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TECHNICAL PAPER

The effects of recycled brick and water/cement ratios on the physical and mechanical performance of recycled aggregates concrete

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Abstract

In this paper, the effects of recycled Refractory Brick Aggregates (RBA) and water/cement ratio (w/c) on the physical and mechanical properties of concrete were experimentally studied. For this purpose, three series of mixes, with different compositions were prepared. In the first series, conventional reference concrete was made with 100% of Natural Aggregates (NA). In the second series, concrete was manufactured by replacing 20% of coarse NA with coarse RBA. In the third series, concrete was produced by replacing 20% of coarse and fine NA with coarse and fine RBA. In all mixes, three w/c ratios (w/c = 0.59, 0.47 and 0.38) were evaluated. The following parameters were examined in this experiment: water absorption, water porosity, density, Ultrasonic Pulse Velocity (UPV), compressive strength and dynamic modulus of elasticity. The experimental results showed that the performance of concrete made with RBA is slightly inferior to that of conventional concrete. On the other hand, the deterioration of UPV and dynamic modulus of elasticity of concrete made with 20% coarse and fine RBA were slightly higher than that of concrete made with 20% of coarse RBA. The same results are observed for the water absorption and water porosity. However, replacing 20% of coarse and fine RBA leads to an improvement in the concrete's compressive strength and density. Meanwhile, based on a comparison with existing data, it is found that lower w/c ratio resulted in lower porosity of concrete, and the decrease of porosity generally led to the improvement of the performance of concrete.

Keywords Recycled refractory brick · Water absorption · Dynamic modulus of elasticity · Water/cement ratios · Recycled aggregates concrete

Abbreviations

NA	Natural Aggregates
RBA	Refractory Brick Aggregates
UPV	Ultrasonic Pulse Velocity
w/c	Water to Cement ratio
CRBA	Coarse Refractory Brick Aggregates
CFRBA	Coarse and Fine Refractory Brick Aggregates

Introduction

Reusing construction and demolition wastes as a new source of aggregates is a very beneficial option to reduce environmental pollution and help to protect raw materials. At present, a large amount of recycled aggregates from construction and demolition wastes are generated, owing to the fact that the civilized growth and increase in the world's population. From the viewpoint of environmental preservation and protection of natural resources, recycling construction and demolition wastes is a good incentive for the production of aggregates, such as coarse and fine aggregates [1–4] or additions [5]. In recent years, several researchers have studied the physical and mechanical properties of concrete made with different type of recycled aggregates (coarse, fine, or both) [4, 6–13]. According to the results obtained, a few conclusions can be drawn: (a) the lower quality recycled aggregates have a negative effect on the physical and mechanical properties of concrete; (b) the recycled concrete exhibit lower performance compared to concretes made with natural aggregate; (d) the physical and mechanical properties

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of recycled concrete deteriorate with the increase of recycled aggregates content;(c) recycled aggregates with a replacement ratio no large than 30%, can be used as aggregates in concrete production with acceptable properties and good quality.

Refractory bricks are solid materials that can withstand high temperatures. The walls and floor of furnaces are mainly covered with refractory bricks to provide favorable thermal insulation. In general, when the refractory bricks have served their service life, they are being demolished and replaced with a new ones. In this regard, about 28 million tons of spent refractory brick wastes are generated each year [14]. Therefore, the removal and disposal of these refractory bricks result in a large amount of waste. Using refractory bricks as aggregates (coarse and fine) or additional material for the production of new concrete is one common means of achieving eco-friendly concrete. In the literature, there is still limited research activity regarding the mechanical and physical properties of concrete prepared with refractory brick wastes as aggregates (coarse and fine), and for this, the experimental investigation of concrete made with refractory brick wastes remains essential.

Kavas et al. [15] stated that the properties of mortar containing refractory waste based- magnesium chromite were comparable to those of the conventional mortar. Saidi et al. [16] tested replacement ratios of 10%, 20%, 30% and 50% of fine natural aggregates by fine refractory brick wastes to manufacture cement mortars. The results by the authors showed that the incorporation of refractory brick wastes up to 20% as fine aggregates on cement mortars has a positive effect on the mechanical tests and development of compressive and flexural strength. In another study, Saidi et al. [17] reported that the refractory brick wastes as fine aggregates can be used in applications that require high temperatures. Aboutaleb et al. [18] investigated the use of refractory brick as fine aggregates in self-compacting mortars. The authors found that the refractory brick wastes could be used successfully as fine aggregates in self-compacting mortars, without affecting the essential properties of mortar. Nematzadeh et al. [19] evaluated the behaviour of concrete containing recycled refractory brick wastes by partial or total substitution of natural sand at different replacement ratios of 0, 25, 50, 75 and 100% after exposure to high temperatures (110 °C, 200 °C, 400 °C, 600 °C, 800 °C and 1000 °C). According to their result, the residual compressive strengths of specimens containing 100% of refractory brick performed better than conventional concretes at higher temperatures. Furthermore, Nematzadeh et al. [20] researched the extent of corrosion of concrete containing fine refractory brick wastes in an acid environment. They found that the performance of concrete containing fine refractory brick aggregates was rather unsatisfactory in the acid environment. Additionally, refractory brick wastes found their place in the concrete production as supplementary cementitious. Recently, Zeghad et al. [21] found that refractory brick wastes finely ground have the potential to be used as cementitious material or additions for concrete manufacture.

Also, some studies have been conducted on the use of refractory brick wastes as coarse aggregates in concrete production [11, 22]. Khattab and Hachemi [11] tested replacement ratios of 10%, 20%, 30%, 40%, 50%, 70% and 100% of coarse natural aggregates by coarse refractory brick wastes (obtained from two different sources) to determine the physical and mechanical properties of concrete. The results obtained by the authors showed that concrete made with refractory brick wastes has lower performance compared to conventional concrete. Nevertheless, the authors concluded that refractory bricks can be used as coarse aggregates for making concrete. In another research, Khattab et al. [22] led to the conclusion that refractory brick wastes as coarse aggregates can help maintain the properties of concrete after heating.

Research significance

From a scientific point of view, this investigation stands by ensuring a potential environmental solution for the refractory brick wastes of collected recyclable wastes. In addition to this, the incorporation of refractory brick wastes as aggregates in the concrete production will contribute to reducing the environmental pollution caused by poorly solid waste disposal. The literature shows that refractory brick wastes can be used as fine aggregates [15–20], coarse aggregates [11, 22] and additions [21] to produce mortar or concrete. However, a brief review of the literature shows that the research results on the properties of concrete made with coarse refractory brick are still very scarce. Moreover, to this day, the literature review showed there is a lack of information regarding the influence of the incorporation of coarse and fine refractory brick wastes on the physical and mechanical properties of concrete. To that end, the present study was designed to characterize the physical and mechanical properties of concrete specimens having different compositions: first, those manufactured by replacing 20% of coarse NA by coarse RBA, second, those manufactured by replacing 20% of coarse and fine NA with coarse and fine RBA. In this regard, some tests such as water absorption, water porosity, density, UPV, compressive strength and dynamic modulus of elasticity were performed. The experimental results of physical and mechanical properties were compared with those obtained with conventional concrete produced by 100% of coarse and fine NA. In particular, this study focused on the effects of water/cement ratio on the physical and mechanical properties of concrete made with RBA.

Experimental research program

Materials

The cement employed for the production of all concrete mixes was Portland cement (CPJ CEM II/A 42.5 N). The chemical composition and mechanical properties of this cement were measured in the LPCMA laboratory and Biskria Cement laboratory, respectively, and the results are presented in Table 1. Natural Aggregates (NA) used in this research were siliceous sand and calcareous crushed stone as fine and coarse aggregates, respectively. Crushed Refractory Brick Aggregates (RBA) were used as coarse and fine recycled aggregates. The RBA used in this study was obtained from wastes of cement factory after being used in the furnace basin (Fig. 1a) (this brick was previously exposed to 1400 °C for one year). The crushing of RBA was prepared in two-stage. The primary crushing stage was crushing the big blocks of refractory bricks using a small jaw crusher into smaller pieces (from 300 to 50 mm). In secondary crushing stage, the size of the pieces was reduced using an abrasion machine to get smaller pieces (from 50 to 1 mm). The crushed RBA was then sieved to obtain the required size of 5/25 mm for coarse RBA (Fig. 1b) and 0/5 mm for fine RBA (Fig. 1c). In this work, superplasticizers based on modified polycarboxylic ether polymers were used to reduce the water quantity. The superplasticizer has the following properties: density is 1.05 ± 0.02 and pH value is 6.0 ± 1. When using a superplasticizer, the dosage was kept constant at 1.4% of the weight of the cement.

Characterization of the aggregates

The standard tests used to characterize physical properties of coarse NA, fine NA, coarse RBA and fine RBA are presented in Table 2, while Table 3 shows the results obtained in the characterization of the aggregates, namely, apparent and absolute density, water absorption, porosity, water content, Los Angeles abrasion, sand equivalent and finesse modulus. In this study, the Scanning Electron Microscopy (SEM) was used to observe the microstructure of RBA, and the results obtained are shown in Fig. 2. According to the images, it is clear that the texture of RBA is irregular due to the heating to 1400 °C during its use in the cement furnace. In addition, Fig. 3 shows the chemical composition of the RBA performed by Energy Dispersive X-Ray Analysis (EDX). It can be concluded that RBA based on Alumina.

Table 1 Chemical composition and mechanical properties of cement used in this study

Chemical composition of cement (%)

CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	SO_3	K_2O	Na_2O
60.10	16.64	3.39	4.34	1.29	3.29	0.68	0.19

Mechanical properties (MPa)

	2 days	7 days	28 days
Compressive strength	18.2	30.40	35
Flexural strength	1	1.39	2.7


(a) (b) (c)

Fig. 1 Recycled refractory brick aggregate used in this study: **a** RBA before crushing **b** coarse RBA **c** fine RBA

Table 2 Test methods used to characterize the coarse NA, fine NA, coarse RBA, and fine RBA

Property under evaluation	Standard used
Determination of density, porosity, absorption coefficient, and water content of coarse aggregates	NF P 18-554 [23]
Determination of density, absorption coefficient, and water content of fine aggregates	NF P 18-555 [24]
Determination of resistance to fragmentation (Los Angeles test)	NF P 18-573 [25]
Determination of Sand equivalent	NF P 18-598 [26]
Determination of particle size distribution by sieving	NF P 18-560 [27]

Table 3 Results obtained in the characterization of the coarse NA, fine NA, coarse RBA, and fine RBA

Physical properties	Coarse NA		Coarse RBA		Fine NA	Fine RBA
	15/25 mm	5/15 mm	15/25 mm	5/15 mm	0/5 mm	0/5 mm
Apparent density (g/cm^3)	1.39	1.43	1.33	1.33	1.55	1.59
Absolute density (g/cm^3)	2.70	2.69	2.90	2.90	2.58	3.00
Water absorption (%)	0.26	0.22	3.53	2.88	0.67	4.32
Porosity (%)	1.56	1.16	9.7	9.30	–	–
Water content (%)	0.10	0.11	0.06	0.06	0.08	0.09
Los Angeles abrasion	30	58			–	–
Sand equivalent (%)	–	–			75.8	86.6
Finesse modulus	–	–			2.51	2.60

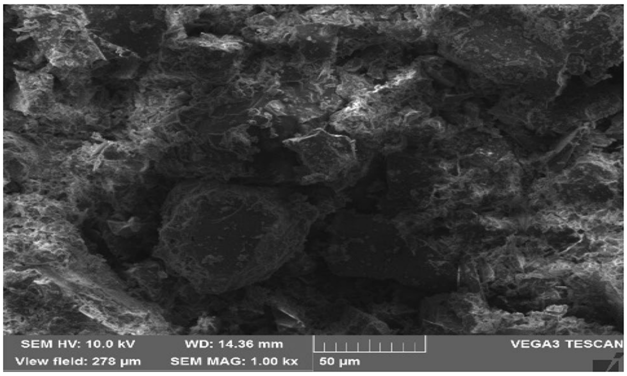


Fig. 2 The microstructure of recycled refractory brick aggregate used in this study

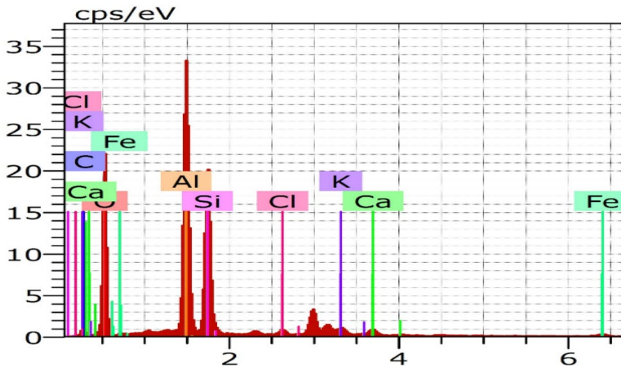


Fig. 3 Chemical composition of the recycled refractory brick aggregate

As given in Table 3, the abrasion resistance of coarse RBA is 93% lower than that of coarse NA, while water absorption of coarse and fine RBA is about 13 and 6 times more than for coarse and fine NA, respectively, which leads to much higher porosity as given in Table 3. Furthermore, the coarse and fine RBA, by comparison with the coarse and fine NA, presents a higher density. The grading curve of coarse NA, fine NA, coarse RBA and fine RBA are presented in Fig. 4. It can be seen from Fig. 4 the grain size distribution of natural aggregates (coarse and fine) and recycled brick aggregates (coarse and fine) is comparable. In addition, it found that the coarse and fine RBA have angular shape and rough surface than the coarse and fine NA, respectively.

Mix designs and procedure

A total of nine concrete mixtures were manufactured into three separate groups. For the first group of natural aggregate concrete M-NA (reference concrete), three mixtures (M1-NA, M2-NA and M3-NA) with cement dosage of 350 kg/m^3 (w/c = 0.59), 400 kg/m^3 (w/c = 0.47) and 450 kg/m^3 (w/c = 0.38), respectively, were made only of natural aggregates (coarse and fine). Reference concrete formulation was prepared according to the Dreux design method [28]. In the second group M-CRBA, three mixtures (M1-CRBA, M2-CRBA and M3-CRBA) with the same cement dosage and w/c ratio of reference concrete were designed by replacing 20% (by volume) of the coarse NA with coarse RBA. For the third group M-CFRBA, three mixtures (M1-CFRBA, M2- CFRBA and M3- CFRBA) with the same

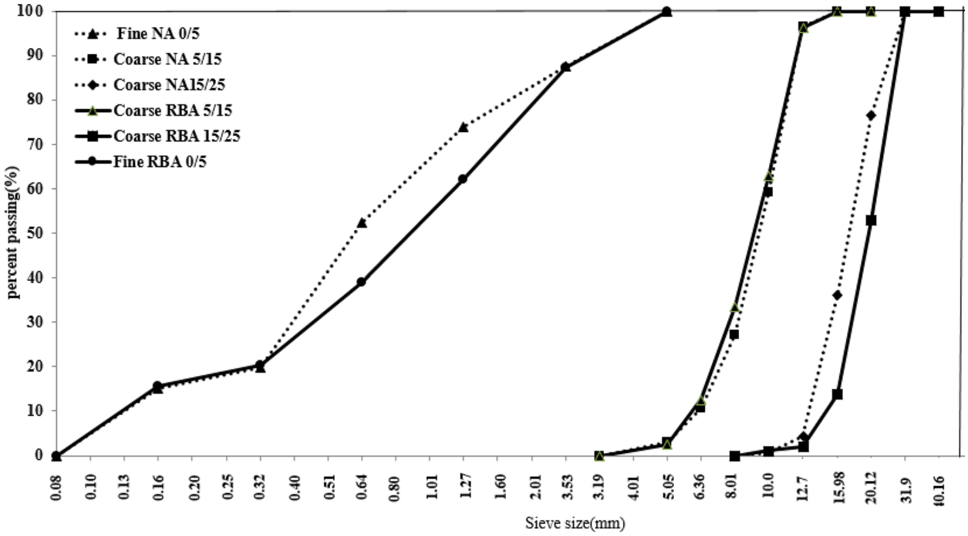


Fig. 4 The grain size distribution for the coarse NA, fine NA, coarse RBA and fine RBA

Table 4 Concrete mixtures composition (kg/m^3)

	C	W	Extra W	W/C	Fine NA	Fine RBA	Coarse NA		Coarse RBA		SP (%)
					0/5 (mm)	0/5 (mm)	5/15 (mm)	15/25 (mm)	5/15 (mm)	15/25 (mm)	
M1- NA	350	206.50	–	0.59	688.34	–	226.63	947.84	–	–	–
M2- NA	400	190.48	–	0.47	654.83	–	239.88	926.06	–	–	–
M3- NA	450	173.08	–	0.38	639.43	–	180.18	958.54	–	–	1.4
M1- CRBA	350	206.50	–	0.59	688.34	–	181.31	758.27	48.93	203.89	–
M2- CRBA	400	190.48	–	0.47	654.83	–	191.91	740.85	51.79	199.20	–
M3- CRBA	450	173.08	–	0.38	639.43	–	144.15	766.83	38.90	206.19	1.4
M1- CFRBA	350	206.50	6.95	0.59	550.67	160.08	181.31	785.27	48.93	203.89	–
M2- CFRBA	400	190.48	6.58	0.47	523.86	152.29	191.91	740.85	51.79	199.20	–
M3- CFRBA	450	173.08	6.42	0.38	511.54	148.70	144.15	766.83	38.90	206.19	1.4

cement dosage and w/c ratio of reference concrete were produced by replacing 20% (by volume) of coarse and fine NA by coarse and fine RBA. The percentage of CRBA and CFRBA (20%) used were taken from the results of the previous studies by Khattab and Hachemi [11] and Saidi et al. [16], respectively. The compositions of the different concretes are presented in Table 4. The code names of each mixture consist of "M" for concrete mixtures, "1" for cement dosage of 350 kg/m^3 (w/c = 0.59), "2" for cement dosage of 400 kg/m^3 (w/c = 0.47), "3" for cement dosage of 450 kg/m^3 (w/c = 0.38), "CRBA" for coarse refractory brick aggregates, "CFRBA" for coarse and fine refractory brick aggregates, "NA" for natural aggregates.

It can be seen from Table 3 that the coarse and fine RBA have a higher water absorption compared to the corresponding coarse and fine NA, respectively. To ensure that the mixing water could not be absorbed by coarse and fine RBA, two methods were adopted to overcome the water absorption of coarse and fine RBA.

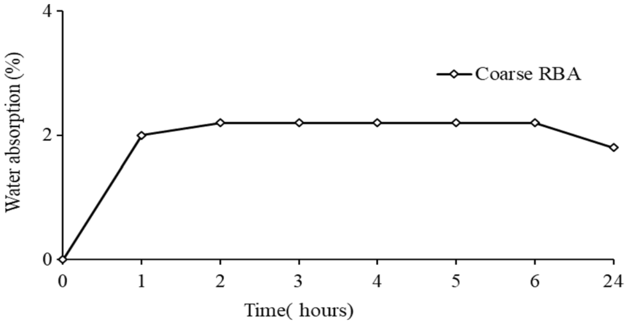


Fig. 5 The evolution of water absorption of the coarse RBA Khattab and Hachemi [11]

(1) Extra amount of water was added to the mixer, corresponding to the water absorbed by the fine RBA.
(2) The methodology proposed by Khattab and Hachemi [11] was followed to overcome the water absorption of coarse RBA. According to this methodology, after

4 h of immersion in water, the water absorption of the coarse RBA is stabilized (see Fig. 5). Then, the coarse RBA was air-dried to a saturated dry condition for use in concrete mixing.

Specimen preparation

For each type of concrete mixture prepared in Table 4, three concrete specimens with dimensions 10 × 10 × 10 cm^3 were cast into cubic steel molds and duly compacted by a vibrating table. After casting, the concrete specimens were kept in the molds at ambient temperature (20 °C ± 2 °C) for 24 h. After 24 h, the concrete specimens were demoulded and were cured in the water at ambient temperature (20 °C ± 2 °C) for 28 days.

Tests on concrete mixes

Density, water porosity and water absorption

Concrete density and porosity were measured according to the standard NF EN 12,390-7 [29]. While the water absorption of concrete was determined in accordance with the BS 1881-122 [30]. The density, water porosity and water absorption were determined through the water saturation method. The dried mass (Ms) of specimens was measured after drying in an electric oven at 60 °C ± 2 °C until a constant mass was reached. All concrete samples were then immersed in water until full saturation. After saturation is complete, samples were weighed after removing surface water with an absorbent cloth to obtain a saturated mass (Mw). In the next step, the mass of the specimens in water was measured by the hydrostatic balance $\left(\mathrm{Mw}'\right)$. Three specimens for each mixture were tested. (Eq. 1), (Eq. 2) and (Eq. 3) were used to calculate the water Porosity (P), Water Absorption (WA) and Density (D) of concrete specimens, respectively.

$$p = \frac{\mathrm{Mw} - \mathrm{Ms}}{\mathrm{Mw} - \mathrm{Mw}'} \tag{1}$$

$$\mathrm{WA} = \frac{\mathrm{Mw} - \mathrm{Ms}}{\mathrm{Ms}} \tag{2}$$

$$D = \frac{\mathrm{Ms}}{\mathrm{Mw} - \mathrm{Mw}'} \tag{3}$$

Ultrasonic pulse velocity (UPV)

The UPV was determined for estimating the quality of concrete in accordance with the AFNOR P 18-418 standard [31]. The value of UPV can be calculated by dividing the path length by the time it takes for the wave to pass through the material. For each mixture, three cubes were tested and the results were averaged. The UPV is determined according to (Eq. 4):

$$V = L/S \tag{4}$$

where V is the pulse velocity (in m/s), L is the length of the sample (in mm) and S is the time (in s).

Dynamic modulus of elasticity

In this study, the values of dynamic modulus of elasticity were determined using the values of UPV according to the standard ASTM C 597-16 [32]. For each mixture, three samples were tested and the average results were reported. The dynamic modulus of elasticity was calculated from the following (Eq. 5):

$$E = \frac{\rho v^2(1+v)x(1-2v)}{(1-v)} \tag{5}$$

where E is the dynamic modulus of elasticity (in GPa), v is the UPV value (in km/s), ρ is the oven-dry density (in kg/m^3) and υ is Poisson's ratio (taken as $\upsilon = 0.2$ for concrete [33]).

Compressive strength

The compressive strength was evaluated following the NF EN 12,390-3 standard [34]. For each mixture, three cubic specimens were tested at the age of 28 days by using a hydraulic press with a maximum load capacity of 3000 kN. The loading rate applied in the compressive strength tests was kept at 0.5 MPa/s until specimen rupture, according to standard NF EN 12,390-4 [35].

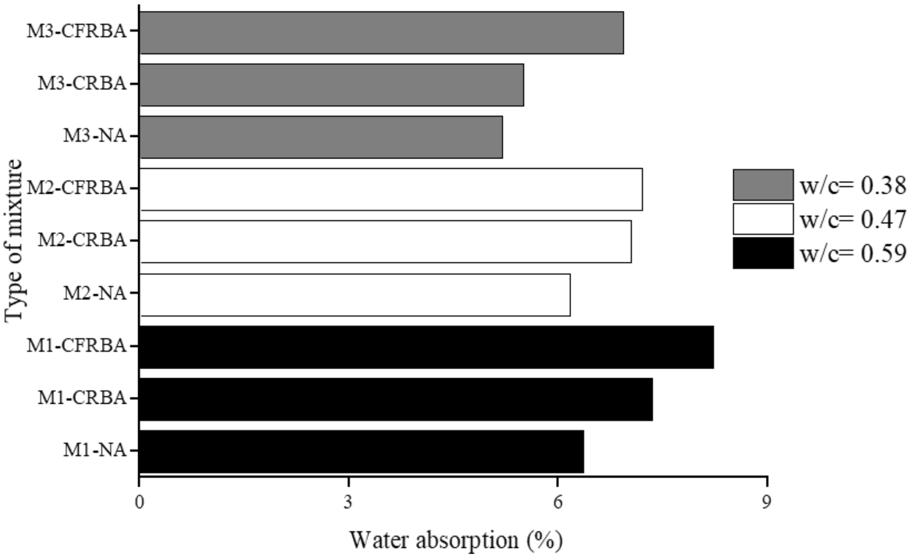
Results and discussion

Water absorption

Water absorption measurements were carried out on three samples for each mixture. Figure 6 shows the effect of replacing 20% of coarse RBA or 20% of coarse and fine RBA on the water absorption of concrete. It can be clearly observed, from Fig. 6, that the inclusion of CRBA or CFRBA in concrete gives it higher water absorption than that of conventional concrete prepared with NA. This was owing to the fact that the water absorption of the RBA (CRBA or CFRBA) was higher than that of the coarse and fine NA (see Table 3).

The water absorption of the conventional mixtures ranged from 5.2 to 6.4%. In the case of concrete mixture made with 20% of coarse RBA, water absorption was increased by 16%

Fig. 6 Influence of the incorporation of RBA and w/c ratio on water absorption of concretes



for M1-CRBA (w/c = 0.59), 14% for M2-CRBA (w/c = 0.47), and 6% for M3-CRBA (w/c = 0.38) compared to the reference mixtures (First group). Moreover, the inclusion of 20% of coarse and fine RBA in concrete results in a higher increase in water absorption when compared to concrete made with 20% of coarse RBA. In other words, water absorption of concrete containing 20% of coarse and fine RBA was increased by 29% for M1-CFRBA (w/c = 0.59), 17% for M2-CFRBA (w/c = 0.47) and 33% for M3-CFRBA (w/c = 0.38) compared to concrete prepared with NA (First group). These results confirmed that concrete mixes made with 20% of coarse and fine RBA showed the highest water absorption values. The M1-CFRBA concrete mixtures had an increase of water absorption by about 11% compared to M1-CRBA. For M3-CFRBA concrete mixtures, the increase in water absorption was about 25% compared to M3-CRBA. This might be due to high water absorption of coarse and fine RBA which was 13.5 and 6.5 times more than for coarse and fine NA, respectively. According to Kou et al. [36], the high adsorption capacity of the recycled aggregate increases the osmotic pressure within the concrete. Therefore, when dry samples are immersed in water during testing, samples with higher osmotic pressure tend to absorb more water.

It is observed also, from Fig. 6, that M1-CRBA and M1-CFRBA concrete mixtures with high w/c ratio (w/c = 0.59) had higher water absorption compared to concrete mixtures with low w/c ratio (M2-CRBA, M3-CRBA, M2-CFRBA and M3-CFRBA). Concretes having low w/c ratio show low water absorption due to their capillary and pore networks being somewhat disconnected, which restrains the water penetration depth [37]. The reduced w/c ratio may be partly responsible for the decrease in water absorption of concrete made with RBA (CRBA or CFRBA).

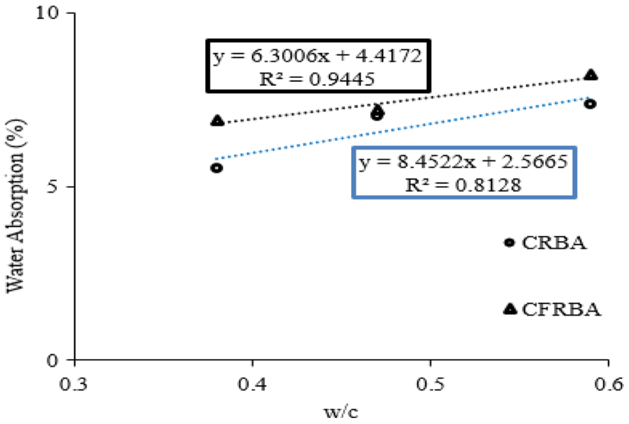


Fig. 7 Correlation between water absorption and w/c ratio

The correlation between water absorption and w/c ratio for concrete made with RBA (CRBA or CFRBA) is shown in Fig. 7. As depicted in Fig. 7, relatively good linear correlation coefficients are obtained between water absorption and w/c ratio. In such a case, the coefficient of R^2 for CRBA concrete mixtures was 0.8128 and for CFRBA concrete mixtures was 0.9445.

Water porosity

As with the trend shown for water absorption, the results in this case also reveal an increase in the water porosity of concrete when replacing natural aggregates with RBA (CRBA or CFRBA). The effects of recycled refractory brick aggregates (CRBA or CFRBA) and w/c ratio on the water porosity of concrete are shown in Fig. 8. As shown in the figure, the water porosity of the concrete mixtures strongly depends on the aggregates type and w/c ratio. The results

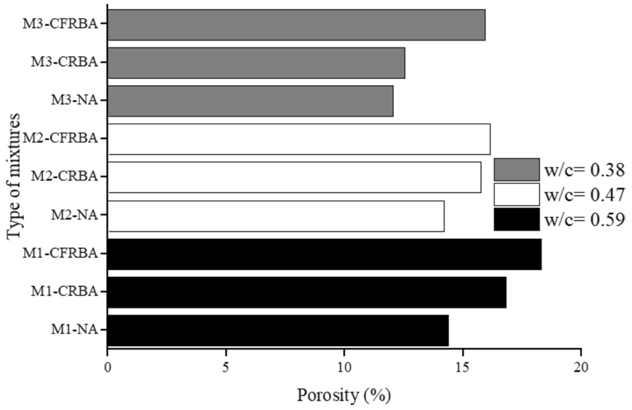


Fig. 8 Influence of the incorporation of RBA and w/c ratio on the porosity of concrete

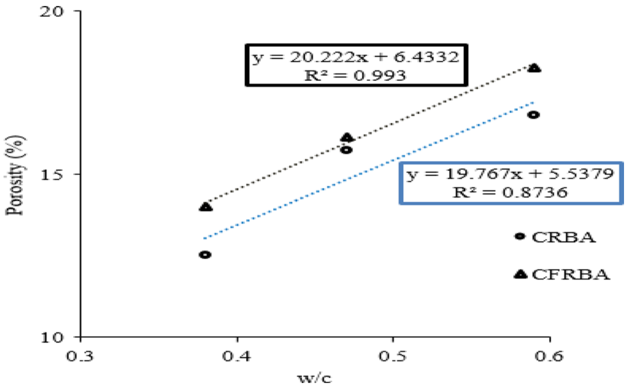


Fig. 9 Correlation between water absorption and w/c ratio

indicated that the utilization of 20% of coarse RBA with a high w/c ratio resulted in higher water porosity of concrete. For example, M1-CRBA concrete mixtures with w/c = 0.59 showed a water porosity of 16.81%, showing an increase of about 17% compared to the reference concretes (M1-NA). For M2-CRBA concrete mixtures with w/c = 0.47, a slight increase in the water porosity was observed (about 11%) compared to concrete prepared with natural aggregates (M2-NA). However, the water porosity of concrete mixtures prepared with 20% of coarse and fine RBA was higher than that of concrete mixtures prepared with 20% of coarse RBA. The M1-CFRBA concrete mixtures with w/c = 0.59 have a water porosity of 18.28%, yielding an increase of about 27% compared to the reference mixtures (M1-NA). Conversely, the increase of water porosity for M2-CFRBA concrete mixtures with w/c = 0.47 was about 14%.

On the other hand, a comparison between the second and third group shows that fine RBA has a greater impact on the increase of water porosity. The M1-CFRBA concrete mixtures had an increase in water porosity by about 8% compared to M1-CRBA. For M3-CFRBA concrete mixtures, the increase of water porosity was about 26% compared to M3-CRBA. This means that the incorporation of 20% of fine RBA imposes a negative effect on the porosity of concrete, which might be attributed to the high water absorption of fine RBA.

It should be noticed from Fig. 8 that the decreasing of w/c ratio in concrete mixes from 0.59 to 0.47 and 0.38 results in reduced water porosity. In general, the water porosity of concrete mixtures made with RBA (CRBA or CFRBA) can be controlled by increase cement content and reducing the w/c ratio. The lower w/c ratio decreases capillary porosity of the concrete and affects the width and microstructure of the interface transition zone between aggregates and cement paste [38]. A study carried out by Dang and Zhao [39] indicates, by scanning electron microscopy, that recycled brick concrete with a low w/c ratio has satisfactory compactness of interface transition zone. The relation between porosity of concrete and w/c ratio is shown in Fig. 9. As it happened with the water absorption, the porosity is also affected by the variation of w/c ratio. From Fig. 9, it is observed a linear relationship between porosity and w/c ratio with the coefficient of correlation $R^2 = 0.8736$ for CRBA concrete mixtures and $R^2 = 0.9930$ for CFRBA concrete mixtures. This means that with the decreasing w/c ratio, the porosity will decrease.

Concrete density

The effects of recycled refractory brick aggregates (CRBA or CFRBA) and w/c ratio on the density of concrete are shown in Fig. 10. It should be noticed from Fig. 10 that the second group of concrete mixtures made with 20% of coarse RBA shows a slightly lower density compared to reference mixtures. For instance, the density of M1-CRBA, M2-CRBA and M3-CRBA was reduced by 2, 5 and 2%, respectively, compared to the reference mixtures concretes (First group).

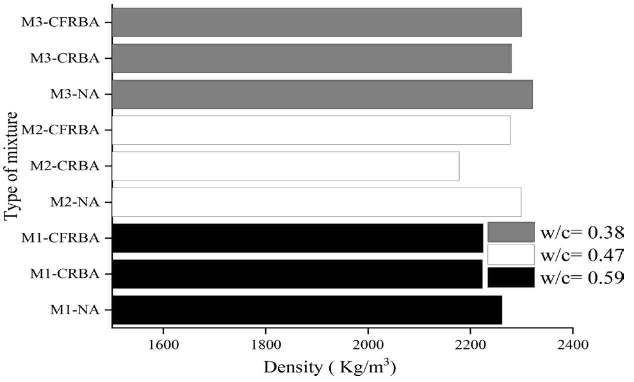


Fig. 10 Influence of the incorporation of RBA and w/c on the density of concrete

However, the inclusion of 20% of coarse and fine RBA in the third group of mixes results in a higher density when compared with that of concrete containing 20% of coarse RBA. This can be attributed to the fact that the fine RBA has a higher density (Table 3), which can contribute to improving the density of concrete. The concrete mixtures in third group had a decrease in density by 1.6, 0.92 and 0.93% for M1-CFRBA, M2-CFRBA and M3-CFRBA, respectively, compared to the corresponding reference mixtures in first group. As can be seen, by incorporating 20% of fine RBA in the third group of mixes, the density starts to improve and becomes closer to the density of the reference mixtures, similar results were observed by Aboutaleb et al. [18] who reported that the sand substitution by refractory brick does not a great effect on bulk density of mortar.

It is observed also, from Fig. 10, that increasing the cement content and reducing the w/c ratio improved the density of the concretes prepared with RBA (CRBA or CFRBA). This can be explained by the fact that cement grains help fill voids in concrete, thus reducing the number of voids and ultimately increasing the density of concretes.

Figure 11 shows the relationship between the density of concrete mixtures made with RBA (CRBA or CFRBA) and the w/c ratio. From the comparison of the results of density experiment and the w/c ratio results, it was also observed that there is a very strong relationship between density and w/c with a coefficient of correlation $R^2 = 0.9961$ for CRBA concrete mixtures and 0.9763 CFRBA concrete mixtures so that the lower the w/c ratio in concrete, the higher the density of CRBA and CFRBA concrete mixtures.

UPV

The UPV is used to assess the uniformity and quality of concrete as a non-destructive method. Table 5 shows the concrete quality classification according to AFNOR P 18–418 standard [31] and Whitehurst [40]. This property is expected to be affected by the incorporation of recycled refractory brick aggregates because it depends more on the quality and porosity of the aggregates used.

The effects of recycled refractory brick aggregates (CRBA or CFRBA) and w/c ratio on the UPV of concrete are shown in Fig. 12. From the obtained results, the UPV value of the reference mixtures was 4470 m/s for M1-NA, 4580 m/s for M2-NA and 4590 m/s for M3-NA. In the tests carried out, it can be seen that concretes prepared with recycled refractory brick aggregates (CRBA or CFRBA) presents a lower UPV value compared to mixtures prepared with natural aggregates. This might be due to high porous structure of these aggregates.

A slight decrease in UPV is observed for concrete mixtures made with 20% of coarse RBA (second group) compared to mixtures made with natural aggregates (first group). A decrease in UPV of about 3% was recorded for M1-CRBA and M2-CRBA, while it was about 2% for M3-CRBA. In the third group of mixes, utilization of 20% of coarse and fine RBA causes a decrease in UPV of concretes slightly higher than that when 20% of coarse RBA was used. As shown in Fig. 12, a decrease in UPV value of about 6%, 7% and 3% was observed for M1-CFRBA, M2-CFRBA and M3-CFRBA, respectively, compared to the reference mixtures. This means that the incorporation of 20% of fine RBA imposes a negative effect on the UPV of concrete. The high porosity of recycled refractory brick aggregates (as discussed in section of Characterization of Aggregates) increased the time travel of wave propagation and

Table 5 Classification of concrete quality by UPV value [31, 40]

Value of UPV (m/s)	<4500	3500–4500	3000–3500	>3000
Concrete quality	(Excellent)	(Good)	(Medium)	(Doubtful)

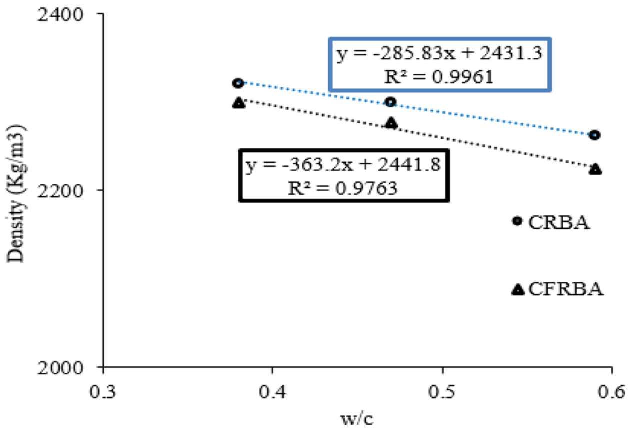


Fig. 11 Correlation between density and w/c ratio

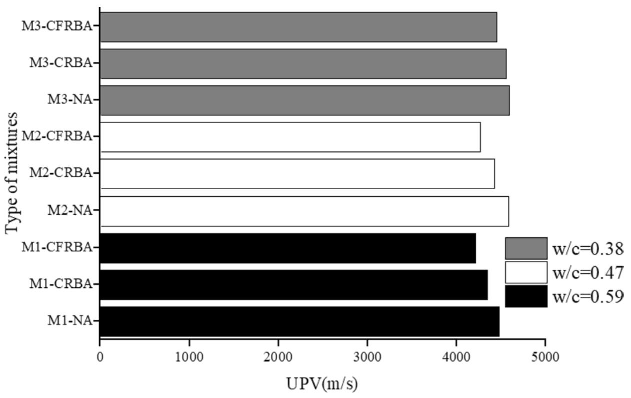


Fig. 12 Influence of the incorporation of RBA and w/c ratio on the UPV of concrete

consequently slow down the pulse velocity. Hence, the UPV of concretes prepared with recycled refractory brick aggregates (CRBA or CFRBA) is relatively lower when compared to those of conventional mixtures. Rao [41] reported similar results in the literature. It is important to note that, the quality of concrete mixtures made with RBA (CRBA or CFRBA) can be classified as good (3500 m/s < UPV < 4500 m/s).

It can be observed, from Fig. 12, that the UPV was also affected by the w/c ratio. For low w/c = 0.38, concrete made with RBA (M3-CRBA and M3-CFRBA) performed better and showed a higher UPV values. This can be explained by the reduction in the volume of voids in the mixtures due to the increase in the cement content and the reduction in the amount of water, which in turn leads to a reduction in the time required to propagate the wave through the samples. It was also seen in Fig. 13 that, the UPV results in a good relationship with the coefficient of correlation $R^2 = 9544$ for CRBA concrete mixtures and $R^2 = 0.8514$ for CFRBA concrete mixtures with the w/c ratio. With the decreasing of w/c ratio, the porosity of concrete mixtures made with RBA (CRBA or CFRBA) is expected to decrease and the UPV value of concrete is increased.

Dynamic modulus of elasticity

Figure 14 shows the effects of recycled refractory brick aggregates (CRBA or CFRBA) and w/c ratio on the dynamic modulus of elasticity of concrete. From the obtained results, the dynamic modulus of elasticity of the reference mixtures was 41 GPa for M1-NA, 43 GPa for M2-NA and 44 GPa for M3-NA.

It can be observed, from Fig. 14, that the incorporation of recycled refractory brick aggregates (CRBA or CFRBA) in concrete decreases the dynamic modulus of elasticity. For the second group, it was observed that with the replacement of 20% of coarse RBA, the dynamic modulus of elasticity decreased by 7% for M1-CRBA, 12% for M2-CRBA and 3% for M3-CRBA compared to the reference mixtures (First group). On the other hand, the replacement of 20% of coarse and fine RBA decreased the dynamic modulus of elasticity by 13, 14 and 7% for M1-CFRBA, M2-CFRBA and M3-CFRBA, respectively, compared to the reference mixtures (First group). It is clearly seen that the replacement of 20% of fine RBA has an effect on the dynamic modulus of elasticity in hardened concrete. The decrease in dynamic modulus of elasticity can be explained by the lower mechanical strength of this type of aggregates (Table 3). González et al. [42] indicated that because of the low rigidity of recycled brick aggregates, the dynamic modulus of elasticity of concrete will also decrease.

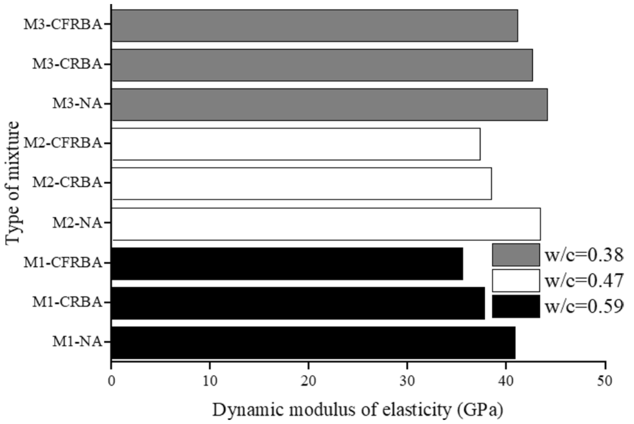


Fig. 14 Influence of the incorporation of RBA and w/c ratio on the dynamic modulus of elasticity of concrete

Figure 15 illustrates the relationship between the dynamic modulus of elasticity and UPV. The dynamic modulus of elasticity was affected by the increase in the UPV value. As it is shown in Fig. 15, there is a very good relationship between dynamic modulus of elasticity and UPV as indicated by high R^2 values. For concrete made with recycled refractory brick aggregates, the value of R^2 is greater than

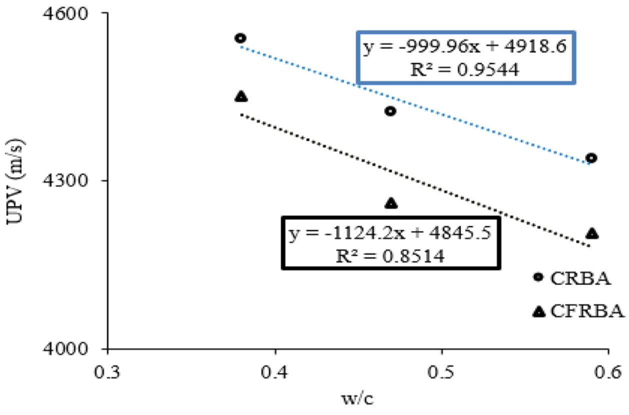


Fig. 13 Correlation between UPV and w/c ratio

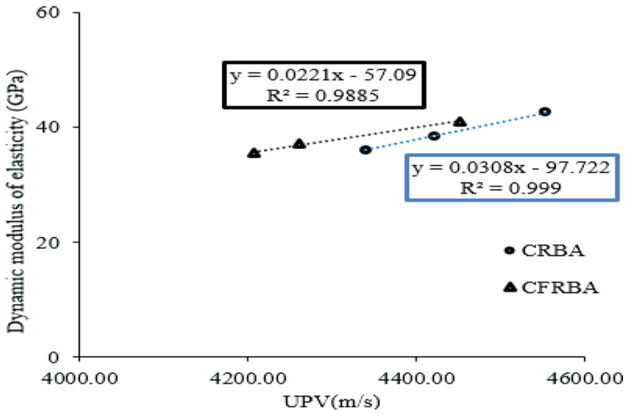


Fig. 15 Correlation between dynamic modulus of elasticity and UPV

0.988. A similar observation was reported by Alves et al. [43]. This means that the dynamic modulus of elasticity of the concrete prepared with RBA (CRBA or CFRBA) can be better predicted by the UPV values.

A significant influence of w/c ratio on the dynamic modulus of elasticity has been observed. For example, concrete containing RBA with w/c = 0.38 (M3-CRBA and M3-CFRBA) performed better and showed a lower decrease in dynamic modulus of elasticity than that of concrete containing RBA with w/c = 0.59 and 0.47. These results also agree with those found by Gesoglu et al. [44]. From the comparison of the results of the dynamic modulus of elasticity experiment and the w/c ratio results, it was found that there is a good relationship between dynamic modulus of elasticity and w/c ratio with a coefficient of correlation $R^2 = 0.9400$ for CRBA concrete mixtures and $R^2 = 0.9192$ for CFRBA concrete mixtures (see Fig. 16), so that the lower w/c ratio in concrete, the higher the dynamic modulus of elasticity. The results agree quite well with those obtained by Gao et al. [38].

Compressive strength

Figure 17 shows the effects of recycled refractory brick aggregates (CRBA or CFRBA) and w/c ratio on the compressive strength of concrete. Reference mixtures have a compressive strength of 27 MPa for M1-NA, 33 MPa for M2-NA and 50 MPa for M3-NA**.** In the second group, the results in Fig. 17 show that the compressive strength decreased. This decrease is 2% for M1-CRBA, 5% for M2-CRBA and 16% for M3-CRBA. The decrease in compressive strength is due to several factors: an increase in porosity of concrete (caused by coarse RBA with a more porous structure) and pre-saturation of coarse RBA. On the other hand, coarse RBAs have a lower abrasion resistance than coarse NAs, which causes the secession of the external layer of coarse RBAs during mixing and transformed into fine aggregates [11].

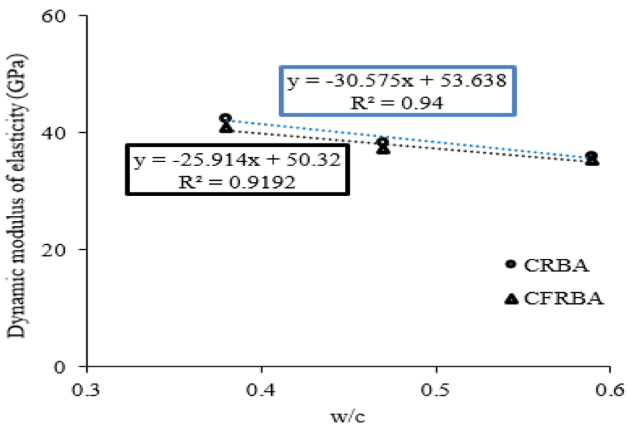


Fig. 16 Correlation between dynamic modulus of elasticity of concrete and w/c ratio

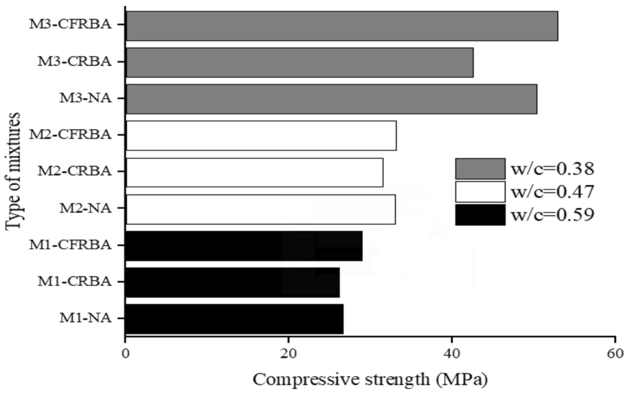


Fig. 17 Influence of the incorporation of RBA and w/c ratio on concrete compressive strength

The results obtained show that there is a slight increase in compressive strength of concrete mixtures prepared with 20% of coarse and fine RBA compared to concrete prepared with natural aggregates (First group). The strength of M1-CFRBA, M2-CFRBA and M3-CFRBA were increased by 9, 2 and 5%, respectively, compared to the reference mixtures. Saidi et al. [17] also reported the same conclusion; replacing 20% of fine natural aggregates with recycled refractory bricks has a positive effect on the performance of cement mortar and the development of compressive strength. A Comparison of the second and third group shows that fine RBA has a greater impact on the increase of compressive strength. For example, with the replacement of 20% of coarse and fine RBA, the compressive strength increased from 7 to 24% relative to the second group (concrete mixtures prepared with 20% of coarse RBA).

It is clearly seen that the replacement of 20% of fine RBA is more play an important role in the increase of compressive strength in hardened concrete. One explanation for that may be due to the fact that fine RBA has a higher density (Table 3) which affect positively the strength of concrete. Another explanation relates to fact that fine RBA has an angular shape and rough surface compared to fine NA, which improves the adhesion of cement paste and creates a good bond between fine RBA and cement pastes. Additionally to those factors, it can be noted that fine RBA does not contain impurities (sand equivalent value of 86.6%); therefore, the use of fine RBA would improve the compressive strength of concrete. In general, the replacement of the natural fine aggregates with recycled fine aggregates shows a positive or even negligible influence on the mechanical properties of concrete [42, 44].

Figure 18 shows the established relationship between compressive strength and UPV. As it happened with the dynamic modulus of elasticity, the compressive strength

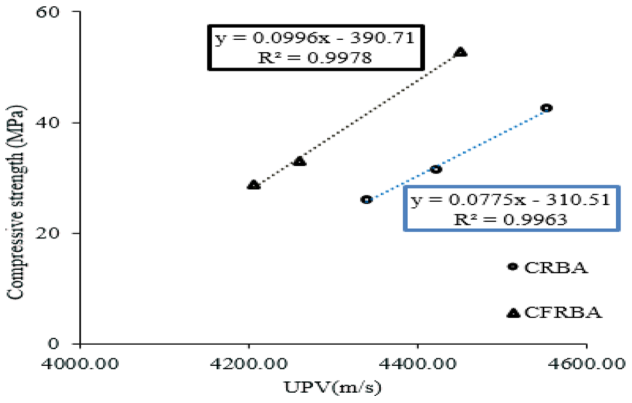


Fig. 18 Correlation between compressive strength and UPV

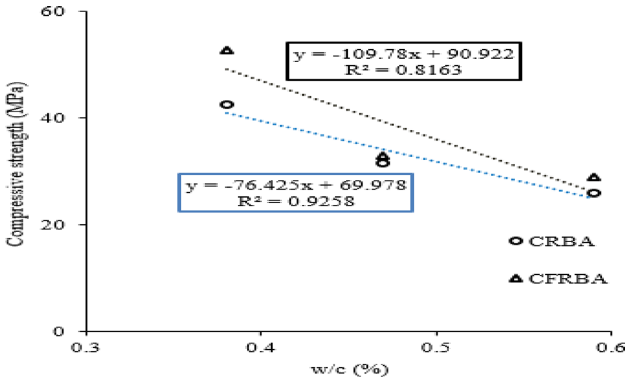


Fig. 19 Correlation between compressive strength and w/c ratio

is also affected by the UPV value. The results obtained show that both concrete groups (concrete mixtures made with 20% of coarse RBA and concrete mixtures made with 20% of coarse and fine RBA) exhibited a strong correlation between compressive strength and UPV. It is seen that the R^2 value of the CRBA concrete mixtures is about 0.9963 and about 0.9978 for CFRBA concrete mixtures. A Similar observation was reported by Kwan et al. [45] and Dilraj Singh and Singh [46]. From Fig. 18, it is noted that the increase of compressive strength goes with the augmentation of UPV value.

The correlations between compressive strength and w/c ratio for the second and third group of concrete mixes are plotted in Fig. 19. All concrete specimens made with recycled refractory brick aggregates (CRBA or CFRBA) have shown a good as the R^2 values were above 0.80. However, it can be observed that the R^2 value of the concrete mixtures in the second group ($R^2 = 0.9258$) is higher than that of the concrete mixtures in the third group ($R^2 = 0.8163$). With the decreasing w/c ratio, the compressive strength is expected to increase. The lower the w/c ratio, the less water separates from the fresh paste, forming a thin film on the aggregate granules, which increases the resistance of the aggregate-cement paste interface and, accordingly, improves the tightness and cohesion of the paste to the aggregate grains [36]. In a conclusion, the results showed that a lower w/c ratio leads to higher strength and improved recycled concrete performance.

Conclusions

This paper presented an experimental program conducted to study the effects of recycled refractory brick (coarse or coarse and fine aggregates) and water/cement ratios on the physical and mechanical properties of concrete and the final conclusions of the experimental work are summarized in the following bullets:

- In general, the performance of the concrete samples made with CRBA or CFRBA is slightly poor compared to reference concrete. On the other hand, concrete mixtures made with 20% of coarse and fine RBA have a lower or even similar performance than concrete mixtures made with 20% of coarse RBA.
- The durability properties such as water absorption and water porosity of concretes are adversely affected due to the inclusion of RBA. Owing to higher water absorption and water porosity of RBA, the water absorption and water porosity of concretes increase. Mixes prepared with 20% of fine RBA have a higher water absorption and water porosity (about 17% to 33% according to water absorption and about 14% to 32% according to water porosity).
- Concrete density decreases slightly when 20% of coarse RBA is used. However, the inclusion of 20% of coarse and fine RBA in concrete gives it higher density (from 1 to 5%) than that of concrete prepared with 20% of coarse RBA.
- Using recycled refractory brick aggregates reduces the UPV value of concrete. However, concrete mixtures made with CRBA or CFRBA show a good quality (3500 m/s < UPV < 4500 m/s). This means that the results are within the acceptable range according to AFNOR P 18-418 standard [30].
- The inclusion of CRBA or CFRBA as a partial replacement of natural aggregates in concrete adversely affects its dynamic modulus of elasticity. This decline is 3% to 12% in concretes containing 20% of coarse RBA and approximately 7% to 14% in mixes containing 20% of coarse and fine RBA.
- The results indicated that the compressive strength of concrete is also affected by the 20% of coarse RBA. Interestingly, the inclusion of 20% of coarse and fine

RBA in concrete gives it higher compressive strength (from 2 to 9%) than that of conventional concrete prepared with natural aggregates.

- The results indicate a good relation between physical and mechanical properties of concrete containing RBA (CRBA or CFRBA) and w/c ratio.
- The lower w/c ratio reduces the porosity of concrete and the width of the interfacial transition zone (caused by recycled refractory brick aggregates with a more porous structure). This leads to a good bond between the cement paste and the aggregate grains. The reduced w/c ratio may be responsible for the improved performance of recycled concretes.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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