind of waste brick suitable for semi-lightweight concrete mixtures [14, 38]. The NCA abrasion loss determined as per ASTM C131 [39] was 26.5 %, while increased to 31.4 % and 32.6 % for the rBCA and rCCA, respectively (Table 2). The materials finer than 75-µm remarkably increased from 0.44 % for NFA to 6.4 % and 5.8 % for rBFA and rCFA, respectively, as per ASTM C117 [40]. The corresponding water absorption varied from 1.31 % for NFA to 12.94 % and 9.25 % for rBFA and rCFA, respectively.

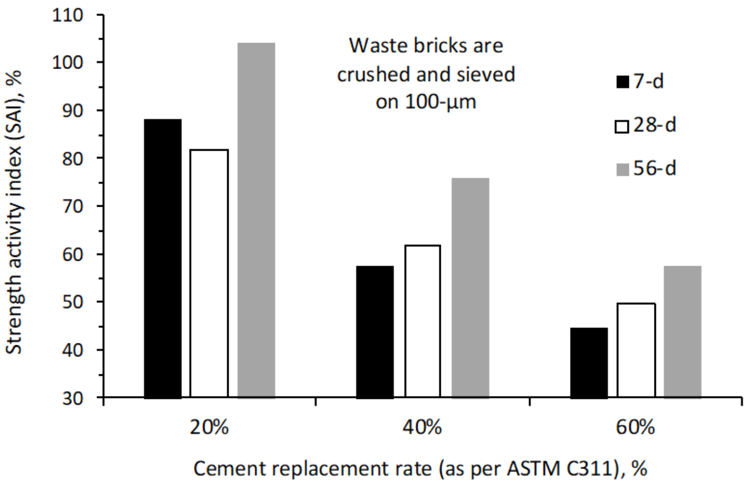

Figure 2. Strength activity index determined using crushed fine bricks.

2.2. Mixture proportions

Three control concrete series proportioned to exhibit lean to high strength grades suitable for residential applications are used in this experimental program (Table 3). The lean mix contained 320 kg/m^3 cement and 180 kg/m^3 water (i.e., w/c of 0.56); its 28-days f'_c is 38.2 MPa. The higher strength concrete mixtures contained either 360 or 400 kg/m^3 cement together with the same amount of water (i.e., 180 kg/m^3), which resulted in 0.5 and 0.45 w/c, respectively; the corresponding 28-days f'_c was 45.7 and 52.3 MPa, respectively. The HRWR was adjusted in all mixtures to secure a similar slump flow of 620 ±10 mm. The fine-to-coarse aggregate ratio remained fixed at 0.45.

Table 3. Effect of recycled waste bricks on fresh concrete properties.

	Cement, kg/m^3	w/c	HRWR, % of cement	Slump* after 30 min, mm	Fresh density, kg/m^3
0.56-Control	320	0.56	1.76	630	2380
0.5-Control	360	0.5	1.98	610	2365
0.45-Control	400	0.45	2.2	625	2390
0.56-100%rBCA	320	0.56	2.13	590	2195
0.5-100%rBCA	360	0.5	2.39	570	2155
0.45-100%rBCA	400	0.45	2.66	590	2130
0.56-50%rBFA	320	0.56	2.53	590	2310
0.5-50%rBFA	360	0.5	2.84	570	2325
0.45-50%rBFA	400	0.45	3.16	550	2350
0.56-100%rBCA-50%rBFA	320	0.56	2.91	560	2170
0.5-100%rBCA-50%rBFA	360	0.5	3.28	550	2120
0.45-100%rBCA-50%rBFA	400	0.45	3.64	540	2150

*Initial slump of tested mixtures = 620 ±10 mm.

Each of the control concrete was tested using three different combinations of coarse and/or fine recycled brick aggregates (Table 3). Hence, a 100 % replacement rate was selected to substitute the NCA by rBCA. The cement content, w/c, and fine-to-coarse aggregate ratio remained fixed as described earlier for the control mixtures, while the HRWR adjusted to secure the targeted workability. The second mixture combination consists of replacing the NFA by 50 % rBFA; in fact, preliminary tests showed that higher replacement rates would excessively increase the HRWR demand, which would lengthen setting times beyond 24 hours and detrimentally alter the concrete strength development [5, 28]. Also, a third combination that involves replacing 100 % NCA and 50 % NFA with recycled bricks was considered.

To compensate for the effect of aggregate water absorption during concrete batching, all coarse aggregates (i.e., NCA, rBCA, and rCCA) were pre-soaked overnight in water, and then drained for about 4 hours prior to batching to ensure saturation at or above the saturated surface dry (SSD) condition [4, 27, 7]. Regarding the fine aggregates, the procedure adopted consisted of homogenizing such materials in the mixer with approximately 50 % of mixing water for about 10 minutes, then introducing the remaining ingredients (i.e., coarse aggregate and cement) for concrete batching. Many researchers preconized this mixing approach, as more than 85% of the recycled fine aggregate water absorption takes place within the first 10 min of exposure to water [13, 27, 41]. The batch proportions were adjusted for aggregate surface moisture to maintain constant w/c. After one minute of concrete mixing, the other 50% of water was added followed by the adjusted amount of HRWR to secure the targeted slump flow. Concrete mixing was resumed for two additional minutes. The ambient temperature during mixing and sampling hovered around 21 ± 3 °C.

2.3. Test methods

Following the end of concrete mixing, the workability and fresh density were determined as per BS EN 12350-5 [42] and BS EN 12350-6 [43]. The workability test method consists of dropping fifteen times the flow table, and measuring the average concrete spread. The initial slump flow of 620 ±10 mm selected in this study represents a flowable type of concrete requiring light mechanical vibration during in-situ casting. The flow was also determined 30 minutes after the end of mixing, during which the fresh concrete was kept in a bowl covered with a wet burlap. Table 3 summarizes the HRWR demand, slump flow after 30 min, and fresh concrete density.

The fresh concrete was then placed into cubic (150 mm^3), cylindrical (100×200 mm and 150×300 mm), and prismatic steel molds (75×75×250 mm) for strength and durability assessment (Table 4). All specimens were lightly compacted using a vibrating table for 5 seconds. The specimens were demolded after 24 hours, moist cured in lime saturated water for 7 days (except for drying shrinkage), and then placed in standard conditions of 22 ±3 °C and 55 ±5 % relative humidity until 28 or 56 days. Averages of three measurements were considered for each strength property.

The hardened concrete density and f'_c were determined using the cubic specimens as per BS EN 12390-7 [44] and BS EN 12390-3 [45], respectively. The splitting tensile strength (f_t) was carried out using the 150-mm cubic specimens as per BS EN 12390-6 [46]; the load was gradually applied (i.e., rate of 0.95 kN/s) until the specimen split into two halves. The 150×300 mm cylindrical specimens were used to determine the modulus of elasticity (E), as per BS EN 12390-13 [47]. Three loading cycles were applied;

the displacement values were recorded using a strain-gauge possessing a 0.2 % sensitivity rate. The upper-stress limit for each cylinder was defined as the one-third value of ultimate f'_c, while the stabilized secant E value is determined from the third cycle of the stress-strain curves.

Table 4. Effect of recycled waste bricks on hardened concrete properties.

	Hard density, kg/m3	7-d f'_c, MPa	28-d f'_c, MPa	f_t, MPa	E, GPa	W_{abs}, %	W_{pen}, mm	Max. shrink, μm
0.56-Control	2325	17.5	38.2	3.84	28.45	10	25.7	630.3
0.5-Control	2310	24.3	45.7	4.05	–	6.5	18.4	474.2
0.45-Control	2345	26.1	52.3	4.25	31.59	5.2	20.5	422.2
0.56-100%rBCA	2125	17.1	32.2	3.51	27.46	15.4	50.8	711.4
0.5-100%rBCA	2010	22	40.6	4.15	–	11.5	31.8	587.5
0.45-100%rBCA	2090	21.1	44.9	4.9	26.46	8.5	41.5	510.3
0.56-50%rBFA	2235	17.5	38.9	3.22	–	11.5	29.6	691.6
0.5-50%rBFA	2235	18.6	41.5	–	–	10.1	24.5	566.4
0.45-50%rBFA	2245	20.5	49	–	28.44	7.7	21.6	447.5
0.56-100%rBCA-50%rBFA	2095	15.9	33.5	3.45	–	14.5	49.8	802.8
0.5-100%rBCA-50%rBFA	2065	19.2	40.6	–	–	13.4	36.6	634.5
0.45-100%rBCA-50%rBFA	2110	21.5	45.5	–	26.15	11.5	36.4	539.3

The concrete permeability was assessed at 56 days by two methods including the water absorption (W_{abs}) and water penetration (W_{pen}) tests. The former test was carried out using 100×200 mm cylinders, as per BS 1881-122 [48]. The specimens were initially oven-dried at 110 ±10 °C for 48 hours, which after cooling down to ambient temperature, were fully immerged in a water tank for 72 hours at 22 ±2 °C. The relative masses were measured using a digital balance for oven-dry and SSD conditions, and the water absorption by mass (%) is determined as the change in mass divided by the oven-dried value. The water penetration (W_{pen}) depth under pressure was performed on 150 mm cubes, as per BS EN 12390-8 [49]. The surfaces of the cubes were adjusted to a water pressure of 500 ± 50 kPa for 72 ± 2 hours. The specimens were then removed from the apparatus and split in two halves, perpendicularly to the face on which the water pressure was applied. The maximum water penetration depth is recorded using a digital caliper with 0.01-mm precision.

The drying shrinkage was performed using 75×75×250 mm prisms, as per ASTM C157 [50]. Right after the demolding, studs were glued on the longitudinal side of the specimens by applying a special adhesive. The changes in length were measured by means of a demountable mechanical strain gauge with 0.001-mm precision in one day offset during the first week, then three days offset until the month is completed. The temperature and relative humidity in the drying room were maintained at 22 ± 2 °C and 55 % ± 5 %, respectively.

3. Results and Discussion

3.1. HRWR demand and slump flow variations

Typical HRWR demand and slump flow loss for 0.56 and 0.45-w/c mixture series are plotted in Fig. 3. The loss in flow was determined as the difference between the initial value of 620 ±10 mm from the one measured 30 minutes after mixing. Regardless of w/c, the use of recycled bricks necessitated higher HRWR to secure the targeted initial slump flow. For example, the HRWR increased from 1.76 % for the control 0.56-w/c mix to 2.13 % when 100 % rBCA is used, while this varied from 2.2 % to 2.66 % for mixtures prepared with 0.45 w/c. Such results are in line with other scholars [11, 24, 51] who attributed this phenomenon to aggregate frictional texture and surface roughness that hinder the ease of flow. The HRWR demand reached respectively 2.53 % and 3.16 % for 0.56 and 0.45-w/c mixtures containing the fine recycled aggregate fraction (i.e., 50 % rBFA), given the porous nature and increased specific surface that could absorb part of the superplasticizer molecules [26–28]. As normally expected, the HRWR demand further increased when both rBCA and rBFA are used, which can be related to the conjuncture detrimental effect of both phenomenon on workability.

As shown in Fig. 3, mixtures incorporating the fine fraction of recycled bricks exhibited remarkable slump flow loss over time. For instance, at 0.45 w/c, a loss of 75 mm was recorded for the concrete containing 50 % rBFA, and reached 85 mm when both rBCA and rBFA are used. While the initial concrete workability is mostly affected by an internal friction phenomenon, the slump flow variation can be associated to the coupled effect of internal friction and water absorption [19, 52]. In fact, as earlier mentioned, the fine recycled aggregate fraction was not in SSD condition prior to batching, thereby increasing the potential of higher water absorption that could reduce concrete workability over time. Actually, the difficulty to control the SSD state of fine recycled aggregates was raised by many researchers, especially since any moisture excess could increase w/c and consequently degrade concrete strength and durability [1, 7, 13].

Generally speaking, the fresh density of control concrete mixtures hovered around 2375 ± 15 kg/m^3, while slightly decreased to about 2330 ±20 kg/m^3 when the fine aggregate fraction was replaced by 50 % rBFA (Table 3). Due to reduced aggregate specific gravity, the fresh density remarkably decreased to 2160 ± 30 kg/m^3 when the NCA was fully replaced by rBCA, which will have direct consequences on the concrete strength, as will be discussed later.

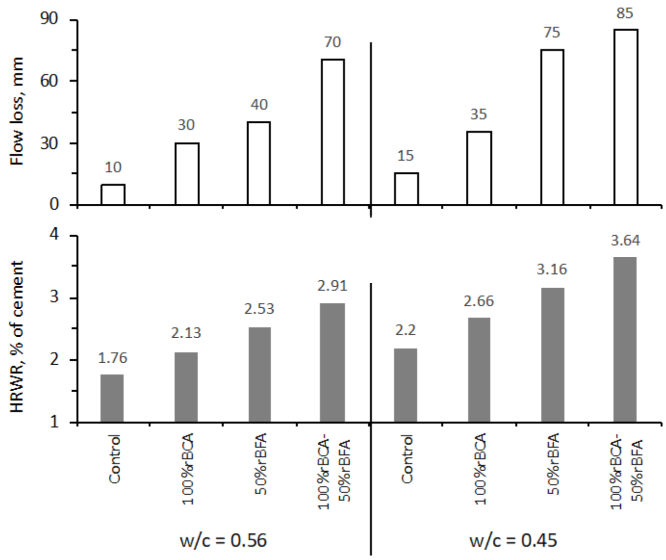

Figure 3. Effect of rBCA and rBFA additions on HRWR demand and slump flow loss.

3.2. Hardened properties of concrete containing recycled brick aggregates

Fig. 4 plots the absolute values of the hardened properties determined for concrete prepared with 0.56 and 0.45-w/c. For better clarity and analysis of results, Fig. 5 illustrates the corresponding change in properties (i.e., Δ(Property)) due to recycled brick additions for all tested w/c series. The Δ(Property) is normalized with respect to each control mix prepared at given w/c as follows:

$$\Delta\left(Property\right),\% = \frac{\left(Property\ of\ \ control\ Mix - Property\ of\ \ mix\ with\ recycled\ aggregates\right)\times 100}{Property\ of\ \ control\ mix}.$$

3.2.1. Effect on f'_c, f_t, and E

Regardless of w/c, the strength reduced when the NCA is fully replaced by rBCA, just like what happens when recycled concrete aggregates are used [7,9]. For example, f'c decreased from 38.2 to 32.2 MPa (i.e., $\Delta(f'_c)$ of -15.8%) for the 0.56-Control and 0.56-100 % rBCA mixtures, respectively (Figs. 4 and 5). The corresponding f_t decreased from 3.84 to 3.51 MPa (i.e., $\Delta(f_t)$ of –8.6 %), while E decreased from 28.45 to 27.46 GPa (i.e., $\Delta(E)$ of –3.5 %). This can be primarily attributed to the reduced hardness of rBCA fraction (compared to NCA), leading to a weaker concrete skeleton. As summarized in Table 2, the abrasion loss increased from 26.5 % to 31.4 % for NCA and rBCA, respectively. Concurrently, the decrease in strength can be associated with higher aggregate porosity that reduced concrete density including its stiffness for a given applied load [20, 29].

The strength of concrete mixtures containing 50 % rBFA additions did not significantly curtail (compared to control NFA concrete), which maintained the f'c, ft, and E responses within the repeatability of testing (Fig. 4). Hence, a positive $\Delta(f'_c)$ of +2% was obtained for the 0.56–50 % rBFA mix, while this was -6.4 % for the 0.45-50%rBFA mixture (Fig. 5). The improvement in concrete strength can be attributed to enhanced filler effect (especially the fraction finer than 75 μm) coupled with some pozzolanic reactions owing to the brick mineralogical composition that is rich in SiO_2 content (Tables 1 and 2). This later phenomenon promotes C-S-H development and densifies the ITZ between the mortar and aggregate particles [16, 23, 26]. Additionally, it is important to note that the hardened concrete density was slightly altered with 50 % rBFA additions (i.e., 2240 ±20 kg/m^3), which helped control the drop in strength.

The ∆(f'c) hovered about -12% for the various w/c concrete series prepared using 100 % rBCA and 50 % rBFA (Fig. 5), while the corresponding hardened density was 2090 ± 25 kg/m^3 (Table 4). Such strength loss remains lower than the values registered using concrete containing only rBCA, given the filler and pozzolanic effects associated with the fine brick fraction. This practically reveals the benefits of combining both coarse and fine brick fractions to control strength loss, despite the reduction in concrete hardened density. Such sustainable concrete mixtures can drastically reduce the consumption of natural aggregates, yet being suitable for semi-lightweight concrete applications having relatively high compressive strengths [14, 30]. As shown in Table 4, the 28-days f'c for mixtures prepared using 100 % rBCA and 50 % rBFA varied from 33.5 to 45.5 MPa, depending on w/c. The E measurement decreased from 31.59 to 26.15 GPa for concrete mixtures having 0.45 w/c.

3.2.2. Effect on water permeability

As expected, the resistance against water permeability improved for mixtures made with reduced w/c, given the decreased matrix porosity that hinders the ease of water percolation [7, 10]. For instance, W_{abs} decreased from 10 % to 6.5 % when w/c was reduced from 0.56 to 0.5, respectively; the corresponding W_{pen} decreased from 25.7 to 18.4 mm, respectively (Fig. 4). Regardless of w/c, the resistance against permeability remarkably degraded when the NCA is fully replaced by rBCA. The resulting Wabs and Wpen reached 15.4 % and 50.8 mm for the 0.56–100 % rBCA mixture (i.e., $\Delta(W_{abs})$ and $\Delta(W_{pen})$ of 55.2 % and 97.8 %, respectively). Such results are in agreement with f'_c, albeit each property is affected by a different phenomenon. While the reduced brick hardness mostly influences the strength [21, 23], the higher permeability can be inherently related to the porous rBCA nature (compared to NCA) that increases the overall concrete porosity and easiness towards water permeation.

The resistance against water permeability considerably improved when 50 % of the fine aggregate fraction is replaced by rBFA (Figs. 4 and 5). Hence, W_{abs} and W_{pen} slightly increased to 11.5 % and 29.6 mm for the 0.56–50 % rBFA mixture (i.e., $\Delta(W_{abs})$ and $\Delta(W_{pen})$ became 15.7 % and 15.3 %, respectively). As earlier explained, this can be related to a combined filler and pozzolanic effects associated with the fine brick fraction, leading to refined pore size that enhances the concrete resistance towards water permeation [52, 53]. In this context, it is worth noting that the preliminary tests made with 30 % recycled fine brick materials yielded pretty similar or slightly better permeability resistance, as compared to mixtures prepared with only NFA. Hence, unlike the rBCA fraction that increased the overall concrete porosity, recycled bricks are better used in fine fractions.

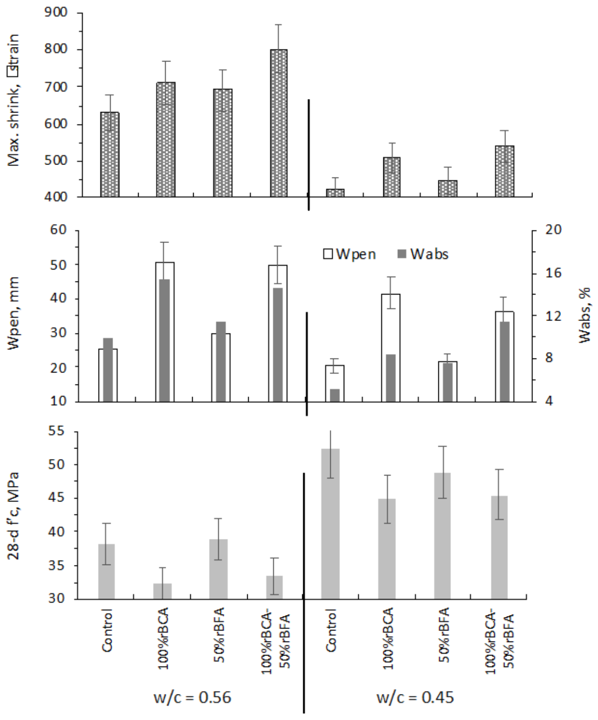

Figure 4. Effect of rBCA and rBFA additions on hardened concrete properties.

As shown in Fig. 5, water permeability degraded when both the recycled fine and coarse brick fractions are incorporated in the same concrete; the resulting $\Delta(W_{abs})$ and $\Delta(W_{pen})$ values were similar to those obtained when only the rBCA fraction is used. This physically implies that the porous rBCA nature overshadows the benefits associated with the fine recycled brick fraction, leading to increased concrete porosity that reduces the resistance against water permeability. Fig. 6 plots the relationships between the 28-days f'c with respect to W_{abs} and W_{pen} for all tested concrete. As expected, mixtures possessing increased f'c are characterized by denser microstructure, leading to better resistance against water permeability.

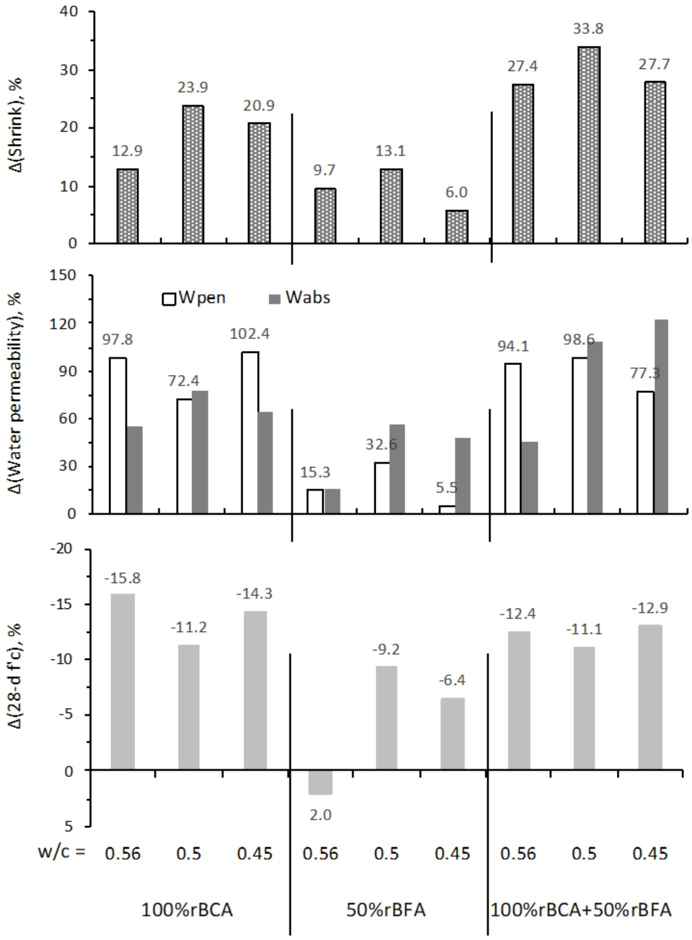

Figure 5. Effect of rBCA and rBFA additions on variations of hardened properties.

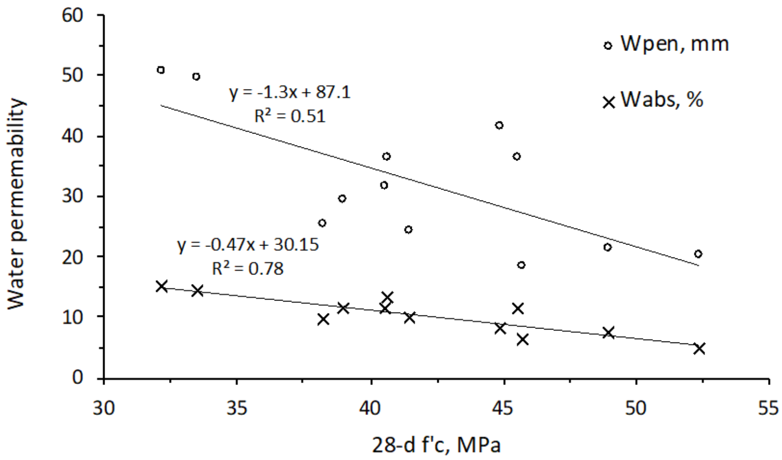

Figure 6. Relationships between 28-days f'_c with respect to Wabs and Wpen for all tested concrete.

3.2.3. Drying shrinkage

Typical variations of drying shrinkage over time for the 0.56 and 0.45-w/c mixtures are plotted in Fig. 7. Clearly, the shrinkage gradually increased during the first 10 days after demolding, and then tends to stabilize over time depending on w/c and aggregate properties [28, 53, 54]. Hence, the maximum shrinkage reached 630 μm for the 0.56-Control concrete, while decreased to 474 and 422 μm for the control mixtures prepared with 0.5 and 0.45 w/c, respectively. Such behavior is mostly attributed to the loss of capillary water due to evaporation and cement hydration reactions, causing increased proneness of hardened concrete to contraction and volume change. Also, mixtures prepared with less w/c contained relatively higher fine and coarse aggregate contents, which help restraining the concrete volume changes [54].

Although the general shrinkage trends remained similar (Fig. 7), it is clear that rBCA additions accentuated the tendency towards concrete contraction, which increased the maximum shrinkage values recorded after 35 days. For example, this reached 711 μm (i.e., Δ(Shrink) of 13 %) and 510 μm (i.e., Δ(Shrink) of 21 %) for the 0.56–100 % rBCA and 0.45-100%rBCA mixtures, respectively (Figs. 4 and 5). Earlier studies showed concrete shrinkage is strongly affected by the aggregate porosity since water may easier diffuse and migrate out of porous aggregates (such as bricks) due to higher gradients [20, 28]. Also, the reduced stiffness (i.e., higher abrasion loss) of rBCA compared to NCA materials could directly degrade the restraining effect, leading to increased shrinkage. This highlights the importance of proper curing to mitigate shrinkage phenomena of concrete containing recycled coarse aggregate bricks.

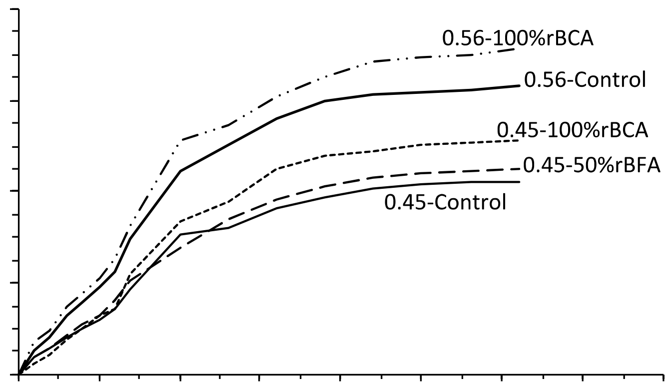

Figure 7. Effect of rBCA and rBFA additions on drying shrinkage over time.

The drying shrinkage considerably decreased when the natural sand is partially replaced by 50 % rBFA, as compared to mixtures prepared with 100 % rBCA replacement. Hence, the maximum recorded shrinkage reached 692 μm (i.e., Δ(Shrink) of 9.7 %) and 448 μm (i.e., Δ(Shrink) of 6 %) for the 0.56–50 % rBFA and 0.45–50 % rBFA mixtures, respectively. This can be attributed to a combination of phenomena including the reduced porosity of the fine aggregate fraction together with enhanced filler and pozzolanic effects that strengthen the ITZ between the coarse aggregate and cement matrix [55–57]. Nevertheless, just like what happened with strength development and resistance against water permeability, the conjuncture usage of 100 % rBCA and 50 % rBFA led to increased drying shrinkage, given the inferior coarse aggregate brick properties. A good relationship exists between the 28-days f'_c and 35-days maximum shrinkage measurements, as shown in Fig. 8. As a general rule, the higher the concrete f'_c, the lower becomes the shrinkage strains.

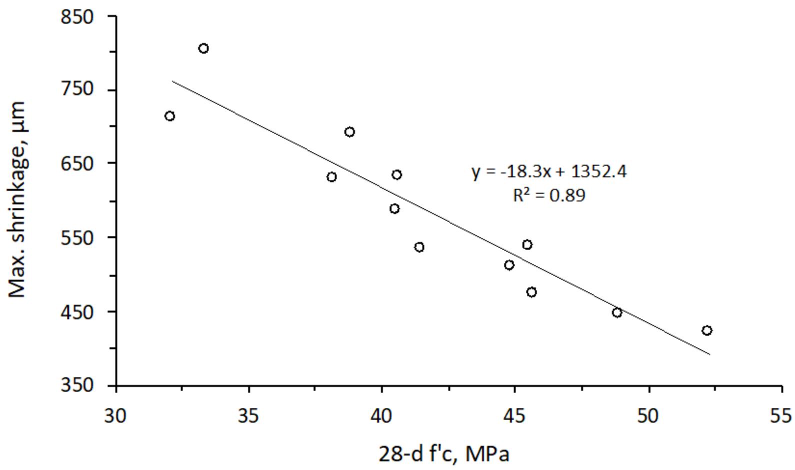

Figure 8. Relationship between 28-days f'c and maximum shrinkage for all tested concrete.

3.3. Comparison between recycled brick vs. concrete aggregates

The comparative effects of recycled aggregates on $\Delta(f'_c$, f_t, E, W_{abs}, and Shrink) for concrete mixtures prepared with 0.56 and 0.45 w/c are plotted in Fig. 9. As noted in the experimental program, the natural coarse aggregate (NCA) fraction was fully replaced by either rBCA or rCCA, while the natural fine aggregate (NFA) fraction was replaced by 50 % rBFA or rCFA.

Although f'_c, f_t, and E responses degraded when the NCA is replaced by either type of recycled aggregates, however, it seems quite hard to determine whether such drop was more affected by rBCA or rCCA additions (Fig. 9). Hence, on average, the $\Delta(f'_c$, f_t, and $E)$ hovered within –10 % ± 5 %, revealing that the drop in concrete properties is practically similar whether rBCA or rCCA materials are used. In contrast, water permeability and drying shrinkage remarkably degraded for concrete containing recycled bricks. Hence, $\Delta(W_{abs})$ and Δ(Shrink) reached respectively about 60 % and 17 % for rBCA concrete, while these were as low as 20 % and 8 % for rCCA concrete. As earlier explained, this can be inherently related to porous rBCA nature that increases the overall concrete porosity and proneness towards water permeation and contraction. In other words, it can be stated that the overall concrete porosity is comparatively less affected by the rCCA fraction since it is composed of NCA particles (having reduced porosity) covered with the adhered porous cement paste [1–3].

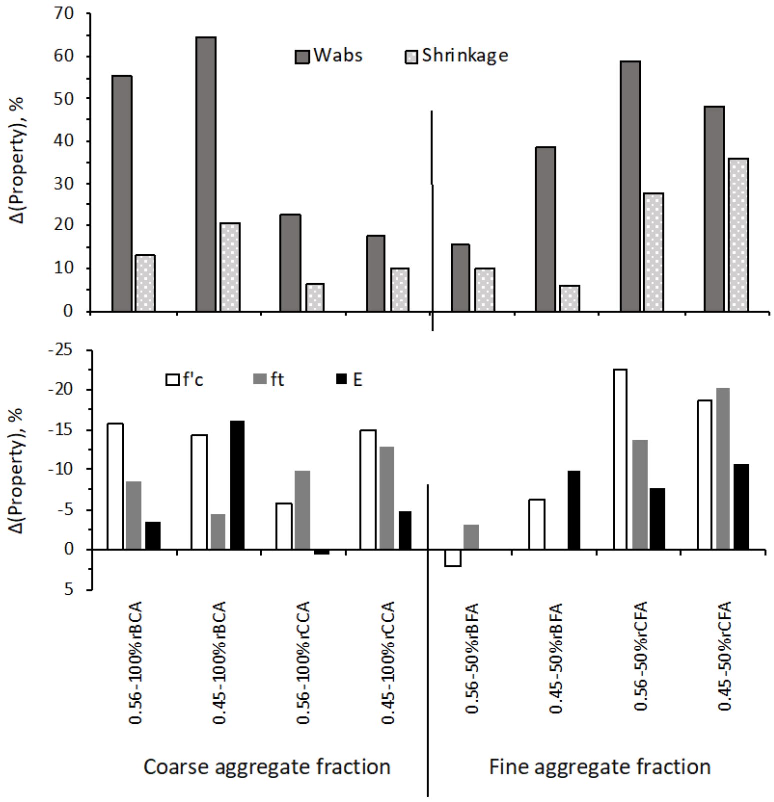

Figure 9. Comparison between recycled fine and coarse brick and concrete aggregates.

Unlike the recycled coarse aggregate fraction, the concrete properties appear to be less altered when the recycled brick fine fraction is considered (Fig. 9). Hence, the average $\Delta(f'_c$, f_t, and $E)$ values hovered within –5 % ± 3 % for rBFA concrete, while these varied within –15 % ± 5 % for rCFA concrete. Considering that the filler effect remains similar in both types of recycled materials, the comparative improvements recorded in f'_c, f_t, and E responses for rBFA concrete can be attributed to the pozzolanic reactions that promoted C-S-H development and densified the ITZ between the mortar and aggregate particles [29, 30]. Also, this phenomenon helped improving the resistance against water permeability and drying shrinkage; the resulting $\Delta(W_{abs})$ and Δ(Shrink) hovered respectively about 27 % and 15 % for rBFA concrete, while these were 53 % and 32 % for rCFA concrete. Thus, unlike the rCFA fraction that is often regarded as an unwanted component in new construction and building materials, the recycled fine brick fraction can better be employed during concrete production.

4. Conclusion

This paper is part of a comprehensive research program undertaken to determine the benefits and limitations of recycled bricks in concrete production. Based on the foregoing, the following conclusions can be warranted:

1. Regardless of w/c, the use of recycled bricks necessitated higher HRWR demand to secure the targeted concrete workability. This was attributed to the frictional texture of the coarse aggregate fraction (i.e., rBCA) that hinders the ease of flow, while the porous nature of the rBFA could absorb part of the HRWR molecules.

2. Mixtures incorporating the recycled fine brick fraction exhibited remarkable slump flow loss over time, which was mainly related to the coupled effect of internal friction and water absorption. In fact, this fraction was not in SSD condition prior to batching, which increased water absorption and reduced concrete workability retention.

3. The concrete strength (i.e, f'_c, f_t, and E) including its resistance to water permeability and drying shrinkage degraded when the NCA is fully replaced by rBCA, given the reduced hardness of this aggregate fraction that weakened the concrete skeleton. The curtail in concrete properties was concurrently associated with higher brick porosity that lowered the concrete density and reduced its stiffness for a given load.

4. Unlike the rBCA effect, the concrete properties did not dramatically curtail when the NFA is replaced by 50 % rBFA. The filler effect and pozzolanic brick nature have promoted higher packing density and refined the concrete microstructure.

5. The concrete strength and resistance to permeability and drying shrinkage improved when both recycled fine and coarse brick fractions are incorporated in the same mixture. This practically reveals the benefits of combining both fractions to maintain proper concrete strength properties, despite the decrease in density.

6. The f'_c, f_t, and E responses degraded almost similarly when the NCA is replaced by either rBCA or rCCA. In contrast, the curtail in water permeability and drying shrinkage was particularly clear for concrete containing recycled bricks, given the porous rBCA nature that increases the overall concrete porosity and proneness towards water permeation and contraction.

7. The concrete properties (f'_c, f_t, and E) including the resistance to permeability and drying shrinkage were less altered with the use of the recycled fine brick fraction, as compared to concrete containing the rCFA fraction. This was mostly attributed to the pozzolanic reactions that promoted strength development over time.

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