Journal of Building Engineering 57 (2022) 104867

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Performance and durability of self-compacting mortar with recycled sand from crushed brick

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ARTICLE INFO

Keywords:
Recycled sand from crushed brick
Limestone sand
Self-compacting mortar
Mechanical behavior
Drying shrinkage
Durability

ABSTRACT

The demolition of brick masonry structures and the rejected non-conform bricks are generating a great volume of brick residues. The use of recycled sand from brick residues in the production of mortar could decrease the amount of waste going into landfills and reduce the consumption of natural resources. This paper investigated the feasibility of using recycled sand from crushed brick (RBS) in the self-compacting mortar (SCM). The crushed limestone sand was partially replaced with RBS at different levels (0, 5, 10, 25 and 50%). The properties at fresh state, mechanical behavoir, drying shrinkage and durability of SCM were discussed. As the substitution of limestone sand by RBS increased, the compressive strength of mortars slightly reduced at the age of 28 days (3.3% and 16.9% lower than the reference mortar, respectively for 25% RBS and 50% RBS content); however, which is within the compressive strength requirement in European standard EN 998-2 for masonry mortars. The incorporation of RBS in SCM showed better resistance to chloride diffusion, whereas more attention should be paid to carbonation and sulphate attack. The results indicate that it is possible to manufacture SCM by partially replacing the crushed limestone sand with RBS up to 25% replacement level.

1. Introduction

Natural resource consumption increases significantly with the increase of world population and urbanization. Meanwhile, large quantities of CDW (CDW refers to the construction and demolition waste, mainly the concrete waste and brick residues that may come from the demolition of old structures and related renovation activities) are generated [1–3]. Thus, the use of CDW becomes a subject of high interest for sustainability development around the world. In order to fulfill the large demand for concrete or mortar, these CDW could be crushed and partially or totally replaced with natural aggregate into concrete and the natural resources can be protected [4, 5].

The quantity of CDW in the European Union (EU) was 868 million tons (for the year 2014), accounting for 1.6 tons per capita per year [6]. A minimum of 70% of non-hazardous CDW should be attained by 2020 according to Waste Framework Directive 2008/98/EC [7]. The main components of CDW are concrete waste and brick residues. The brick waste is mainly generated from the demolition of brick masonry structures and the rejected non-conform bricks from the brick industry [8–10]. The use of recycled aggregate from ceramic bricks in the production of concrete could decrease the amount of waste sent to landfills and reduce the consumption of natural

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https://doi.org/10.1016/j.jobe.2022.104867
Received 10 April 2022; Received in revised form 1 June 2022; Accepted 22 June 2022
Available online 28 June 2022

resources (beneficial to the society and environment) [5,8,10–12]. Thus, it is very important to fully understand the properties of recycled aggregates obtained from waste brick and the performance of concrete made with them.

According to the literature, numerous studies have investigated concrete or mortar with recycled brick aggregate (RBA), but most of them only focused on the coarse fraction of RBA [13–16]. The effect of rejected fired clay brick waste on the performance of self-compacting concrete (SCC, or self-compacting mortar: SCM) has not been fully carried out yet, especially the effect of RBS on the durability of SCM. Therefore, this study intends to fill this gap by investigating the feasibility of incorporating RBS as a substitution for natural sand in the production of SCM.

2. Literature review

There are lots of research on the use of coarse RBA (replacing partial or total coarse natural aggregate) or the use of recycled brick powder (RBP, replacing partial cement) on the properties of concrete in the past decades [12,16–20]. The research on the effect of RBS on the properties of concrete or mortar is less than that on the use of coarse RBA and RBP. A few selected studies only regarding the performance of concrete or mortar made with RBS (or fine RBA) are briefly described in the next section (Table 1).

2.1. Properties of recycled brick sand

All authors mentioned that RBS had relatively higher water absorption with a range of 8.8%–17% than that of natural sand (NS: range of 0.3%–3%, Table 1), which was due to the presence of higher porosity in the original brick waste compared with natural stone [21–29]. In addition, the RBS absorbed 84% of the maximum absorption during the first 10 min [23]. They also pointed out that the bulk density of RBS showed a lower value with a range of 1032–1263 kg/m^3 than that of natural sand (1456–1847 kg/m^3) according to Refs. [22–24,27], despite the different sources of brick waste used in their studies.

2.2. Properties of fresh concrete

Some authors reported that a relatively lower slump was obtained for the concrete made with RBS than that of the reference one (with identical water/cement ratio). The RBS affected negatively the workability of concrete [21,24]. The workability of concrete decreased as the RBS content increased (the slump value of the reference concrete and concrete made with 100% RBS was measured

Table 1
Summary of past studies on the use of RBS replacing NS in the production of concrete or mortar (density and water absorption (WA) of natural sand (NS) are presented in the parentheses).

Reference	Origin of RBS	Density of RBS and NS (kg/m^3)	WA of RBS and NS (%)	Replacement levels	Tested properties of concrete or mortar
Khatib [21]	RBS from demolished structures	–	14.8 (0.8)	0%, 25%, 50% and 100% (by weight)	Concrete: fresh properties, Rc, ultrasonic pulse velocity, density, dynamic E, shrinkage
Debieb and Kenai [22]	RBS and coarse RBA from Meftah local factory	Bulk density: 1010 (1847)	14.0 (1.0)	0%, 25%, 50% and 100%, NS, coarse aggregate, or both	Concrete: fresh properties, Rc and Rf, capillary WA, shrinkage, water permeability
Alves et al. [23]	RBS provided by the company	Bulk density: 1032 (1559)	12.2 (0.3)	0%, 20%, 50% and 100% (by volume)	Concrete: W, Rc, splitting tensile strength, E and abrasion resistance
Bazaz and Khayati [24]	RBS from demolition sites	Bulk density: 1100–1200 (1600–1800)	26-30 (1.0–3.0)	0% and 100%, NS, coarse aggregate, or both for two W/C ratios	Concrete: W, Rc, freeze-thawing resistance and permeability
Boukour and Benmalek [25]	Crushed clay brick filler (74% of RBS and 26% of RBP)	Absolute density: 2500 (–)	–	0%, 2.5%, 5%, 7.5% and 10% of NS (by volume)	Mortar: dry unit weight, WA by immersion (and capillarity), Rc and Rf, shrinkage
Ledesma et al. [26]	RBS from ceramic masonry waste (53.9% red RBS and 39.8% masonry mortar)	Apparent density: 2140 (2630)	9.0 (0.8)	Mortar (class M10): 0%, 25%, 50%, 75% and 100% (by volume)	Mortar: bulk density, air content, W, Rc and Rf, shrinkage, capillary WA, adhesive strength, leaching and Su
Dang et al. [27]	RBS from the demolition of masonry structure buildings	Bulk density: 1263 (1456)	8.8 (1.0)	Three series of mortar: 0%, 25%, 50%, and 75% (by weight)	Mortar: W, Rc and Rf, microstructure properties of three series (replacement ratio, particle size and additional water)
Liu et al. [28]	RBS from CDW	Bulk density: 1850 (–)	14.2 (–)	Three series of mortar: 0%, 10%, 20% and 30% (by volume)	Mortar: W, Rc and Rf, shrinkage and microstructural properties
Wu et al. [29]	RBS from the clay brick waste from CDW	Apparent density: 2030 (2510)	17 (0.6)	Three series of mortar: 0%, 25%, 50% and 100% (by volume)	Mortar: W, pore structure properties, Rc and Rf, drying shrinkage, water and chloride transport properties
Abbas et al. [30]	RBS from clay bricks	–	21.2 (–)	20% (by volume)	Concrete: fresh properties, Rc, steel corrosion
Zhang et al. [31]	RBS from the waste clay brick from a demolition site	Apparent density: 2120 (2660)	15.7 (1.8)	0%, 25%, 50%, 75% and 100% (by volume)	Concrete: fresh properties, Rc, splitting tensile strength, E, shrinkage and microstructural properties
Ge et al. [32]	RBS from the waste clay brick from a demolition site	Apparent density: 2120 (2660)	15.7 (1.8)	0%, 25%, 50%, 75% and 100% (by volume)	Concrete: drying shrinkage, chloride ingress and freeze-thaw resistance

*W/C refers to water-to-cement ratio; Rc refers to compressive strength; Rf refers to flexural strength; E refers to the modulus of elasticity; WA refers to water absorption; W refers to workability; Su refers to resistance to sodium-sulphate attack.

from 155 to 85 mm, respectively), which was due to the higher water absorption of RBS than that of RBS.

Alves et al. [23], Debieb and Kenai [22] and Ledesma et al. [26] conducted the study with the constant or similar workability for all concretes with the changing the apparent water/cement ratio. The additional water used for the RBS was higher than the reference concrete as the RBS had higher porosity and soaked the water. The workable life of mortar made with RBS showed a lower value than that of the reference mortar without RBS, which was caused by the higher water absorption of RBS compared with NS and no extra water was used [26]. Liu et al. [28] found that the slump of the mortar made with all fractions of RBS showed a reduction as the replacement ratio of NS by RBS increased. For the mortar made with coarse RBS, the slump value of mortar containing 30% RBS, was 95, 70 and 57 mm, respectively at 5, 10 and 15 min after mixing, which was caused by the absorption of water by RBS and the adsorption of superplasticizer by RBS during the mixing.

Dang et al. [27] mentioned that the replacement ratio and the additional water used had a great effect on the rheological properties of mortar, while the effect of the different particle size distribution of RBS was little. When fully additional water was used for the production of mortar, the workability of mortar increased (ranging from 130 mm to 160 mm, for the reference mortar and mortar made with RBS, respectively). When partial additional water (75% of water absorption) was used, the slump of mortar made with RBS decreased as the substitution ratio of NS by RBS increased (from 130 mm to 110 mm, for the reference mortar and mortar made with 75% of RBS, respectively).

Debieb and Kenai [22] and Alves et al. [23] showed that the bulk density of concrete containing RBS at a fresh state was lower than that of the reference concrete, and this density decreased when the substitution of NS by RBS increased (the decreasing rate could be up to 8% compared with the reference concrete in Alves et al. [23] and 17% for the study of Debieb and Kenai [22]), which is probably attributed to the lower density of RBS than the natural river sand.

2.3. Properties of hardened concrete

2.3.1. Compressive strength

Khatib [21] demonstrated that the compressive strength of concrete containing RBS reduced with the increase of RBS content. Concretes made with 25% and 50% RBS showed only 4% and 10% reduction of compressive strength than that of reference concrete after 90 days (while the reduction rate with 25% and 50% RBS was 16.3% and 19.1% respectively after 28 days). They explained that this outcome was attributed to the pozzolanic reaction between RBS (silica and alumina components) and Portlandite (hydration product of cement).

Debieb and Kenai [22] showed the compressive strength of concrete made with fine RBA decreased by about 30%, and it could reach up to 40% reduction when both fine and coarse RBA were used, the decreasing trend could be because of higher water absorption of the RBA compared with natural aggregates. They pointed out that the use of coarse and fine RBA should be done carefully and it can decrease the compressive strength.

Alves et al. [23] reported that the reduction rate of compressive strength of concrete made with RBS was 24.9%, 9.6% and 7.1% respectively, compared with the reference concrete. They explained that the reduction was attributed to the decreased paste's strength with the increase in substitution rate. When the curing age increased, the strength difference between concrete made with RBS and that of reference concrete decreased.

Ledesma et al. [26] presented that the compressive strength of mortar decreased as the RBS content increased. For the mortar made with 50% RBS, the compressive strength exceeded 10 MPa after 28 days and it was only 11.3% less than that of the reference mortar.

Wu et al. [29] demonstrated that the compressive strength of mortar made with 25%, 50% and 100% RBS was 1.9%, 6.9% and 14.2% lower than that of reference mortar, respectively, which was probably attributed to the lower properties of RBS compared with natural sand. However, the reduction was not so significant because of the beneficial internal curing effect of RBS. The same trend was found for the flexural strength of mortar.

Dang et al. [27] demonstrated that the additional water content and different particle sizes of RBS had a great effect on the mechanical properties of mortar, while the effect of the replacement ratio of RBS was little. The strengths of mortar made with partially additional water of RBS were increased compared with the mortar made with the full additional water, which was attributed to the different efficient water to cement ratio (the compressive strength of mortar made with 25%, 50% and 75% RBS was 16%, 15%, and 12% higher than that of reference mortar, respectively).

Liu et al. [28] reported that the compressive strength of mortar made with all fractions of RBS showed an increasing trend when the replacement ratio of NS by RBS increased. For the series of mortar made with coarse RBS, the compressive strength of mortar made with 10%, 20% and 30% was 25.2, 27.6 and 28.5 MPa, respectively, which was 1.3%, 11.2% and 14.9% higher than that of the reference mortar (24.8 MPa). The same trends were obtained for the series of medium RBS and fine RBS.

2.3.2. Water absorption

Debieb and Kenai [22] showed that water absorption of concrete containing RBS had higher values than that of the reference concrete. The capillary water absorption of concrete containing RBS was significantly greater than that of the reference concrete. The water absorption by mass of 100% RBS based concrete was measured as 8.0%, while it was only 5.0% for the reference concrete made without RBS.

Boukour and Benmalek [25] tested the water absorption by total immersion. They found that the studied mortars containing crushed brick filler had a slightly higher value (the maximum decrease was only 4.71% for the 10% crushed brick filler) than that of reference mortar. The capillary water absorption of mortars containing crushed brick filler decreased as the increase of crushed brick filler content. The amount of absorbed water decreased by 42.8%, 49.4%, 57.1% and 61% respectively for the mortar made with the crushed brick filler content of 2.5%, 5%, 7.5%, and 10%.

Wu et al. [29] demonstrated that water absorption of mortar increased with the increase of substitution ratio of NS by RBS. The maximum absorbed water of mortar made with 25%, 50% and 100% RBS was 5.5%, 49.1% and 98.2% higher than that of the reference mortar. They stated that it was probably attributed to the higher porosity and higher water absorption of RBS compared with NS.

2.3.3. Drying shrinkage

Khatib [21] demonstrated that shrinkage of concrete containing RBS presented higher values than that of reference concrete. In addition, the shrinkage of concrete made with RBS decreased as the replacement of NS by RBS increased. The most shrinkage of concrete occurred at an early age (10 days) after the mixing and then slow down.

Debieb and Kenai [22] mentioned that the shrinkage of concrete containing RBS at an early age was six times greater than reference concrete, and the shrinkage of concrete increased slightly as RBS increased, which was due to the water movement in RBS when the drying proceeded to.

Ledesma et al. [26] measured drying shrinkage up to 203 days and showed that the drying shrinkage increased linearly as RBS content increased, which was probably attributed to the greater water-to-cement (W/C) ratio used and the loss of water by the evaporation.

Wu et al. [29] reported that the drying shrinkage of mortar made with RBS increased as the RBS content increased. Drying shrinkage of mortar made with 25%, 50% and 100% RBS was 6.5%, 18.6% and 63.1% higher than that of reference mortar, respectively. They explained that it was attributed to the higher water absorption and also the lower hardness of RBS, which obtained more free water and lead to the increase in drying shrinkage.

2.4. Durability of concrete or mortar

There is some research concerning the durability of concrete containing coarse RBA [33–39]. Only a few papers were found regarding the durability of mortar or concrete made with RBS.

2.4.1. Carbonation resistance

Zong et al. [40] investigated the durability of concrete made with coarse RBA. They stated that the carbonation depth of concrete made with the coarse RBA was greater than that of reference concrete. The carbonation depths of concrete made with coarse RBA increased as the coarse RBA content increased.

2.4.2. Sulphate resistance

Ledesma et al. [26] investigated the resistance to sodium sulphate attack only for the mortar with 0%, 50% and 100% of RBS. They found that there was no visible damage or cracks in all tested samples. However, the mortar made with 100% RBS had greater weight loss than that reference mortar. They explained that the reason was attributed to the crystallization of salts in fissures and pores of mortar and thus more mortar particles were separated after the sodium sulphate attack.

2.4.3. Chloride resistance

Wu et al. [29] evaluated the chloride ingress of mortar made with RBA and RBP. They showed that the incorporation of RBP could improve the chloride diffusion properties, but the impact of the chloride ingress on the incorporation of RBA was not mentioned in their study.

Pacheco-Torgal and Jalaji [10] evaluated the properties of concrete made with 100% ceramic sand. The used RBS had a water absorption of 6.1% and a density of 2210 kg/m^3. They demonstrated that the concrete made with 100% ceramic sand had better resistance to chloride ion diffusion and better performance after the accelerated aging test.

Higashiyama et al. [41] conducted a study of the chloride ion penetration of mortar made with RBA obtained from the ceramic electrical insulator. The water absorption of this RBA was only 0.7%, which is greater than that of normal RBS. The mortar made with this special RBA showed better resistance than that of reference mortar.

Ge et al. [32] investigated the chloride ion penetration resistance of SCC made with RBS. The results indicated that the use of RBS reduced the chloride ion penetration resistance. However, the chloride ion penetrability was considered low (electric flux: 877–2000) for the replacement level up to 50% and moderate (electric flux: 2000–4000) for the replacement levels of 75% and 100%.

2.4.4. Freeze-thaw resistance

Ge et al. [32] investigated the freeze-thaw resistance of SCC made with RBS. The results showed that the incorporation of RBS decreased the freeze-thaw resistance of SCC. When the NS was replaced by 100% of RBS, the relative dynamic elastic modulus reduced to 78% compared with the reference concrete, which fulfilled the frost resistance according to Chinese standard JGJ/T193-2009. In addition, the mass loss of SCC reduced as the replacement level increased, which was due to the high water absorption capacity of RBS.

According to the literature, the durability of SCC or SCM based on the RBS is not well explored up to now [32,42–44]. Therefore, this study intends to fill this gap and evaluates the feasibility of using RBS in SCM. The crushed limestone sand is partially replaced with RBS at different levels (0, 5, 10, 25 and 50%). The properties of the fresh state, mechanical behavoir, drying shrinkage and durability (such as resistance to carbonation, resistance to sulphate and chloride diffusion) of SCM are conducted and explored in this study.

3. Experimental program

3.1. Materials

3.1.1. Cement and limestone filler

The Ordinary Portland Cement (CEM I 52.5 N, provided by a Belgian company CBR) was used. The mineralogical composition of CEM I 52.5 N is mainly composed of 67.0% C_3S, 12.1% C_2S, 7.2% C_3A and 9.5% C_4AF. The density of cement used was measured as 3.10 g/cm^3 by Micromeritics AccuPyc 1330 (helium pycnometer). A commercial limestone filler (which had more than 98.1% of calcite) provided by a Belgian Company was used to decrease the quantity of cement and the environmental impact. The density of limestone filler was determined as 2.73 g/cm^3 using a helium pycnometer. The D50 diameter and specific surface area of cement determined by the BET method were 11.1 μm, 1.3 m^2/g respectively, while it was 18.3 μm and 0.8 m^2/g respectively for limestone filler.

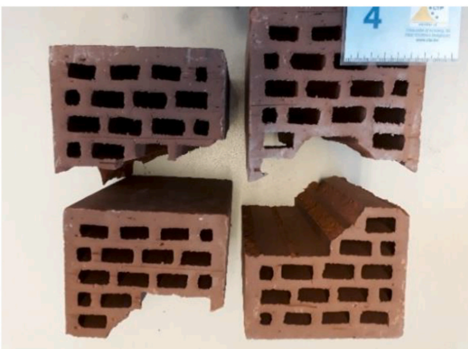
3.1.2. Recycled brick sand and natural sand

The red waste bricks (288 × 138 × 138 mm^3) were obtained from a Belgian brick company, and the compressive strength of this brick block was 35 MPa (Fig. 1) [45]. The semi-industrial jaw crusher was used for the production of RBS (200 kg of brick waste) and two fractions were generated (fraction 0/4 mm, fraction 4/10 mm) [46]. The fraction 0/4 mm was used to substitute the natural sand. The water absorption of RBS with the fraction 0/4 mm was measured as 11.3% according to the European standard EN 1097-6 [47]. The water absorption value obtained is similar to the ones found by Alves et al. [23] and Dang et al. [27]. The real density based on the oven-dried basis of RBS was 2.67 g/cm^3 determined by the European standard EN 1097-6.

A commercial crushed limestone sand was used as natural sand (NS) for the manufacture of SCM. The water absorption and real density on the oven-dried basis of limestone sand were 1.0% and 2.70 g/cm^3 determined by the European standard EN 1097-6. The water absorption of RBS had a higher value than that of NS, which was probably attributed to the higher porosity presented in the original brick waste. This result is consistent with all the works reported in Section 2. The chemical composition of RBS (grinding RBS for the chemical analysis) was determined by using X-ray fluorescence (XRF, Bruker AXS, S4 Pioneer). The result indicated that the major chemical elements of RBS were SiO_2 (62.8%), Al_2O_3 (10.4%), and Fe_2O_3 (16.3%), which is consistent with the results obtained by other researchers [25,27,28]. SiO_2 and Al_2O_3 account for 73.2% of the total chemical composition of the RBS. The mineral composition of RBS (grinding RBS for the mineral analysis) was also measured by using X-ray diffraction (XRD, Brucker AXS D2 phaser diffractometer, with the parameters: 0.2° pitch, 6–80° angle and acquisition time of 0.5s). The major mineral compositions of the RBS were α-Quartz (SiO_2, accounting for 55.0%), hematite (α-Fe_2O_3, accounting for 12.8%) and microcline ($KAlSi_3O_8$, accounting for 9.2%). Moreover, 16.0% of the amorphous phase was found in RBS, which is an important component related to the pozzolanic activity [12,48,49]. This is consistent with the results obtained from the XRF test.

3.1.3. Mortar design

The self-compacting mortar (SCM) offers several benefits associated with the operation process both in precast plant and direct applications at construction sites. The mortar composition was obtained by using the concrete equivalent mortar (MBE) method developed by Schwartzentruber [50], which allowed for the transformation of the self-compacting concrete mix into the mortar mixtures displaying correlative rheological properties for analysis. The compositions of SCM are given in Table 2. Five self-compacting mortars were made with RBS substituting the same volume of NS at replacement levels of 0, 5, 10, 25 and 50% (noted M-BS0, M-BS5, M-BS10, M-BS25 and M-BS50, respectively). An important aspect is that even though different sands were used in the manufacture of SCM, the grading curves of NS, RBS and NS50-RBS50 (50% replacement of NS by RBS) were within the range of requirement described in ASTM C33 [51] except for the fraction less than 0.4 mm (Fig. 2). RBS and limestone sand were 24 h pre-saturated before the manufacture of mortars. An efficient water-to-cement (W/C) ratio of 0.9 was used for all the mixtures. It should be pointed out that the objective is to evaluate the effect of RBS substituting limestone sand on the properties of SCM and the other variable parameters (e.g. use of superplasticizer) were kept constant. Thus the high W/C ratio of 0.9 was conducted in the manufacture of SCM but no



(a)

(b)

Fig. 1. RBS preparation: (a) red brick waste; (b) RBS crushed by semi-industrial jaw crusher and the fraction 0/4 mm was used for the production of SCM. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Compositions of SCM (g).

Mix Type	Cement	Limestone filler	NS	RBS	Effective water	Absorbed water	Total water
M-BS0	392.0	261.0	1181.2	0.0	352.8	11.8	364.6
M-BS5	392.0	261.0	1121.1	58.5	352.8	17.8	370.6
M-BS10	392.0	261.0	1063.1	116.9	352.8	23.8	376.6
M-BS25	392.0	261.0	885.9	292.4	352.8	41.9	394.7
M-BS50	392.0	261.0	590.6	584.7	352.8	72.0	424.8

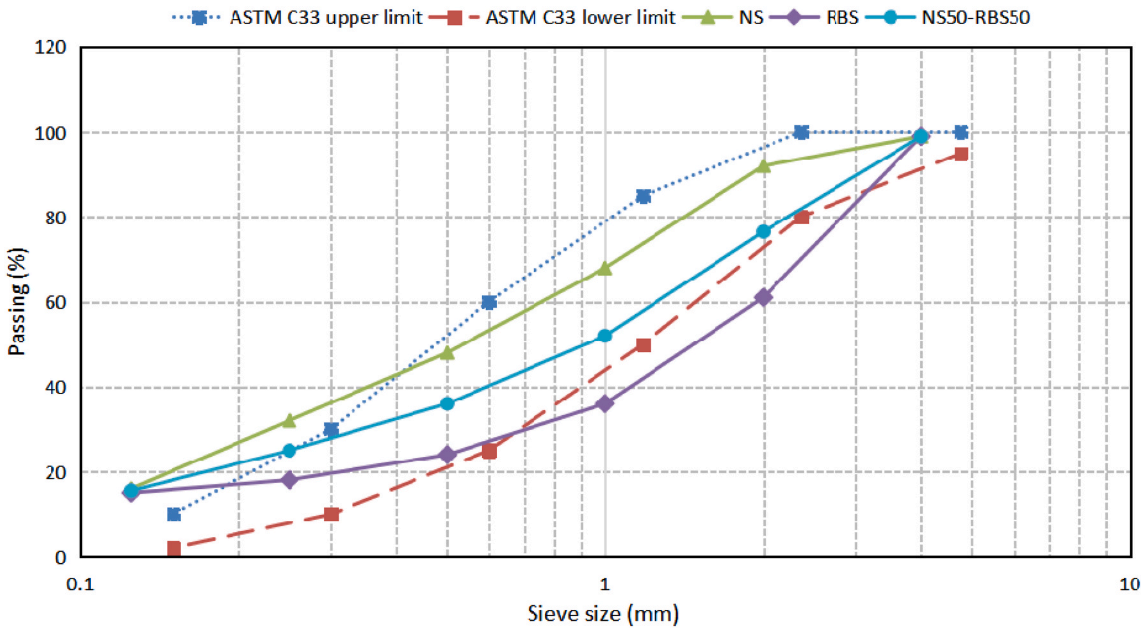


Fig. 2. Grading curves of NS, RBS and NS50-RBS50 (50% replacement of NS by RBS).

superplasticizer was used in this study.

3.2. Experimental methods

Table 3 presents the experimental program and test methods used in this study. Detailed information on the experimental methods can be found in the previous work [52] and corresponding standards.

3.2.1. Mixing procedure for the production of mortar

The European standard EN 196-1 was followed to produce the mortar in this study [55]. All the RBS and limestone sand was pre-saturated 24 h with the quantity of efficient water before the manufacture of mortars.

3.2.2. Tests on the mortars at fresh state

After mixing, two tests were followed to determine the rheological property of mortar at a fresh state: a spreading (flow index) test

Table 3
Experimental program and test methods used in this study.

Studied properties	Curing time (days)	Samples per test	The standard test method used in this study
Spreading property (flow index)	0	2	MBE cone [50]
Density of fresh mortar	0	3	EN 1015-6 [53]
Shear stress and shear rate	0	1	Rheocad 400 [52]
Air content	0	1	EN 1015-7 [54]
Compressive strength	28	6	EN 196-1 [55]
Flexural strength	28	3	EN 196-1 [55]
Water absorption	28	3	NBN B15-215 [56]
Drying shrinkage	1	3	NBN B14-217 [57]
Carbonation resistance	28	3	EN 13295 [58]
Sulphate resistance	28	3	ASTM C1012-04 [59]
Chloride ion diffusion	28	2	Courard et al. [60,61] and ASTM C1202-05 [62]

and a rheometer method. The spreading of mortar at a fresh state was determined with the MBE cone [52]. Fundamental rheological characteristics were evaluated using a rheometer (Rheocad 400). The shear stress and shear rate were obtained with the measurement of the torque. The air content of mortars and the density of mortar at fresh state were measured by the European standard EN 1015-7 [54] and EN 1015-6 [53], respectively.

3.2.3. Mechanical performance of mortars

The flexural strength and compressive strength of mortar after 28 days were determined according to the European standard EN 196-1 [55] and carried out by an INSTRON 5585.

3.2.4. Water absorption of mortars

Water absorption of mortars by immersion was measured after 28 days of curing and the standard NBN B15-215 [56] was used for this test.

3.2.5. Drying shrinkage of mortars

The drying shrinkage measurements of mortar (length variances of specimens) were performed at ages of 1, 3, 7, 14 and 28 days within the chamber at 21 ± 2 °C and 60 ± 5% relative humidity (RH) following the standard NBN B14-217 [57].

3.2.6. Carbonation resistance of mortars

The carbonation depth of mortar after 28 days and 56 days' accelerated test within the chamber of 1% CO_2 concentration and 60 ± 5% RH was obtained by phenolphthalein indicator according to the European standard EN 13295 [58].

3.2.7. Sulphate resistance of mortars

The sulphate resistance of mortars was conducted after storage periods of 7, 14, 21, 28, 35, 42 and 77 days in the sodium sulphate concentration of 50 g/L according to the ASTM C1012-04 [59].

3.2.8. Chloride ion diffusion of mortars

Two-compartment diffusion cells method was used for the determination of the chloride ion diffusion coefficient of mortars [60, 61]. The tests after 14, 28, 42, 56, 70, 84, 98 and 112 days were measured. Meanwhile, the chloride ion diffusion resistance was also conducted in accordance with ASTM C1202-05 [62]. A potential difference of 30 V (a lower voltage was used to avoid any overheating harmful to the measurements since the mortar has a higher porosity and a higher current intensity compared with the classic concrete) was used in this study and current intensity was recorded during the test period (6 h).

4. Results and discussion

4.1. Properties of mortars at fresh state

Fig. 3 presents the flow index (spreading) of mortars containing RBS. The spreading of mortars slightly increased (the maximum value of flow index was presented for the mortar M-BS10), and then slightly decreased with the replacing percentage of limestone sand by RBS. However, all the values of the flow index were within the range of 200–225 mm. After considering the water absorption of RBS and pre-saturated the RBS 24 h before the manufacture of mortar seems to be able to satisfy the spreading property of the mortars made with up to 50% of RBS, i.e. the pre-saturation of RBS 24 h before the manufacture of mortar is necessary to achieve the flow property of mortar. In fact, the increase in the apparent W/C ratio is needed for the mortar containing RBS to obtain similar workability as that of

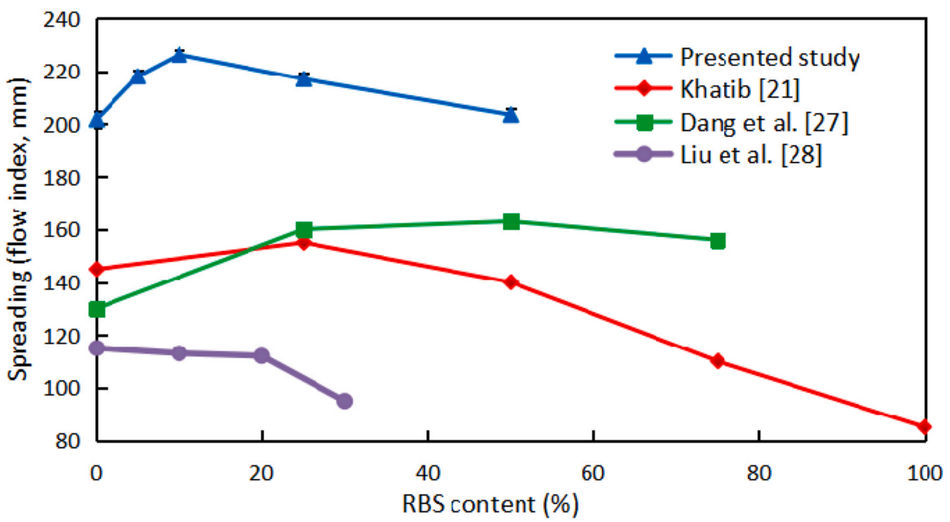


Fig. 3. Benchmarking of flow index (spreading) of mortars at fresh state as a function of RBS content for this study and the results described from other studies.

reference mortar, which was probably attributed to the higher water absorption of RBS compared with NS [21,24,27,28]. In the studies by Debieb and Kenai [22], Alves et al. [23], Dang et al. [27], they obtained the same result.

Fig. 4 presents the flow curve of mortars through the Rheocad apparatus. The results indicated that a perfect fit to a straight line was performed for the shear rate within the range of 1–22 s^{-1}. In addition, Table 4 shows the yield stress, plastic viscosity and the correlation coefficient (R^2) of mortars in a fresh state. The mortars substituting NS by RBS (for mortars M-BS5 and M-BS10) showed a lower yield stress and plastic viscosity than that of reference mortar. The yield stress and plastic viscosity of mortar M-BS50 showed a higher value compared with the reference mortar. The Rheocad tests confirmed the results obtained from the flow index measurement. The RBS had a higher porosity and greater internal friction between the particles than NS [25,27,28]. At low replacement ratios, the higher porosity in RBS (some pre-saturated water from the RBS was released into the mixing system during the manufacture of mortar while the same effective W/C ratio was used for all the mixes), led to the slight increase of free water present in the mix, and thus the viscosity and torque of mortar decreased slightly for the mortars M-BS5 and M-BS10. The mortar M-BS50 presented a lower flowability (higher yield stress and plastic viscosity) than that of the reference mortar, which was probably attributed to the role of the higher internal friction of RBS compared with the limestone sand when the replacement ratio increased up to 50%.

Fig. 5 indicates the density and air content of mortars. When the replacement of limestone sand with RBS increased, the air content of mortars increased, which was attributed to the higher porosity of RBS compared with NS [26,29]. Generally, the incorporation of a higher porosity of RBS will lead to an increase in the micro porosity and vacuum generated by the angular form of RBS. These results are consistent with other researchers [26,63]. In addition, the density of fresh mortar slightly decreased with the replacement percentage of limestone sand by RBS, which is mainly attributed to the lower density of RBS compared with NS [21,24,26]. The same results and explanations are also obtained by other researchers [22,23,64].

4.2. Properties of hardened mortars

4.2.1. Mechanical properties of mortars

Fig. 6 shows the compressive strength and flexural strength of mortars. The compressive strength of mortars slightly decreased after 28 days when the replacement of NS by RBS increased, which was probably attributed to the higher porosity of RBS compared with the limestone sand and greater air content for the mortar containing RBS. The compressive strength of mortar made with RBS (25% RBS and 50% RBS content) was 3.3% and 16.9% respectively, lower than the reference mortar. Alves et al. [23] stated that introducing RBS in the mortar could decrease the strength of the paste and lower the mortar strength because of the lower strength and more porous structure of RBS compared with the natural ones. In addition, the decreasing trend of compressive strength could be compensated by the possible pozzolanic activity of the brick aggregates [18,21,23,28,29,31]. Fig. 7 presented the results of this study, together with the results obtained from other studies. The compressive strength of concrete or mortar decreased linearly with the increase of the substitution ratio (with coefficient $R^2 = 0.7752$). Debieb and Kenai [22], Khatib [21], Alves et al. [23] obtained the same conclusion as presented in this study. One explanation is that the pre-saturation process could affect negatively the mechanical performance of concrete or mortar [31,65]. Another explanation is that the RBS had lower strength and higher porosity when compared with the natural sand [23,26,31]. All the mortars tested in this study were within the compressive strength requirement for masonry mortars Grade "Md" according to the European standard EN 998-2 [66].

The flexural strength of mortars containing RBS was equivalent to the reference mortar, which was probably due to the possible pozzolanic activity of RBS. It is also confirmed by other studies [27,28]. Another reason is that the pre-saturation of RBS leads to internal curing at a later time. In fact, the RBS itself could perform as an internal curing agent, the pre-saturated RBS could release the pre-saturated water and provide this water to promote the pozzolanic reactions between the cement hydrated products (Portlandite)

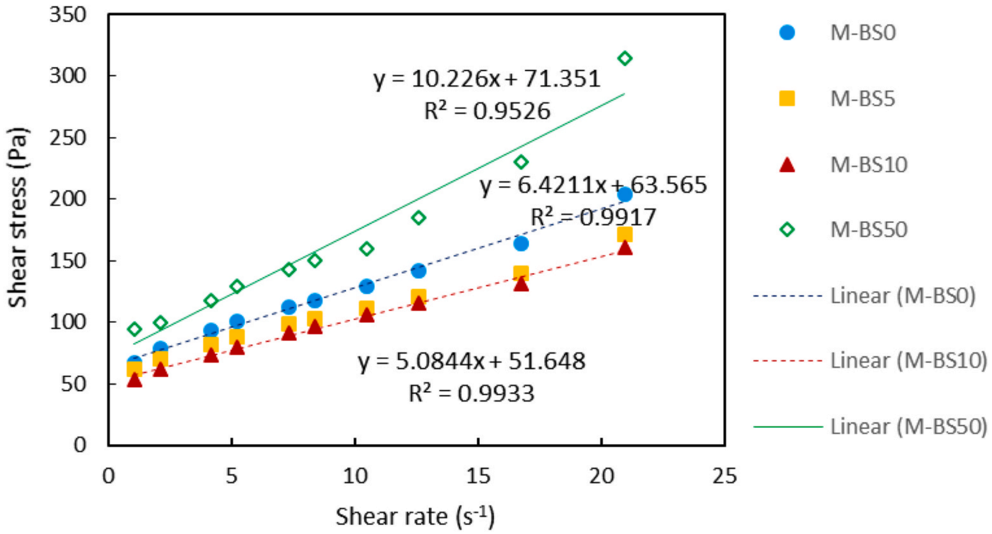


Fig. 4. Flow curve of mortar and evaluation of yield stress obtained from Rheocad test.

Table 4
Rheological properties of mortars determined by the Rheocad test.

Mortar	τ_0 (yield stress)	μ (plastic viscosity)	R^2
M-BS0	63.565	6.421	0.99
M-BS5	58.445	5.167	0.99
M-BS10	51.648	5.084	0.99
M-BS50	71.351	10.226	0.95

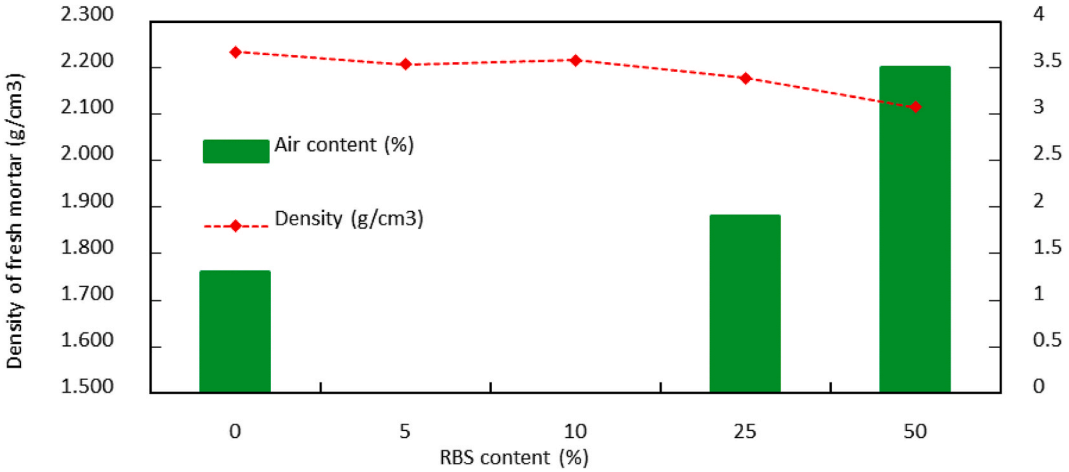


Fig. 5. Density and air content of mortars as a function of RBS content.

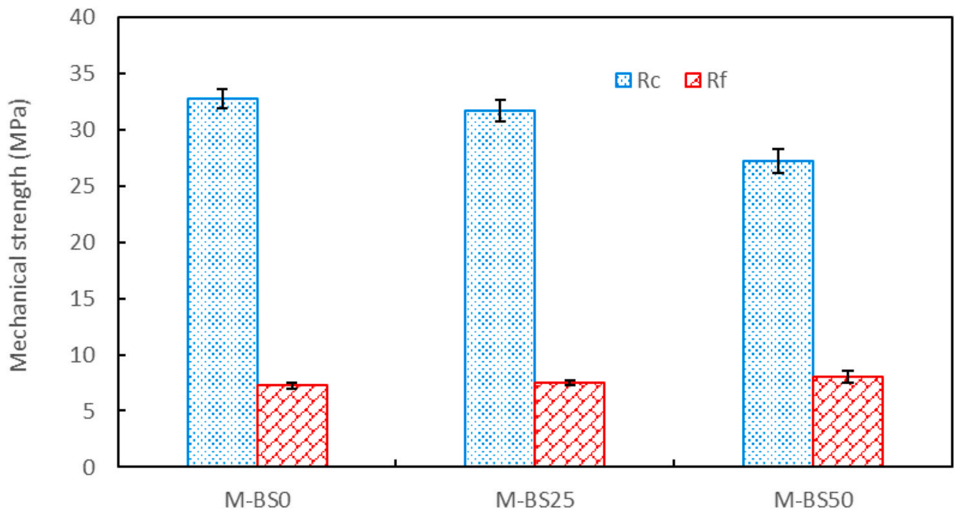


Fig. 6. Mechanical strength of mortars after 28 days.

and the amorphous phase presented in the RBS (silica and alumina phases) [31,52].

4.2.2. Water absorption of mortars

The water absorption of mortars measured by immersion is shown in Fig. 8. As can be seen in this figure, the water absorption values of mortar made with RBS increased with the increase of the RBS content (it is slightly higher for the cases of mortars made with the lower replacement of RBS up to 10%). Firstly, the RBS had higher porosity than limestone sand. Then, the mortars made with RBS had a higher value of air content, and thus it will induce the increase of porosity of mortar made with RBS. Therefore, the water absorption values of mortars made with RBS were greater than the reference mortar. This conclusion is consistent with other studies [22,29].

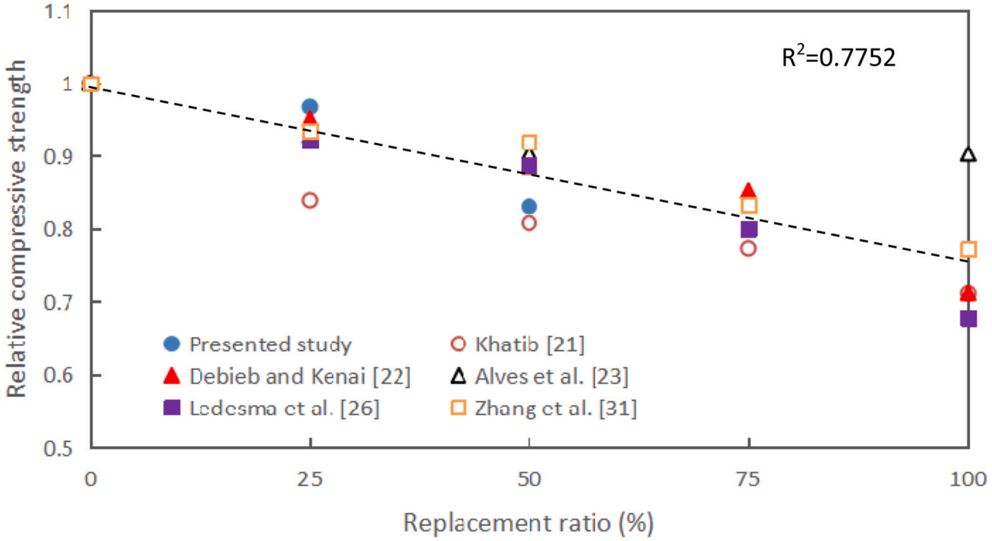


Fig. 7. Benchmarking of the compressive strength of mortar after 28 days of this study and the results obtained from other studies.

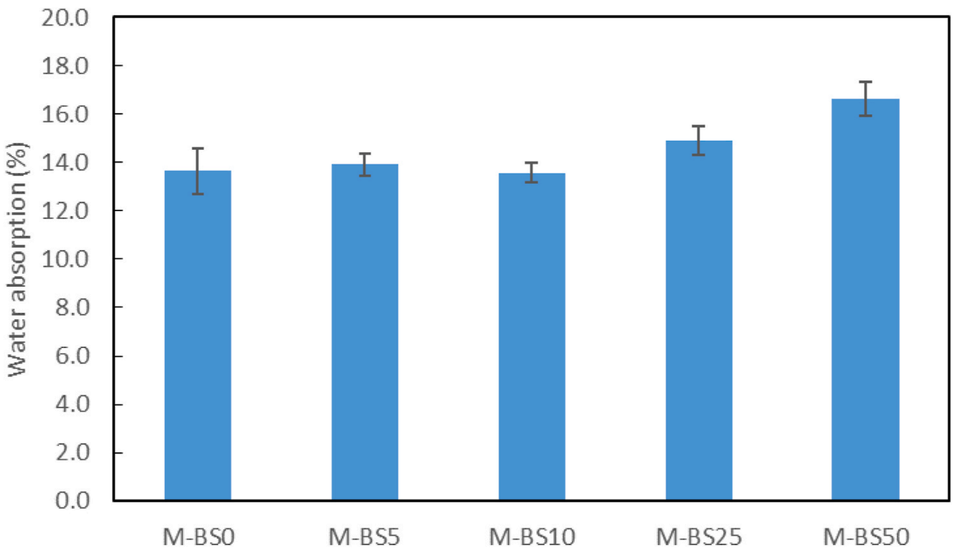


Fig. 8. Water absorption of mortars at 28 days.

4.2.3. Drying shrinkage of mortars

Fig. 9 presents the drying shrinkage of mortars. As can be seen, the incorporation of RBS in mortar led to a slight reduction of drying shrinkage in comparison with that of NS (except for the mortar M-BS10 at 7 days). Liu et al. [28] stated that similar shrinkage was obtained in their study. They explained that it may be due to the balance between increasing due to the lower elastic modulus of RBS and the reduction resulting from the pozzolanic activity. Additional water was used for the pre-saturation of RBS, which served later as the contribution of providing the water; the refined pore network could be generated by the reaction between $Ca(OH)_2$ and the amorphous phases (mainly silica and alumina) present in RBS; thus this effect contributed to a decrease in drying shrinkage [52]. In the studies of other authors, Debieb and Kenai [22], Wu et al. [29], and Ledesma et al. [26] stated that the shrinkage of concrete containing RBS presented higher values than that of the reference concrete, and the shrinkage increased as the RBS content increased. They demonstrated that the increase in shrinkage was attributed to the higher water absorption, lower hardness of RBS and the water movement in the fine RBA when the drying proceeded (the loss of water by evaporation).

4.3. Durability of mortars

4.3.1. Carbonation resistance of mortars

Fig. 10 indicates the evolution of carbonation depth of mortars as a function of time. The substitution of NS with RBS increased the

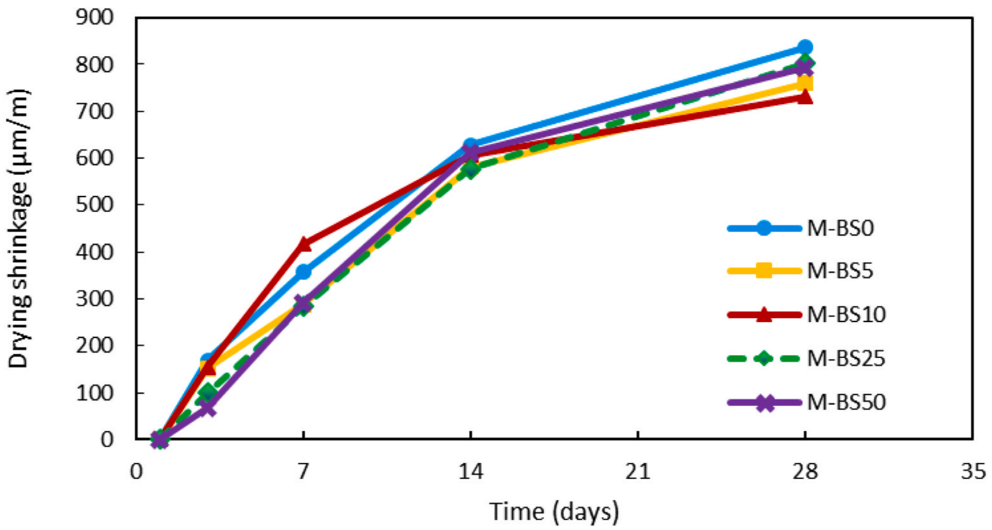


Fig. 9. Drying shrinkage of mortars.

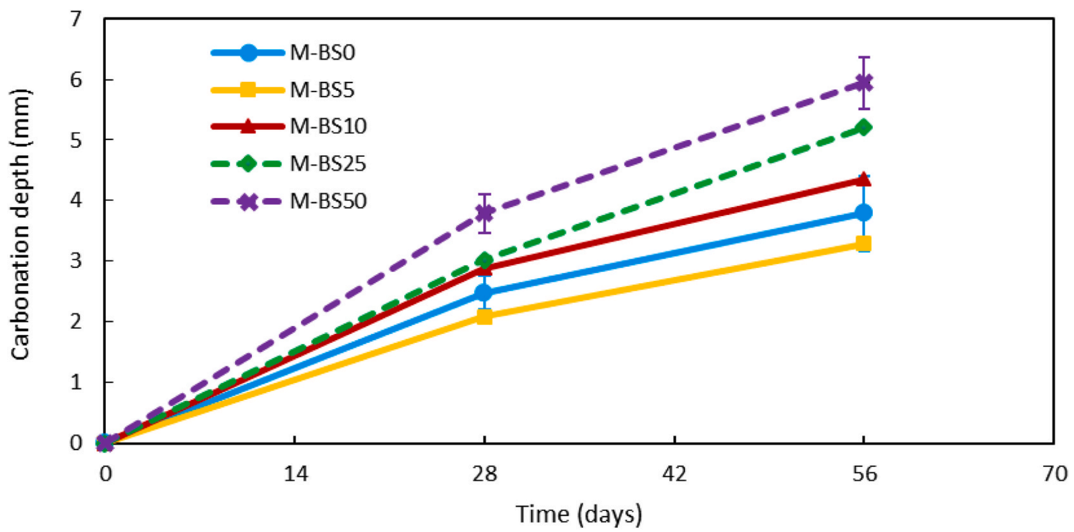


Fig. 10. Carbonation depth of mortars (the standard deviations of measurement of M-BS0 and M-BS50 are also included).

carbonation depth of mortars (except the mortar M-BS5). The carbonation depth of M-BS50 was 5.9 mm after 56 days' carbonation within 1% of CO_2, while it was only 3.8 mm for the reference mortar. The carbonation depths of all mortars increased with time, which was consistent with other studies [4,11]. The carbonation process in mortar strongly depends on the moisture content pore structure and porosity of concrete or mortar [67,68]. The incorporation RBS in SCM increased the permeability of the open pore structure and water absorption of mortar, which could promote the diffusion of CO_2 in pore water of mortar and induce an increase in carbonation rate [40,52].

4.3.2. Sulphate resistance of mortars

Fig. 11 shows sulphate resistance of mortars after immerging into Na_2SO_4 solution for up to 77 days. The expansion of mortars made with RBS presented higher values than that of the reference mortar. The expansion of mortars M-BS25 and M-BS50 after 77 days was 443 and 400 μm/m, respectively, while it was only 226 μm/m for reference mortar. The sulphate attack is defined as the sulphates reacting with aluminate hydrates and water to form secondary ettringite, which could cause a volumetric deformation [69,70]. The resistance to sulphate depends on the pore sizes, the total porosity and the permeability of concrete or mortar [4,70,71]. The substitution of NS by RBS increased the permeability of the open pore structure, and the diffusion of sulphates could be more easily and thus favoring the expansion of the mortar. The substitution of NS by RBS in the mortar seems to impair the resistance to sulphate attack. This conclusion is also drawn from the study of Ledesma et al. [26].

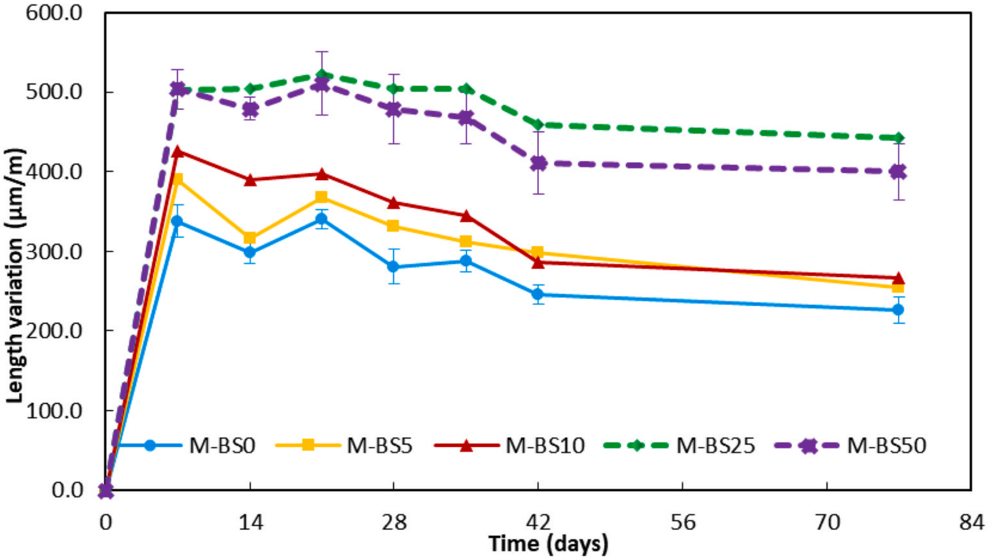


Fig. 11. Length variation of mortars made with RBS in sulphate solution (the standard deviations of measurement of M-BS0 and M-BS50 are also included).

4.3.3. Chloride resistance of mortars

Fig. 12 presents the chloride resistance of mortars as a function of the type of mortar. Table 5 presents the apparent chloride ion diffusion coefficient of mortars. An apparent chloride diffusion coefficient of 1.78×10^{-12} m^2/s was observed for the reference mortar after 112 days. The apparent chloride diffusion coefficient of SCM containing RBS presented lower values than that of reference mortar (it was only 8.53×10^{-13} m^2/s for mortar prepared with 50% RBS), which means the mortar made with RBS had better resistance to chloride penetration. The chloride ion diffusion of mortar or concrete depends on the total porosity and the pore structure (pore particle size distribution and pore tortuosity) [11,72,73]. Despite the slightly higher porosity of mortar made with RBS, the parameter of pore structure such as the pore particle size distribution or tortuosity could be refined by the pozzolanic reaction between $Ca(OH)_2$ and the amorphous phases (mainly silica and alumina) present in RBS [27,64,74], and thus led to the better performance concerning chloride ion diffusion for the RBS based mortar.

Fig. 13 shows the total charge passed on different types of mortars by the migration and indirect test, which is accelerated by the external electrical field. The total charge passed of 3692 Coulombs was observed for the reference mortar while it was only 1722 Coulombs for the mortar made with 50% RBS. The total charge passed of mortar made with 50% RBS showed a reduction of 53.5% when compared with the reference mortar. These tests confirmed the point that the mortar made with RBS had better resistance to chloride penetration, which is consistent with the previous results [10,41].

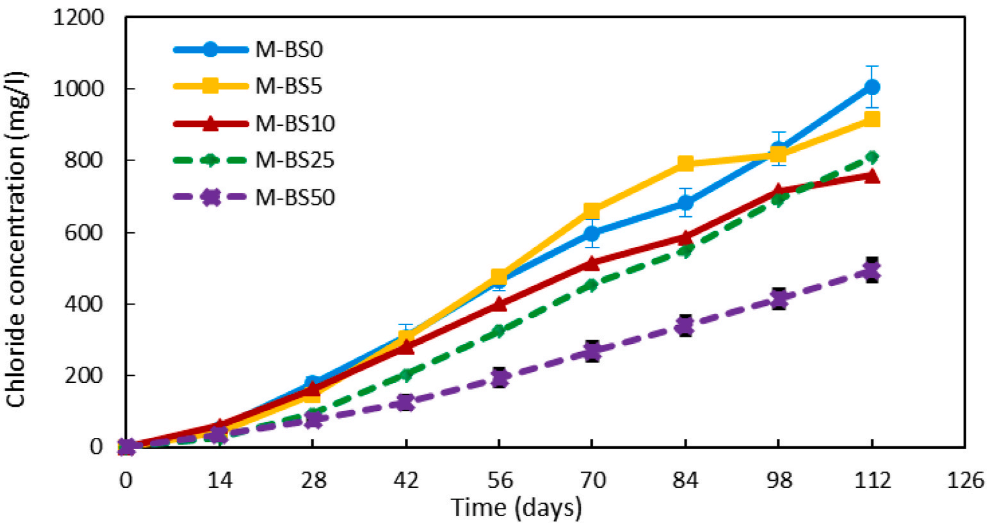


Fig. 12. Chloride concentration for mortars made with RBS as a function of time (the standard deviations of measurement of M-BS0 and M-BS50 are also shown in the figure).

Table 5
Chloride diffusion rates for mortars made with RBS.

Mortar	Apparent chloride diffusion coefficient at 112 days (m^2/s)	Standard deviation (m^2/s)
M-BS0	1.78×10^{-12}	1.24×10^{-13}
M-BS5	1.44×10^{-12}	1.16×10^{-13}
M-BS10	1.11×10^{-12}	2.43×10^{-14}
M-BS25	1.35×10^{-12}	2.88×10^{-14}
M-BS50	8.53×10^{-13}	4.72×10^{-14}

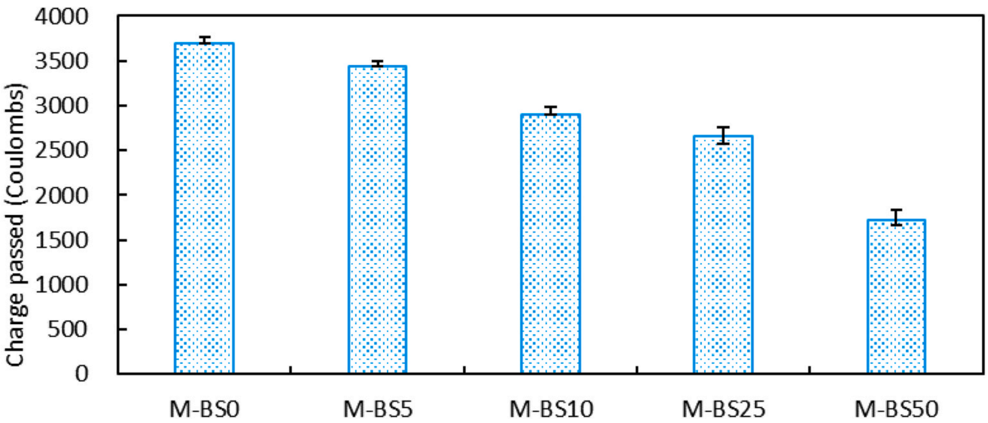


Fig. 13. Total charge passed on SCM mortars as a function of the type of mortars.

5. Conclusions

The feasibility of substituting limestone sand with recycled brick sand (RBS) in the self-compacting mortar (SCM) has been studied and evaluated. The performances of SCM including rheological properties, mechanical properties, drying shrinkage and durability were investigated. The main conclusions can be drawn as follows:

1) The spreading of mortars slightly increased (the maximum value for the mortar M-BS10), and then slightly decreased with the replacing percentage of limestone sand by RBS. However, all the measured spreading (flow index) values were within the range of 200–225 mm. After considering the water absorption of RBS and pre-saturating the RBS 24 h before the manufacture of mortars, it seems to be able to achieve the spreading flow property for the mortars made with up to 50% of RBS. In addition, the density of fresh mortar slightly decreased with the replacement increase of limestone sand by RBS.
2) The Rheocad results showed that mortars containing RBS (for mortars M-BS5 and M-BS10) presented a lower yield stress and plastic viscosity than that of reference mortar. The mortar M-BS50 had a lower flowability (higher yield stress and plastic viscosity) than that of reference mortar, which was probably due to the role of the higher internal friction of RBS compared with limestone sand when the replacement ratio increased to 50%.
3) As the replacement of NS by RBS increased, the compressive strength of mortars slightly decreased after 28 days. Incorporating RBS in SCM, with lower strength and a more porous structure than the natural ones, decreased the strength of the paste, which led to the lower mortar strength. In addition, the decreasing trend of compressive strength could be compensated by the possible pozzolanic activity of the brick sand, specifically smaller particles. The compressive strength of mortar made with RBS (25% RBS and 50% RBS content) was 3.3% and 16.9% respectively, lower than the reference mortar. It is important to notice that all the specimens fulfil the compressive strength requirements of the European standard EN 998-2 for masonry mortars Grade “Md”.
4) The incorporation of RBS in SCM induced a slight reduction of the drying shrinkage of mortar in comparison with that of limestone sand (except the mortar M-BS10 at 7 days). The substitution of limestone sand by RBS increased the carbonation depth of mortars, which is due to the higher porosity of the mortar. The substitution of limestone sand by RBS seems to impair the behavior of mortars with regard to sulphate attack. But the apparent chloride diffusion coefficients of mortars made with RBS presented lower values, which means the mortar made with RBS had better resistance to chloride penetration. The tests of total charge passed also confirmed that the mortar produced with RBS had better resistance to chloride penetration.
5) Incorporating RBS in the production of SCM proves to be a good opportunity for recycling brick waste. It is feasible to manufacture SCM by partially replacing the crushed limestone sand with RBS up to 25%. In the case of a higher replacement level, particular attention should be noted to the risks associated with sulphate attack and carbonation.

Credit author statement

Zengfeng Zhao: Methodology, Investigation, Writing - Original draft preparation, Writing – Review & Editing, Funding acquisition; **Jianzhuang Xiao:** Writing – Review & Editing, Validation; **Zhenhua Duan:** Validation; **Julien Hubert:** Data Curation; **Sophie**

Grigoletto: Formal analysis; **Luc Courard:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the "Institut Interuniversitaire des Silicates, Sols et Matériaux (INISMa)" and the "Centre Terre et Pierre (CTP)" for participation in preparation of RBS. The authors would like to thank the Master's students (Martin Wintgens and Enrico Tabarelli) who conducted the tests. The authors would like to thank the Interreg VALDEM project (Interreg France-Wallonie-Vlaanderen Convention No. 1.1.57, 2014-2020) for its financial support. The authors would also like to thank the Fundamental Research Funds for the Central Universities (Tongji University, funding numbers: 22120210317 and 22120220084) for their financial support.

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