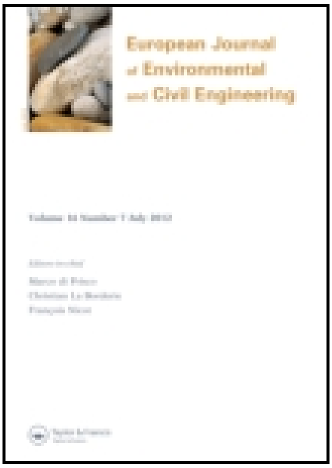

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Performance of concrete containing crushed brick aggregate exposed to different fire temperatures

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This paper presents an experimental investigation of the effect of high temperatures applied to a conventional concrete made with natural coarse aggregate (NCA) and different water/cement ratios (*w/c* of 0.6, 0.42 and 0.27). The experimental results of physical and mechanical properties were compared with those obtained with recycled brick aggregate (RBA) produced by replacing 30% of NCA by RBA. The following parameters: compressive strength, ultrasonic pulse velocity, concrete mass loss, apparent volume, apparent density and water porosity were examined in this experiment. A scanning electron microscopy study was made to appreciate the change of surface texture. The results show that concrete could be produced using RBA and reveals that at high temperatures, recycled aggregate concrete preformed similar or even better than natural aggregate concrete. Hence, this paper is a contribution to the general understanding of the impact of RBA in concrete at high temperatures, and emphasises the important influence of RBA on the physical and mechanical properties of concrete.

Keywords: high temperature; compressive strength; mass loss; ultrasonic pulse velocity; recycled brick aggregate

1. Introduction

During the last decades, it has been recognised with growing concern that waste materials from construction and demolition are of large volume and that is increasing year by year. The large quantities of construction and demolition waste becomes one of the main factors that cause environmental damage and pollution to the earth and depletion of natural resources such as coarse aggregates and sands. Governments over the world are encouraging research efforts to use these waste materials in a greater quantity in secondary building materials.

Recycling is the reprocessing of old or used materials into the new products, in order to prevent the waste of potentially useful materials reducing of consumption of raw materials. However, the aggregates obtained from constructions and demolition wastes, usually called “recycled aggregates”, have different characteristics than those of the natural aggregates.

In the last years, different research works have been dedicated to find new methods in order to use recycled aggregates for the fabricate concrete (Abed, 2009; Butler, West, & Tighe, 2011; Finoženok, Žurauskienė, & Žurauskas, 2013; Kesegić, Netinger, & Bjegović, 2008; Kwan, Ramli, Kam, & Sulieman, 2012; Nassar & Soroushian, 2012;

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Nelson, Shing Chai NGO, 2004; Rahman, Hamdam, Mujahid, & Zaidi, 2009; Thomas et al., 2013; Tsujino, Noguchi, Tamura, Kanematsu, & Maruyama, 2007). Crushed brick aggregates recovered from demolished masonry structures can be utilised in the fabrication of new concrete mixtures. From the durability point of view, the performance of conventional concretes exposed to high temperatures has been widely studied, but it is not a very well-known subject for recycled concrete (Abrams, 1971; Arioz, 2007; Bazant & Kaplan, 1996; Behnood, 2005; Castillo & Durrani, 1990; Chan, Peng, & Anson, 1999; Cheng, Kodur, & Wang, 2004; Diederiches, Jumppanen, & Schneider, 1995; Felicetti & Gambarova, 1998; Hertz, 2005; Hoff, Bilodeau, & Malhotra, 2000; Husem, 2006; Kodur & Sultan, 2003; Kowalski, 2007; Lea, 1920; Malhotra, 1956; Menzel, 1943; Mindeguia, Pimienta, Carré, & La Borderie, 2012; Phan & Carino, 2002; Poon, Azhar, Anson, & Wong, 2001; Sarshar & Khoury, 1993; Yuzer, Akoz, & Ozturk, 2004; Zega & Di Maio, 1926). However, considering the characteristics of the recycled aggregates is necessary to know the performance of recycled aggregates concrete when it is exposed to high temperature.

Fire represents one of most severe risks to buildings and structures. Being a primary construction material, the properties of concrete after exposure to high temperatures have gained a great deal of attention since the 1940s. The physical and mechanical properties of concrete at high temperature degrade mainly because of two relevant mechanisms: mechanical and physic-chemical damage (Arioz, 2007; Bazant & Kaplan, 1996; Hertz, 2005; Kodur & Sultan, 2003; Kowalski, 2007; Yuzer et al., 2004; Zega & Di Maio, 1926). In the case of increasing heating conditions, the dehydration of calcium silicate hydrate (CSH) gel, the thermal incompatibility between the aggregates and cement paste and the pore pressure within the cement paste are the main detrimental factors. To investigate the effect of high temperature and to obtain necessary information for evaluating the structural safety and establishing reparation methods, the residual strength and physical properties of concrete that has been exposed to high temperatures should be determined.

Generally, concrete with recycled brick as an aggregate has a relatively lower strength than a normal aggregate concrete. This characteristic can be attributed to the higher water absorption of recycled crushed brick aggregate compared with natural aggregate (Kesegić et al., 2008). Increasing the rate of substitution of natural coarse aggregate (NCA) with recycled brick aggregate (RBA) decreases the compressive strength (Hachana, 2008; Kesegić et al., 2008). It has been observed through previous experience that the compressive strength of concrete mixtures with percentage of replacement ratios of RBA 30,50, 70 and 100% were decreased by (12, 14, 25 and 31%) and (10, 12, 22 and 26%) for cement contents 350 and 400 kg/m^3, respectively, comparing with control mixtures (Hachana, 2008). From this study, it can be concluded that the compressive strength of concrete decreases when the percentage of substitution of NCA with RBA exceeds 30%.

The main objective of this study is to evaluate the mechanical and physical properties of concretes having different characteristics: first, those made with NCA, and second, those made by replacing 30% of NCA by RBA. The performance of these concretes was studied when they were exposed to the following temperatures: 150, 250, 400, 600 and 900 °C. The compressive strength, ultrasonic pulse velocity (UPV), concrete mass loss, apparent volume, apparent density and water porosity are evaluated on recycled brick concrete (RBC) before and after heating, some of these properties were compared with the values obtained on similar conventional concrete (equal *w*/*c* ratio and mixture proportions) made with the same type of NCA.

2. Experimental details

2.1. Materials

A Portland cement (CPJ CEM II/A 42.5) was used for the experiment. Chemical composition, mechanical and physical properties of the used cement are given in Table 1.

Natural sand composed of siliceous grains with a diameter below 5.0 mm was used as fine aggregate. Table 2 shows the physical properties of the sand.

For conventional concrete, a natural crushed stone (calcareous), with a maximum size of 25 mm, was employed as coarse aggregate. For RBC, 30% of NCA was replaced by RBA with the same maximum size. The percentage of RBA used was taken from the results obtained in a previous study (Hachana, 2008). The RBA used were obtained from crushing new bricks, and were then separated into two distinct fractions: 5–15 mm and 15–25 mm. The physical properties determined on coarse aggregates (NCA and RBA) such as maximum and minimum size, apparent and absolute density and "Los Angeles" abrasion are presented in Table 2. It can be observed that the RBA have lower density than the NCA. In the abrasion test, the recycled aggregates have a high percentage of loss weight.

Figure 1 shows the particle size distribution of different natural and recycled aggregates used.

In this study, in order to obtain the same workability without increasing the water content, a superplasticiser was used. The latter has the following properties: density is 1.04 ± 0.015 and ph value is 4.71 ± 1.

2.2. Mix proportions

Six concretes mixtures were developed as a part of this research programme in two separate groups: conventional concretes and recycled aggregate concretes. For the first category, the three control mixtures (NAC-1, NAC-2 and NAC-3) used NCA and were proportioned to achieve compressive strengths of 30, 50 and 60 MPa. The NAC-1 concrete formulation was determined according to Dreux and Festa (1998). In order to obtain the other compositions (NAC-2 and NAC-3), the cement content was increased (water/cement ratio equal to 0.42 and 0.27) and the aggregate content was kept constant. For the second category, the three mixtures (RBC-1, RBC-2 and RBC-3) were developed by replacing 30% of the natural aggregate from the control mixtures by crushed brick aggregates with no other changes in the mixture proportions. The mixture proportions of the different concretes are presented in Table 3.

Table 1. Chemical, physical and mechanical properties of cement used.

Chemical composition (%)		Physical properties	
CaO	60.41	Specific gravity (g/cm^3)	3.00
Al_2O_3	5.19	Initial setting (h:mn)	2 h: 06'
SiO_2	21.91	Final setting (h:mn)	3 h: 03'
Fe_2O_3	2.94		
MgO	1.60	Compressive strength (MPa)	
Na_2O	0.16	2 days	19.03
K_2O	0.54	7 days	44.93
Cl^-	0.02	28 days	53.41
SO_3	2.19		

Table 2. Physical properties of natural sand, NCA and RCA.

Properties	Sand	NCA	RBA
Maximum size (mm)	5.0	25	25
Minimum size (mm)	0.0	5.0	5.0
Los angeles abrasion (%)	–	21.98	61.16
Apparent density (g/cm^3)	1.70	1.27	0.98
Absolute density (g/cm^3)	2.60	2.63	2.22
Sand equivalent (%)	87.0	–	–
Finesse modulus	2.65	–	–

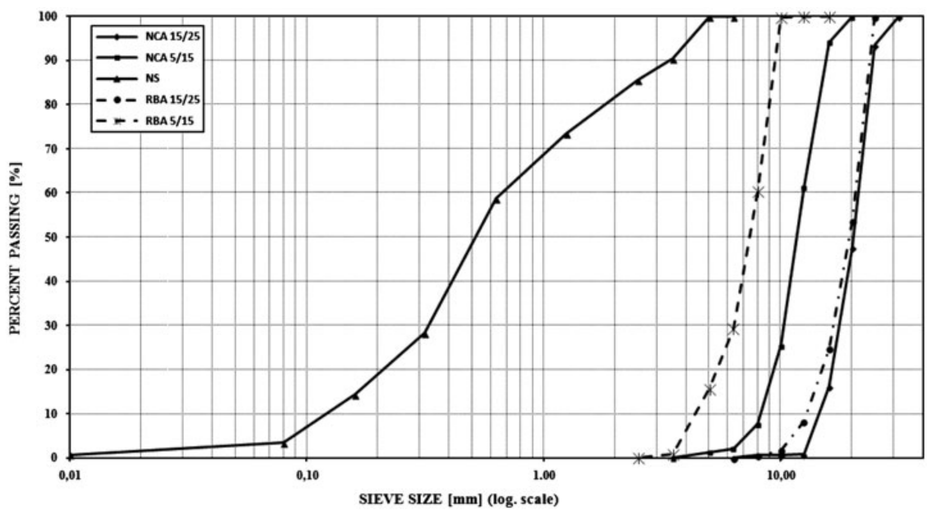

Figure 1. Grading of natural and recycled aggregates.

Table 3. Mix proportion of concrete (kg/m^3).

					Natural aggregate		Brick aggregate		
Notation	*w/c*	Cement	Water	Sand	25 mm	15 mm	25 mm	15 mm	SP (%)
NAC-1	0.60	329	199	715	646	390	–	–	–
NAC-2	0.42	475	199	715	646	390	–	–	–
NAC-3	0.27	610	168	715	646	390	–	–	1.50
RBC-1	0.60	329	199	715	452	273	194	117	–
RBC-2	0.42	475	199	715	452	273	194	117	–
RBC-3	0.27	610	168	715	452	273	194	117	1.50

For each concrete mixture, 18 cubes of 100 mm × 100 mm × 100 mm were prepared. All the cubic samples were then covered with a thin plastic sheet and left in the laboratory at room temperature for 24 h; the specimens were then demoulded and cured under water at an average temperature of 20 ± 2 °C. At the age of 28 days, specimens were removed from water and dried for next 2 days in room temperature. It is necessary to minimise the risk of spalling of the concrete specimens when subjected to high temperature in the furnace. The initial moisture content in concrete specimens was not measured.

2.3. Test methods

2.3.1. Heating procedure

Three specimens from each mixture were placed in an electrical furnace and heated at a constant rate of 3 °C/min from room temperature (20 ± 2)°C up to 150, 250, 400, 600 and 900 °C. The rate of heating refers to the recommendations of the ISO/TR 15655:2003 (ISO/TR 15655, 2003). Once the electrical furnace reached the target temperature, the temperature was maintained for one hour in order to ensure uniform heating throughout the concrete samples and to minimise the thermal gradient between the surface and centre of the concrete samples (Fares, Noumowe, & Remond, 2009). After this heating treatment, the specimens were allowed to cool naturally to room temperature inside the electrical furnace in order to prevent thermal shock. The average cooling rate was about 1 °C/min. Physical and mechanical tests were performed on unheated (20 ± 2)°C and heated samples in order to compare the initial and residual properties. Figure 2 shows the theoretical temperature evolution as a function of time for the five temperatures cycles.

2.3.2. Compressive strength

Uniaxial compression tests are performed on 100 mm cubic specimens using a hydraulic press. Three specimens were tested for each heating/cooling cycle and the average values are reported.

The testing conditions of the specimens for the mechanical properties after exposure high temperature were in accordance with the ISO/TR 15655 (2003) recommendations (ISO/TR 15655, 2003). The loading rate was 0.5 MPa/s until the failure.

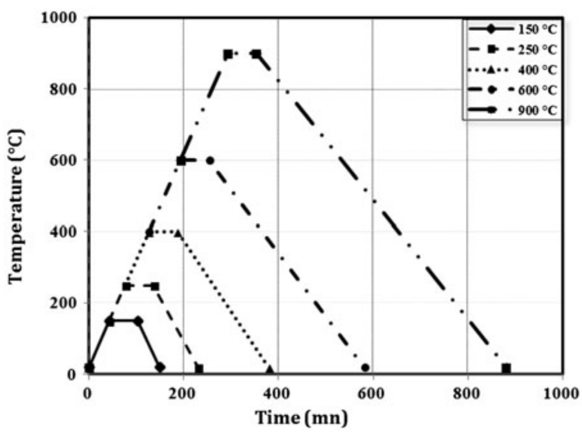

Figure 2. Heating and cooling curves.

2.3.3. Ultrasonic pulse velocity (UPV)

The UPV of a material can be determined by placing a pulse transmitter on one face of a sample of the material, and a receiver on the opposite face. A timing device measures the transit time of the ultrasonic pulse through the material. If the path length is known, then the UPV can be calculated from the path length divided by the transit time.

The UPV value was determined for quick checking of the uniformity of concrete specimens after each heating. The average UPV values were taken from three cubes from each mixture using the portable ultrasonic. Grease was used as interfacing agent between cube surface to transmitter and receiver. UPV tests were performed in accordance with the AFNOR P 18-418 standard (AFNOR P 18-418, 1989).

2.3.4. Concrete mass loss

Concrete mass before and after each heating temperature was determined using an electronic digital balance with an accuracy of ±0.1 g. Concrete mass loss was calculated according to Equation (1), where M_{initial} is the initial mass (before heating) and M_{heated} is the heated mass (after heating) weighed in the air.

$$M_{\text{loss}} = \frac{M_{\text{initial}} - M_{\text{heated}}}{M_{\text{initial}}} \tag{1}$$

2.3.5. Water porosity and apparent density

Density and total porosity of the different mixes of recycled brick concrete (RBC) were studied. The concrete porosity and apparent density were measured by a technique of water intrusion. The operation of such a test is conducted according to AFNOR P 18-554 standard (AFNOR P 18-554, 1990) and is based on measuring the mass of a specimen of concrete.

Two samples were tested for each RBC and each temperature cycle. The samples were weighted before testing, and then they were immersed in water and weighted regularly until completed saturation. The immersed mass was determined with a hydrostatic balance, and the samples were wiped in order to remove excess water on the surface. Finally, the saturated mass was measured.

The porosity is determined according to below equation:

$$P = \frac{M_{\text{sat}} - M_{\text{heated}}}{M_{\text{sat}} - M_{\text{sat+imm}}} \tag{2}$$

where M_{sat} and $M_{\text{sat+imm}}$ are the saturated mass of a sample measured in the air and in the water, respectively.

The apparent density D of RBC specimen for each mix and each temperature was determined according to below equation:

$$D = \frac{M_{\text{heated}}}{M_{\text{sat}} - M_{\text{sat+imm}}} \tag{3}$$

2.3.6. Specimens dimension

Test specimen dimension was measured using the Vernier Measurement, which is capable to measure 300 mm long and had a measurement resolution of 0.01 mm. The dimensions of width, length and height are measured to get the cube size and area of loading applied.

3. Results and discussion

3.1. Residual compressive strength

The results of residual compressive strength of the different NAC and RBC are shown in Table 4. The evolution of the residual compressive strength of NAC and RBC specimens after being subjected to the elevated temperature are shown in Figure 3; the dotted and solid lines represent the residual strength of RBC and NAC specimens, respectively. The relative residual strength (ratio of residual compressive strength at elevated temperature to initial compressive strength at ambient temperature) of NAC and RBC specimens is shown in Figure 4.

The evolution of the compressive strength with the temperature is similar for both categories of concrete. The evolution of the strength can be separated in two temperature ranges: first between 20 and 400 °C, then between 400 and 900 °C.

It can be noticed that up to 400 °C, strength is slightly changed. At 150 °C, the changes of the initial strength ranged from −10 to +12% for NAC and from –15 to +7% for RBC. Also, at 250 °C, the changes of strength ranged from −14 to 0% of the initial strength for NAC, and from −17 to +5% of the initial strength for RBC. In fact, most of the damage in this step comes from the elimination of free water and from the dehydration of CSH in concrete (AFNOR P 18-418, 1989; AFNOR P 18-554, 1990; Bazant & Kaplan, 1996; Dreux & Festa, 1998; Fares et al., 2009; Gaweska, 2004; Hachana, 2008; ISO/TR 15655, 2003; Kodur & Sultan, 2003; Mindeguia et al., 2012; Savva, Manita, & Sideris, 2005; Xing, Beaucour, Hebert, Noumowe, & Ledesert, 2011; Yuzer et al., 2004).

We also observed that the compressive strength slightly increased around 400 °C. The initial strength of RBC increased from −4 to +29% and from −2 to +21% for NAC. It is important to mention that several hypotheses have been proposed in the literature to explain the increase in compressive strength around 400 °C. It is supposed that the removal of moisture from the interlayer of cement gel would reduce the disjoining pressure and increase the binding forces between the particles of hydration products and, thus, the compressive strength of concrete (Behnood & Ghandehari, 2009; Chen, Li, & Chen, 2009; Zain, Safiuddina, & Mahmud, 2000). The increase in compressive strength of specimens exposure to 400 °C might be due to a shorter duration of exposure at the centre of a cube specimen to a temperature of 400 °C (Xing et al., 2011), and because the transportation of moisture in concrete is rather gradual, some unhydrated cement grains in the concrete specimens continue to hydrate and gain strength after exposure to high temperature (Chen et al., 2009).

For temperatures higher than 400 °C, the loss of strength becomes more significant. When the specimens are exposed to 600 °C, the residual compressive strength decreases by 17, 9 and 19% for conventional concrete NAC-1, NAC-2 and NAC-3, respectively. Whereas for RBC-1 and RBC-2, the compressive strength decreases by 28 and 6%, respectively. The RBC-3 has the best residual compressive strength, after heating at 600 °C; its residual strength is higher than the initial strength. At 900 °C, all tested concretes suffered from thermal deterioration and only a small part of initial strength is left, ranging from 7 to 19% for NAC and from 22 to 32% for RBC.

There are several possible reasons that can be given to explain the decrease in compressive strength with the increase in temperature. The main reason for such a loss in strength is attributed to the dehydration of the CSH as well as to the volumetric

Table 4. Results of compressive strength test at different temperatures.

Concrete mixes	Compressive strength (MPa)					
	20 °C	150 °C	250 °C	400 °C	600 °C	900 °C
NAC-1	27.68 (100%)	24.77 (89.49%)	23.54 (85.04%)	26.95 (97.36%)	22.93 (82.84%)	5.22 (18.86%)
NAC-2	47.56 (100%)	45.87 (96.45%)	42.77 (89.93%)	51.70 (108.70%)	43.00 (90.41%)	3.47 (7.30%)
NAC-3	62.06 (100%)	69.55 (112.07%)	62.07 (100.02%)	75.44 (121.56%)	49.93 (80.45%)	12.33 (19.87%)
RBC-1	36.30 (100%)	30.52 (84.08%)	29.88 (82.31%)	34.72 (95.65%)	25.93 (71.43%)	9.50 (26.17%)
RBC-2	40.16 (100%)	43.31 (107.84%)	38.66 (96.26%)	42.03 (104.66%)	37.44 (93.23%)	12.85 (32.00%)
RBC-3	49.31 (100%)	48.93 (99.23%)	51.81 (105.07%)	63.66 (129.10%)	52.56 (106.59%)	10.89 (22.08%)

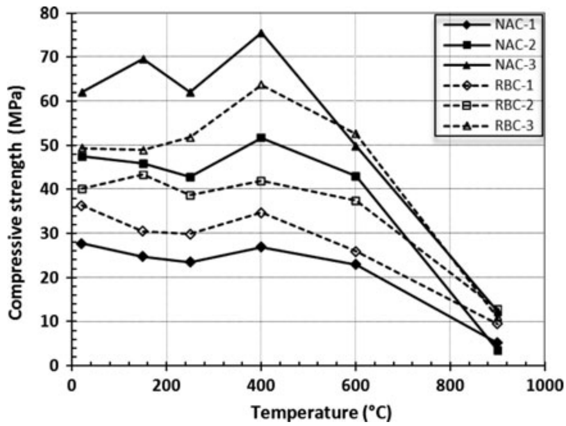

Figure 3. Residual compressive strength of NAC and RBC after exposure to elevated temperature.

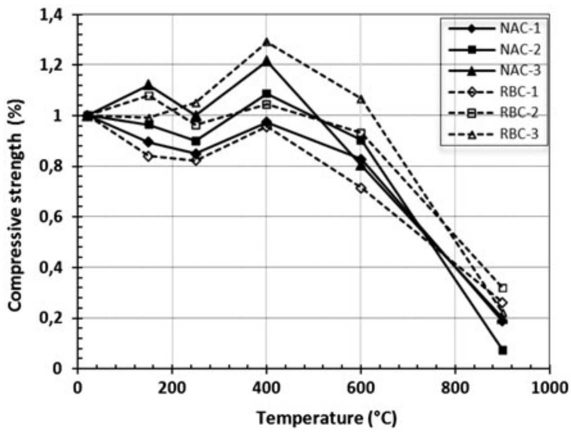

Figure 4. Relative residual compressive strength of NAC and RBC after exposure to elevated temperature.

expansion resulting from the transformation of the chemical compound $Ca(OH)_2$ to CaO. It was known that cement paste starts to dehydrate at about 180 °C. The completely decomposition of the CSH gel occurs at about 900 °C. Additionally to those factors, for temperatures higher than 400 °C, a third parameter may contribute to the decrease in compressive strength. This parameter is the development of microcracks at the interfaces between aggregates and cement matrix due to the thermal incompatibility between aggregates and hardened cement paste (Gardner, Lark, & Barr, 2005; Gaweska, 2004).

RBC-1 concrete shows an improved behaviour under elevated temperature compared with NAC-1. It can be explained by the absorption of crushed clay bricks. Recycled aggregate normally has higher water absorption which is greater than that of natural aggregates that reduces the amount of mixing water of RBC-1 (w/c = 0.6) and increases the compressive strength.

RBC-2 and RBC-3 samples unheated and after heating at different elevated temperature shows a lower strength than NAC-1 and NAC-2, respectively. This characteristic can be attributed to the higher water absorption of recycled crushed brick aggregate compared with natural aggregate.

As a conclusion, the results showed that concrete could be produced using crushed clay bricks as the coarse aggregate for applications in which the high strength is not necessary.

3.2. Residual UPV

The velocity of an ultrasonic pulse through a material is a function of the elastic modulus and density of the material. The pulse velocity can, therefore, be used to assess the quality and uniformity of the material. The pore structure in the concrete may have impact on the UPV values and concrete strength. Thus, the decrease in pulse velocity with increasing temperature is a sensitive measure of the cracking progress in the material.

The values of UPV determined on different conventional and recycled brick concretes are presented in Figure 5 for both unheated and heated specimens. Each data point represents the average of three measurements. The ratio V_t/V_{20} vs. temperature T is presented in Figure 6: V_t is the pulse velocity after heating at T °C and V_{20} is the initial pulse velocity of concrete at 20 °C. The pulse velocity has a continuous drop as the temperature increased.

It is known that concrete quality can be classified by UPV value: if the value is >4500, 3500–4500, 3000–3500, 2000–3000 and <2000, the concrete is classified as “excellent”, “good”, “doubtful”, “poor” and “very poor”, respectively (Whitehurst, 1951). Therefore, the NAC and RBC specimens degraded from “excellent” to “good”, “good” to “poor” and “poor” to nearly “very poor”. Table 5 shows the summary of concrete specimens quality at different temperatures.

When the specimens are exposed to 400 °C, the UPV of the RBC shows a decrease of 21, 18 and 19% for RBC-1, RBC-2 and RBC-3, respectively, while in the case of NAC, the decrease is 32, 23 and 21% for NAC-1, NAC-2 and NAC-3, respectively. At a temperature of 400 °C, the evaporation process will increase for all concrete

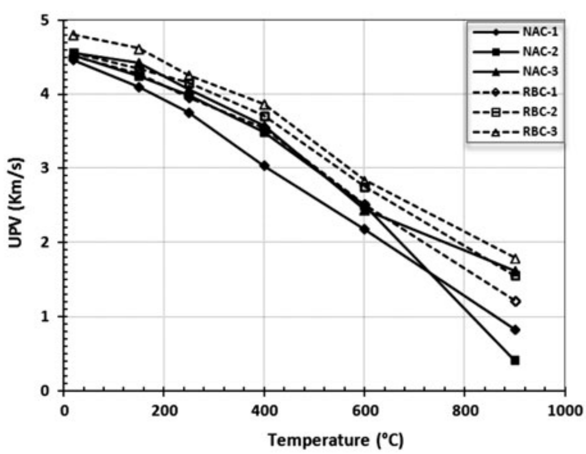

Figure 5. UPV as a function of elevated temperature.

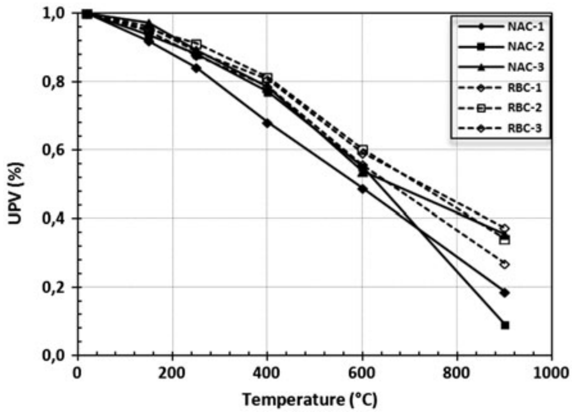

Figure 6. Relative UPV as a function of elevated temperature.

specimens. The evaporation of water will leave gap between aggregate and cement paste. The process caused the loss of more pores water, and also micro cracking occurred. This cracking increased the time travel in pulse velocity testing.

The decrease in the UPV values for NAC is higher than that of RBC. When the specimens are exposed to 900 °C, the UPV values of NAC show a decrease of 81, 91 and 64% for NAC-1, NAC-2 and NAC-3, respectively. For the RBC, the decrease is 73, 65 and 62% for RBC-1, RBC-2 and RBC-3, respectively.

As stated above, RBC shows a decrease in the UPV lower than that of conventional concrete NAC. Recycled crushed clay brick is one of the best aggregates for concrete that may have to resist fire, and it performs much better than similar concrete containing granite aggregate (Khalaf, & DeVenny 2004). Brick aggregate is a thermally stable aggregate; it is probably why it performs well when used as an aggregate in concrete subjected to high temperatures (Kesegić et al., 2008).

3.3. *Concrete mass loss*

Previous studies have indicated that the type of aggregate has a strong influence on the mass loss and, therefore, on the density of the concrete at elevated temperatures.

Table 5. Pulse velocity of concrete specimens at different temperatures.

Temperature		20 °C	150 °C	250 °C	400 °C	600 °C	900 °C
NAC-1	UPV	4459	4100	3752	3037	2180	830
	quality	good	good	good	fair	poor	very poor
NAC-2	UPV	4524	4241	4066	3575	2447	409
	quality	excellent	good	good	good	poor	very poor
NAC-3	UPV	4554	4426	4066	3575	2447	1617
	quality	excellent	good	good	good	poor	very poor
RBC-1	UPV	4513	4279	3960	3549	2515	1217
	quality	excellent	good	good	good	poor	very poor
RBC-2	UPV	4560	4346	4159	3711	2750	1557
	quality	excellent	good	good	good	poor	very poor
RBC-3	UPV	4798	4619	4259	3869	2839	1793
	quality	excellent	excellent	good	good	poor	very poor

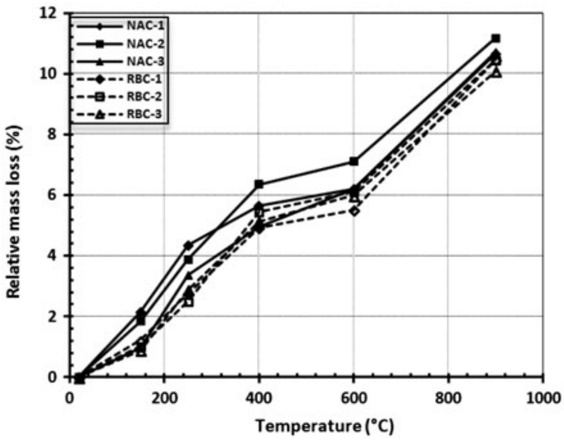

Figure 7. Mass loss of the NAC and RBC specimens subjected to elevated temperature.

Figure 7 shows the concrete mass loss of the RBC and NAC specimens as a function of temperature. We can observe, for all the specimens, an increase in mass loss with increase in temperature.

The loss of mass between the ambient temperature and 150 °C corresponds to the departure of free water contained in the capillary pores. When temperature rises from 150 to 400 °C, a mass loss corresponding to an average of 4.8 and 3.9% of the initial mass for the NAC and RBC is observed, respectively. The mass loss in this domain is owing to the release of both capillary water and gel water (Hoff et al., 2000). The rate of concrete mass loss is lowered when the heating temperature increases from 400 to 600 °C. Beyond 600 °C, the mass loss rate increases again. This could be the consequence of the calcareous aggregates decomposition, the release of CO_2 and the sloughing off of the concrete surface (Xiao & Falkner, 2006). At 900 °C, the average mass loss of 10.8 and 10.3% for the NAC and RBC were observed, respectively. As can be seen, concretes with crushed brick aggregates have the lowest weight loss according to the results obtained on concretes with natural aggregates.

3.4. Residual density and water porosity

Water porosity is an important indicator of the hardened concrete durability. Reduction of porosity can greatly enhance the long-term performance and service life of concrete in aggressive service environments. Decreased porosity also benefits the mechanical properties of concrete, as a fundamental inverse relationship exists between porosity and strength of solids (Nassar & Soroushian, 2012).

Figure 8 shows the water porosity of the RBC specimens as a function of temperatures. It can be observed that concrete porosity varies very slightly when the temperature does not exceed 150 °C. The concrete specimens heated up to 900 °C present a higher porosity than that at ambient temperature.

After exposure to high temperature up to 900 °C, the porosity of RBC have a great increase in which RBC-3 has the largest increase (309%). Additionally, the difference of porosity between the three RBC decreases when they are exposed to 600 and 900 °C. From 400 °C, we have observed several cracks due to the heating, which could be correlated to the evolution of porosity and microstructure changes.

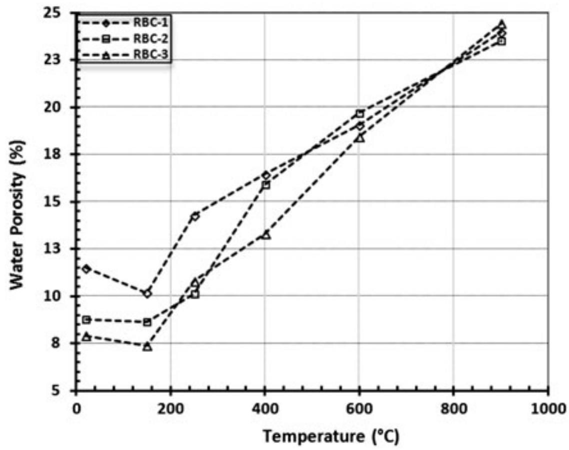

Figure 8. Water porosity of RBC specimens after exposure to elevated temperatures.

Alonso, Andrade, and Khoury (2003) attributed the pore evolutions in the temperature range 100–300 °C to the loss of bound water from the CSH gel. At higher temperatures, the pore size of the dehydrated cement paste increases up to even 1 μm; which can be attributed to microcracking and the changes in porosity are also due to changes in aggregates stability.

The effect of elevated temperatures on the apparent density of the RBC specimens is plotted in Figure 9. The results indicate that the elevated temperature affects the loss of density. A decrease in density with increasing of temperature is observed. We noted that whatever the mixture, the density decreases between 150 and 900 °C. At 400 °C, the overall decrease is around 1% for RBC-1 and RBC-2 and 3% for RBC-3. At 900 °C, the overall decrease in apparent density is 7% for RBC-1, 8% for RBC-2 and 13% for RBC-3. We conclude that the decrease in density is due to the departure of water during heating (dehydration of hydrates like the CSH and Portlandite CH) (Fares et al., 2009).

The evolution of density is correlated with the evolution of porosity; because the density and the porosity are normally related to each other.

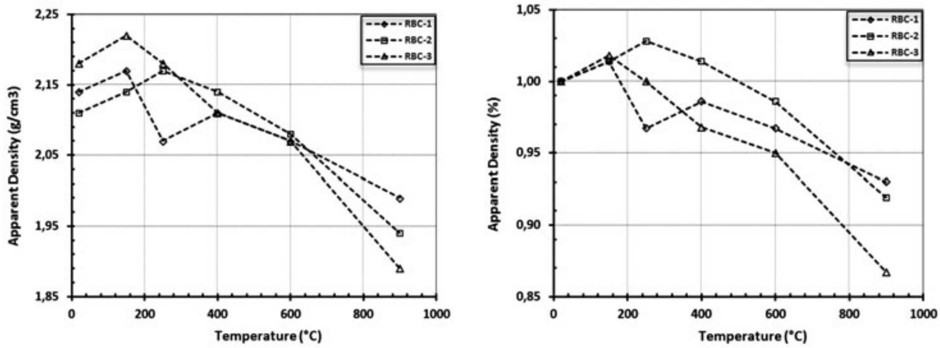

Figure 9. Residual density of RBC specimens after exposure to elevated temperatures.

3.5. *Effect of high temperature on volume*

As with any other material, the volume of concrete changes as its temperature changes. Depending on its curing condition, concrete presents volumetric variations, and it usually shrinks but sometimes it swells (Aïtcin, 2003).

Figure 10 gives the relative changes in volume of NAC and RBC specimens as function of elevated temperature. Dimensional changes directly affect the volume of the material. After fire exposure, the volume of NAC-2 increases with the increasing temperature, while the volume of the other concretes specimens gradually decreases between 150 and 400 °C for NAC-1 and RBC-1, and at 150 for NAC-3, RBC-2 and RBC-3. During heating, cement paste initially experiences thermal expansion and then shrinkage. When the hardened cement paste is heated up to 150 °C, the paste expands by up to 0.2% of the initial volume. Beyond 300 °C, the paste shrinks in the order of 1.6–2.2% caused by loss of moisture from the cement paste (Bazant & Kaplan, 1996).

Between 600 and 900 °C, the volume of NAC and RBC specimens increases. The reason of the increase in volume is mainly the result of gradual increase in microcracks developing in the structure of the material due to the thermal expansion of aggregates (Niry et al., 2013). At 700 °C, calcareous aggregates are cracked and the grain surface has whitened. This is due to the decarbonation: a proportion of calcite ($CaCO_3$) is converted into lime CaO releasing CO_2. After cooling, the free CaO reacts with ambient relative humidity and is transformed into $Ca(OH)_2$ (portlandite) with a volume expansion of 200% (Rayssac et al., 2009).

Figure 10 shows that NAC expands more than RBC; this is mainly because the crushed brick aggregates tend to give good fire performance and they have a lower coefficient of thermal expansion than calcareous aggregates.

3.6. *Microscopic study of surface texture*

A number of SEM micrographs illustrating the texture of the concrete samples of RBC-3 after exposure to 150, 250, 400 and 600 °C are shown in Figure 11. After heating to a high temperature, the texture of the sample becomes coarse and several

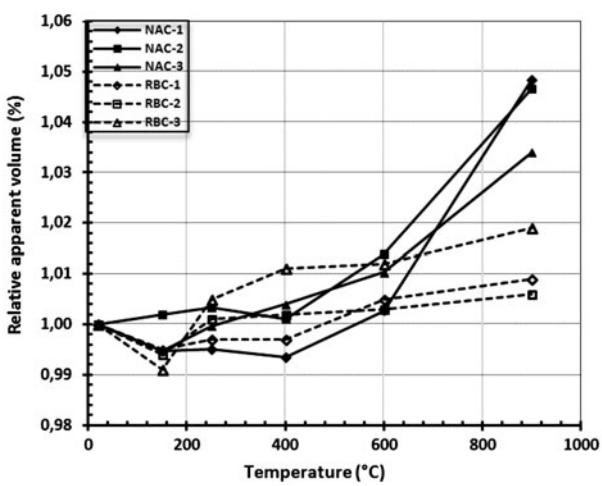

Figure 10. Relative volume of NAC and RBC specimens as a function of elevated temperatures.

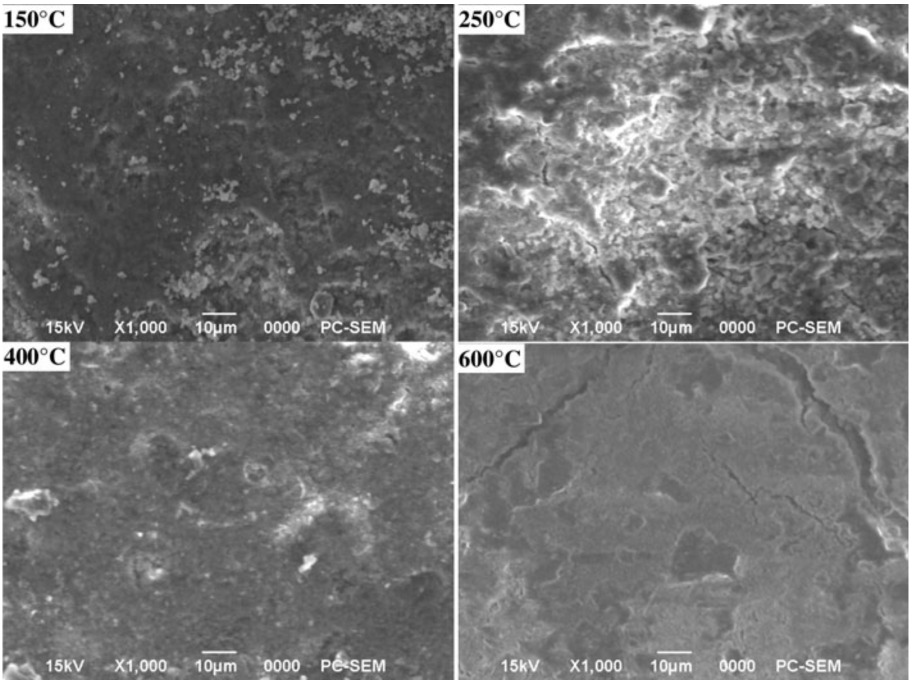

Figure 11. SEM micrograph of surface microstructure of RBC-3 exposed to elevated temperature (scale bar 10 μm).

microcracks appears, which gradually worsen the strength character of the sample. The water attached to the microstructure after heating at high temperature evaporates and pores in microstructure gradually increase. The specimens lost their binding properties after exposure to 600 °C; it is attributed to continuous crack formation. The density of cracks increases with the elevating temperature.

3.7. Cracking of concrete

The surface cracks started to appear at around 400 °C and continued to grow till the final rise in temperature up to 900 °C. Immediately after cooling, the crack widths were

Table 6. Crack width of NAC and RBC specimens at different temperatures.

	Crack widths (mm)					
	400 °C		600 °C		900 °C	
Concrete mixes	Min	Max	Min	Max	Min	Max
NAC-1	<0.05	0.08	<0.05	0.25	<0.05	0.70
NAC-2	<0.05	0.05	<0.05	0.10	<0.05	0.50
NAC-3	<0.05	0.05	<0.05	0.08	<0.05	0.35
RBC-1	<0.05	0.05	<0.05	0.10	<0.05	0.50
RBC-2	<0.05	0.04	<0.05	0.05	<0.05	0.30
RBC-3	<0.05	0.04	<0.05	0.10	<0.05	0.20

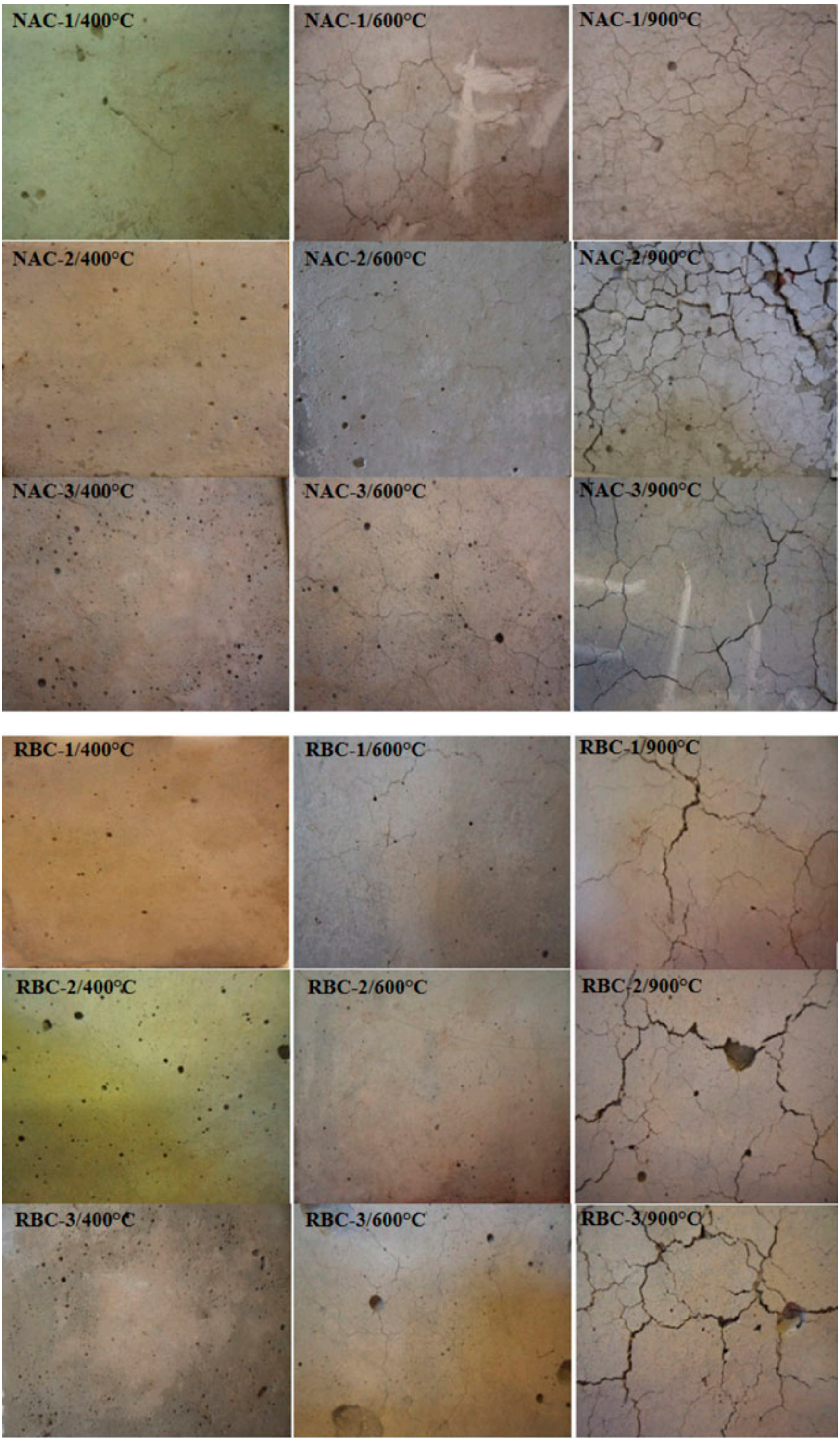

Figure 12. Typical crack patterns observed in NAC and RBC at 400, 600 and 900 °C.

measured using a microscope (MPB-2 Magnit 24×) that can measure the surface crack widths beyond 0.05 mm. The concrete specimens exposed to elevated temperatures (900 °C) showed cracks and deterioration that increased with increasing the post-fire age. The crack widths are reported in Table 6. Figure 12 shows typical crack patterns observed in different concretes at 400, 600 and 900 °C.

The crack widths increased with the increase in temperature it can be seen that concrete started to crack when the temperature exceeds 400 °C. From Figure 12, it can be seen that the surface cracking of concrete become significant when the exposure temperatures were higher than 400 °C. The cracks become very pronounced at 600 °C and extensively increased at 900 °C. The internal cracks commenced after 600 °C. This was attributed to the thermal incompatibility of the cement past and aggregates and the dehydration of cement past due to heating (Felicetti & Gambarova, 2008). Furthermore, Figure 12 shows a change in colour. This change gives a visual indication of a significant modification in the concrete's properties (Biolzi, Cattaneo, & Rosati, 2008).

4. Conclusion

In this paper, the results of elevated temperature on the mechanical and physical properties of NAC and RBC are presented. From the experimental results, we conclude that:

- In general, RBC sample performs similar to NAC sample exposed to elevated temperature.
- High temperature can be divided into two ranges. In the first range, between 20 and 400 °C, a little increase in compressive strength for all concretes specimens at 400 °C was observed. In the second range, beyond 400 °C, the compressive strength of all tested concretes decreased quickly.
- Both NAC-2 and NAC-3 samples unheated and after heating at different elevated temperatures show higher compressive strength values than the RBC-2 and RBC-3, respectively. RBC-1 has slightly higher compressive strength values than the NAC-1. The concrete with recycled crushed brick aggregate has a strength that would make it suitable aggregate for applications in which the high strength is not necessary.
- The RBC is good in terms of its UPV value compared with NAC; it shows a decrease in the UPV lower than that of NAC.
- Concretes with crushed brick aggregates RBC have the lowest weight loss according to the results obtained on concretes with natural aggregates NAC.
- It is revealed that the total pore volume of a concrete mixture increases after exposure to an elevated temperature.
- The RBC with a lower *w*/*c* ratio performs better than conventional concretes when they are exposed to high temperatures.
- After fire exposure, the increase in volume specimens is due to the thermal expansion of the material. No explosive spalling is observed with an average rate of 3 °C/min, during the high temperature tests.
- Overall degradation of concrete after heating to an elevated temperature broadly due to the microstructure of concrete becomes coarser due to high temperature, and total pore volume increases after heating which leads to higher strain in concrete as well as lower compressive strength.

Abbreviations

NCA	natural coarse aggregate
RBA	recycled brick aggregate
NAC	natural aggregate concrete
RBC	recycled brick concrete
w/c	water/cement
UPV	ultrasonic pulse velocity
M_{initial}	the initial mass (before heating)
M_{heated}	the heated mass
M_{sat}	saturated mass of a sample measured in the air
$M_{\text{sat+imm}}$	saturated mass of a sample measured in water
P	porosity
D	apparent density

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