EVALUAREA EFICIENȚEI TRATAMENTULUI TERMOMECANIC APLICAT PENTRU ÎMBUNĂTĂȚIREA CALITĂȚII AGREGATELOR RECICLATE DIN BETON
THE ASSESSMENT OF EFFICIENCY OF THERMO-MECHANICAL TREATMENT APPLIED ON RECYCLED CONCRETE AGGREGATE

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In order to improve the properties of recycled aggregate resulted by the crushing of concrete from construction and demolition waste stream, a thermo-mechanical treatment was applied. This treatment, performed in a muffle furnace and a Los Angeles machine, simulates the conditions specific for a rotary kiln. Recycled concrete aggregate (RCA) was obtained by the crushing of a concrete C20/25 class. The crushed concrete aggregate (RCA), the one resulted after the thermo-mechanic treatment of RCA and the initial natural aggregate where compared from the point of view of physical properties (apparent and bulk densities). A good efficiency of thermo-mechanic treatment was appreciated based on these results.

New concretes were prepared using the recycled concrete aggregates (before and after thermo-mechanic treatment) in order to determine the density and compressive strength. Thus, the compressive strength values, determined on concrete prepared with recycled concrete aggregates subjected to thermo-mechanical treatment, are similar with those prepared with natural aggregate.

The thermo-mechanic process applied for the removal of cement paste/mortar adhered to natural aggregate grains is a possible solution for the improvement of recycled aggregates quality.

În vederea îmbunătățirii proprietăților agregatelor din betoane reciclate acestea s-au supus unui tratament termomecanic efectuat într-un cuptor electric cu muflă şi ulterior într-un aparat Los Angeles. Acest tratament simulează condițiile de funcționare ale unui cuptor rotativ. Agregatul de beton reciclat a provenit din concasarea unui beton de clasa C20/25. Agregatul rezultat din concasarea betonului (RCA), agregatul rezultat în urma tratamentului termomecanic a RCA şi agregatul natural folosit la prepararea betonului de clasa C20/25 au fost comparate din punct de vedere al unor proprietăți fizice (densitatea aparentă şi în vrac). Cu agregatele recuperate după concasare şi după tratamentul termomecanic a betonului reciclat s-au realizat probe de beton, pe care s-au determinat densitatea şi rezistența la compresiune. Comparând valorile obținute pentru aceste proprietăți în cazul betoanelor cu agregate reciclate, cu cele obținute în cazul betonului preparat cu agregat natural, s-a constat o bună eficiență a tratamentului termomecanic. Astfel, rezistențele mecanice obținute pe betoane cu agregat de beton reciclat supus tratamentului termomecanic au fost comparabile cu cele obținute pe betoane similare preparate cu agregat natural. Tratamentul termomecanic de îndepărtare a pastei de ciment/mortarului care aderă la granulele de agregat provenite din betonul concasat reprezintă o posibilă soluție de obținere a unor agregate reciclate de calitate.

Keywords: *recycled aggregate, thermo-mechanic treatment, concrete*

1. Introduction

Today concrete is one of the most used construction material. About 2 billions tons of concrete are produced every year in the world [1].

In the same time, large volumes of concrete rubble are being generated. After demolition of old roads and buildings, the removed concrete is often considered worthless and disposed of as demolition waste. By collecting and crushing of concrete rubble, recycled concrete aggregate (RCA) is created. RCA is mainly used for embankment, earth construction works and as aggregate in granular base or sub-base applications. This is manly due to the lower quality of RCA as compared with natural aggregate [2,3]. The use of recycled concrete aggregate (RCA), as a substitute of natural aggregate, in concrete production is considered a valuable recycling method ("up-cycling") opposite to it's use in road works or as filling material in quarries ("down-cycling").

The use of RCA in new construction applications is still a relatively new technique, with some positive environmental aspects [2,4,5]. According to life cycle analysis the use of RCA (instead of natural aggregate) has important environmental impact values because of avoidance of traditional demolition methods, saving of natural

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aggregate resources and landfill space [2,4]. On the other side the main cost savings when using RCA obtained from conramined concrete, are landfill avoidance savings; cost savings due to avoiding purchasing natural aggregate represents a minor part of the total savings [5].

Nevertheless, due to the present EU policy and legislation on waste management, emphasis is placed on recovering, recycle and reuse (RRR) of various waste streams including construction and demolition waste (CDW). According to Waste Framework Directive [6], EU Member States should increase, by 2020, the reuse, recycling and material recovery of non-hazardous construction and demolition waste to a minimum of 70% by weight. From 2011, Romanian law no. 211 [7] sets also this RRR target for national waste producers and authorities. In this current juncture the supplementary processing of RCA, in order to improve its properties and enable its "up-cycling", despite the marginal increase of production costs, is feasible and possible.

The use of concrete rubble as RCA in new concrete formulation has some shortcomings:

- The aggregate obtained by the crushing of concrete generated in demolition activities has an additional cost due to comminution operations (usually high energy demanding processes).
- The porosity of harden concrete prepared with RCA is higher as compared with concrete made with natural aggregates, the concrete mixture with RCA usually need more water to achieves a plastic consistence and consequently a reduction of new concrete mechanical strength and a higher drying shrinkage is noticed [8].

The above mentioned shortcomings of concrete prepared with RCA are mainly due to the presence of hardened cement paste/mortar at the surface of natural aggregate grains; this cement paste/mortar has a high porosity and this is the main reason for the high water demand in new concrete formulations. Moreover, at the interface cement paste/mortar - natural aggregate grain a low strength transition zone is present.

In order to overcome these shortcomings, several methods where proposed, ranging from modified dosage and mixing procedure of concrete components [9,10] to different treatments of RCA surface in order to reduce its porosity [11,12] or to remove the cement paste/mortar [13-15].

Several studies report the improvement of RCA quality when heated at temperatures between 300-900°C and then cooled fast; this treatment increases the friability of mortar/cement paste adhered on natural aggregate grains and clean surfaces can be obtained by crushing and sieving [14,16-18].

In this study was assessed the possibility to improve the quality of RCA by a thermal treatment (in a muffle furnace) combined with an autogenous grinding treatment (in Los Angeles machine, without grinding balls). This combined treatment simulates the conditions specific for a rotary kiln. This study was performed in order to compare some properties of recycled aggregate concrete (before and after thermo-mechanical treatment) to those of the natural siliceous aggregate. Moreover, new concretes were prepared using the recycled concrete aggregates (before and after thermo-mechanic treatment) in order to determine the density and compressive strength and to compare them with those of the concrete prepared with natural aggregate (siliceous river aggregate).

2. Materials and methods

Concrete of class C20/25 [19] and slump class S2 [20] was prepared using Portland cement type II-B-M 42.5R and river aggregate in 0/4 mm, 4/8 mm, 8/16 mm and 16/32 mm sorts, according to CP 012/1 [21]. The dosage of components is presented in Table 1.

The main characteristics of the natural river aggregate i.e. apparent and bulk densities and water absorption were determined by the methods described in European and national standards SR EN 1097-6: 2002 [22] and SR EN 1097-3:2002 [23]. The results are presented in Table 2.

Table 1

Composition of concrete C20/25 class/ *Compoziția betonului de clasa C20/25*

Components/*Componenți*	Dosage/*Dozaj* (kg/m^3)
Cement/*Ciment*	300
Water/*Apa*	180
Additive/*Aditiv* (superplasticizer*)	3
Aggregate/*Agregat* 0/4 mm	750
Aggregate/*Agregat* 4/8 mm	375
Aggregate/*Agregat* 8/16 mm	375
Aggregate/*Agregat* 16/32 mm	375

Table 2

Characteristics of natural river aggregate/*Caracteristicile agregatului de râu*

Aggregate fraction *Sort aggregat*	Apparent density *Densitate* (kg/m^3)	Bulk density *Densitate în vrac* (kg/m^3)	Water absorption (%) *Absorbția de apă*
2/4 mm	2644	1509	ND
4/8 mm	2648	1466	0.79
8/16 mm	2656	1460	0.70
16/32 mm	2676	1455	0.46

**ND – not determined*

Cubic concrete specimens (L=150 mm) were prepared and kept in water for 83 days and then in air for the next 7 days. The cubic specimens were then broken and crushed until all the material passed through the 32 mm sieve. This material represents the recycled concrete aggregate (RCA).

RCA was graded into 16/32 mm, 8/16 mm, 4/8 mm and 2/4 mm fractions and then thermally treated in a muffle furnace at 400^{o}C and 700^{o}C, for 7 minutes. Average surface temperature of RCA grains after exposure for 10 minutes at 400^{o}C was approximately 250°C and 450^{o}C for those thermally treated at 700^{0}C.

After the thermal treatment the aggregates were introduced for different periods of time (1, 2, 3, 4, 5 and 10 minutes) in a Los Angeles machine (without grinding balls). On the resulted RCA, before and after thermo-mechanical treatment, were determined apparent and bulk densities according to European and national norms [22,23].

RCA and aggregates subjected to the thermo-mechanical treatment (400^{o}C and 700^{o}C), were used for the preparation of a new concrete with the same dosage of components as used for the preparation of C20/25 class concrete (Table 1). Density [24] and compressive strength [25] of these concretes after 28 days of hardening were also determined.

3. Results and discussion

Grain size distributions of natural river aggregate (NA) and RCA obtained by the crushing of C20/25 concrete until complete passing through 32 mm are presented in Figure 1.

As it can be noticed, RCA contains a lower amount of fine fraction as compared with the natural aggregate (NA).

The grain size distribution of aggregates, obtained by the thermal treatment of RCA (fractions 2/4 mm, 4/8 mm, 8/16 mm) and grinding treatment in Los Angeles machine for different periods of time, are presented in Figures 2-5.

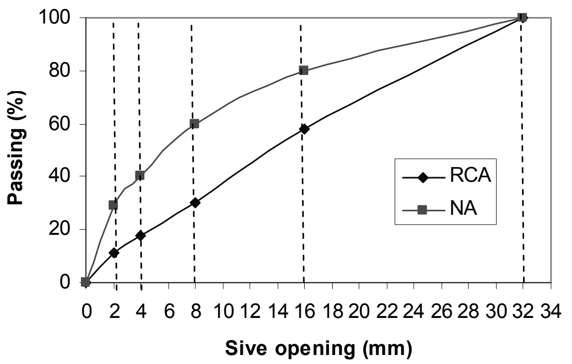


Fig.1 - Grain size distribution of RCA and natural aggregate (NA)./*Distribuția granulometrică a agregatelor de tip RCA şi natural (NA)*

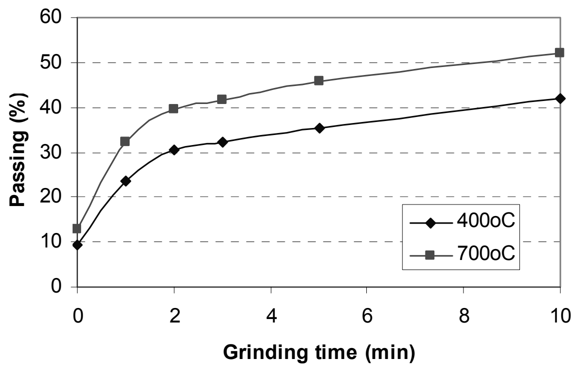


Fig. 2 - The amount of material passing through the 2 mm sieve after different times of grinding treatment in Los Angeles machine of RCA (fraction 2/4 mm) treated at 400^{o}C and 700^{o}C./*Trecerea pe sita de 2 mm a RCA (fracția 2/4 mm) tratat termic la 400^{o}C şi 700^{o}C funcție de timpul de mărunțire în aparatul Los Angeles.*

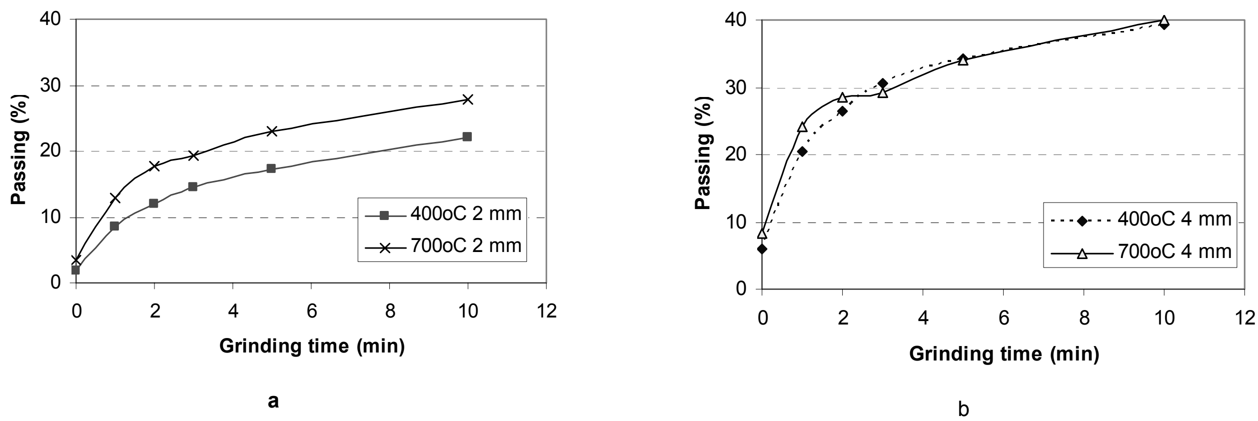
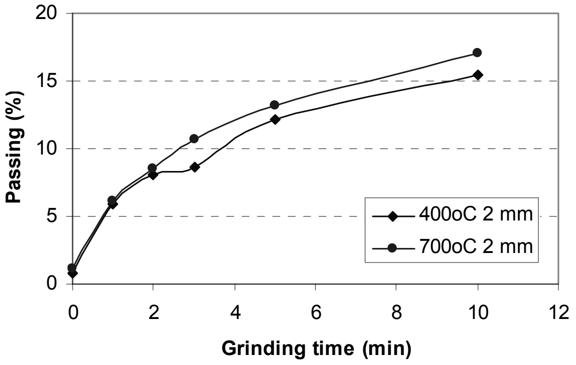


Fig. 3 - The amount of material passing through the 2 mm (a) and 4 mm (b) sieves after different times of grinding treatment in Los Angeles machine of RCA (fraction 4/8 mm) treated at 400^{o}C and 700^{o}C./*Trecerea pe sita de 2 mm (a) şi 4 mm (b) a RCA (fracția 4/8 mm) tratat termic la 400^{o}C şi 700^{o}C funcție de timpul de mărunțire în aparatul Los Angeles.*



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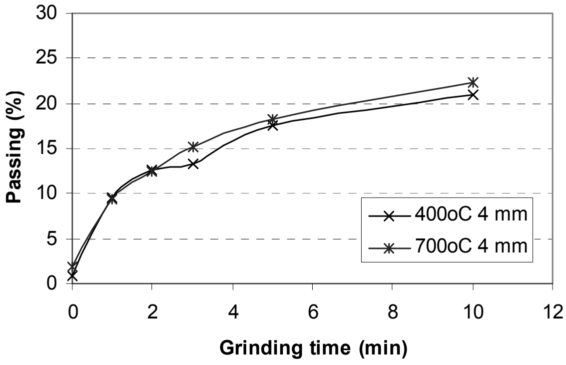

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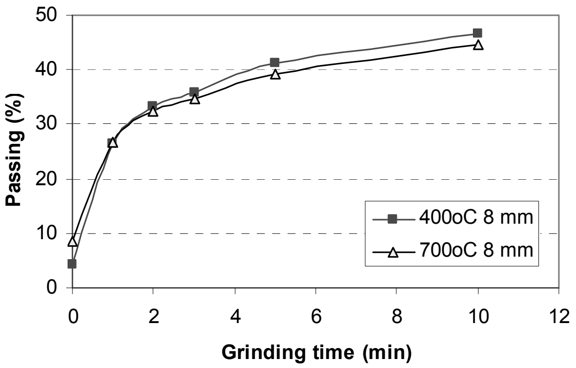
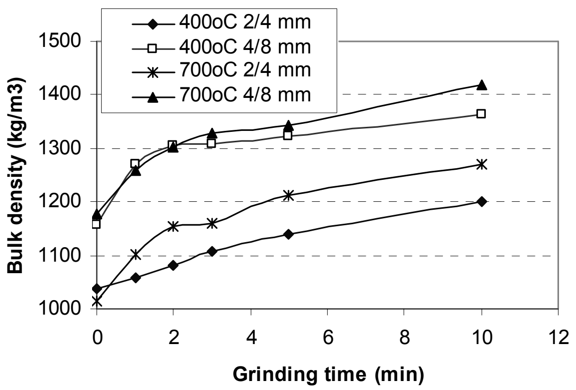


c

Fig. 4 - The amount of material passing through the 2 mm (a), 4 mm (b) and 8 mm (c) sieves after different times of grinding treatment in Los Angeles machine of RCA (fraction 8/16 mm) treated at 400°C and 700°C./*Trecerea pe sita de 2 mm (a) şi 8 mm (b) a RCA (fracția 8/16 mm) tratat termic la 400°C şi 700°C funcție de timpul de mărunțire în aparatul Los Angeles.*



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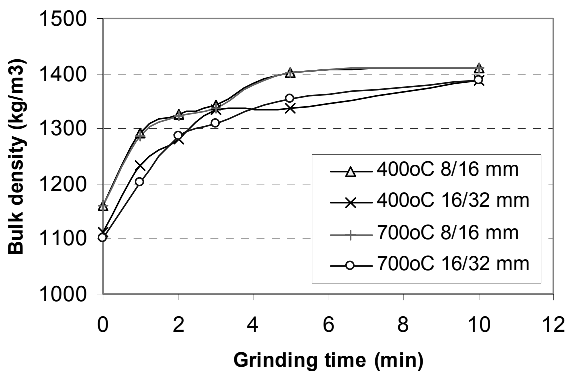

b

Fig. 5 - Bulk density of RCA thermally treated at 400°C and 700°C and grinded for different times: a) fractions 2/4 mm and 4/8 mm; b) fractions 8/16 mm and 16/32 mm./*Densitatea în vrac a RCA tratat termic la 400°C şi 700°C şi durate diferite de mărunțire: a) fracția 2/4 mm şi 4/8 mm; b) fracția 8/16 mm şi 16/32 mm.*

The data presented in Figures 2-4 show a significant increase of the amount of cement paste/mortar removed in the first 2-3 minutes by the autogenous grinding treatment in Los Angeles machine; the efficiency of this grinding process decreses for longer times.

It is interesting to notice the influence of thermal treatment temperature for the studied fractions. The total passing through 2 mm sieve is more important for the small aggregates (2/4 mm and 4/8 mm) because the superficial heated zone is bigger (as percent of their mass or volume); still, the amount of heated matrix (cement paste/mortar) with weakened mechanic resistance/adherence is significant lower for small grains than for the bigger aggregates. The temperature of thermal treatment is significantly more important for the 2/4 mm sort.

The bulk density of an aggregate sort can be a measure of the amount of matrix (cement paste/mortar) adhered to the natural aggregate; this matrix have lower values of the density (as compared with natural aggregate) therefore will determine a decrease of RCA bulk density. Gradual removal of this matrix lead to an increase in the RCA bulk density, as it can be seen in Figure 5. Important differences of the values of bulk density are achieved for the smaller sort (2/4 mm) when the thermal treatment temperature increases from 400°C to 700°C (Figure 5a). For bigger sorts (4/8 mm, 8/16 mm and 16/32 mm) these differences are less important due to the decrease of the percentage of volume of heated matrix, as previously explained.

The bulk densities of natural aggregate and RCA thermally treated and subjected to autogenous grinding for 10 minutes are presented in Figure 6.

It can be noticed that the thermally treated RCA (RCA-T) has low values of bulk density meaning a significant amount of cement paste/mortar is still adhered on natural aggregate grains; the mechanic treatment (RCA-TM) determines the reduction of cement paste/mortar amount especially for sorts with bigger grains (over 4 mm).

The mechanic treatment influence can be appreciated also considering the ratio between the apparent density of RCA grains and the apparent density of the natural aggregate, presented in Table 3.

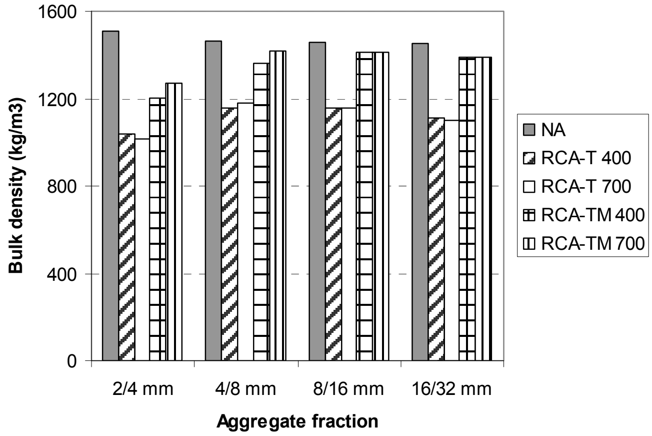

Fig.6 - Bulk density of natural aggregate (NA), RCA thermally treated at 400°C (RCA-T 400) and 700°C (RCA-T 700) and after 10 minutes of autogenous grinding (RCA-TM 400, RCA-TM 700)./ *Densitatea în vrac a agregatului natural (NA) şi RCA tratat termic la 400°C (RCA-T 400) şi 700°C (RCA-T 700) şi după 10 minute de mărunțire autogenă (RCA-TM 400, RCA-TM 700).*

Table 3

Ratio of apparent density of RCA thermally and mechanically treated and apparent density of natural aggregate/ *Raportul între densitatea aparentă a RCA tratat termomecanic şi densitatea aparentă a agregatului natural*

Fraction *Sort*	Apparent density ratio of RCA-TM 400°C/NA (%) *Raport densitate RCA-TM 400°C/NA (%)*	Apparent density ratio of RCA-TM 700°C/NA (%) *Raport densitate RCA-TM 700°C/NA (%)*
2/4 mm	97.3	97.8
4/8 mm	99.2	99.5
8/16 mm	99.0	99.4
16/32 mm	99.7	99.1

Table 4

Density and compressive strength of concretes prepared with natural aggregate (NA), recycled concrete aggregate (RCA) and RCA subjected to thermal treatment at 400°C and 700°C and mechanical treatment for 10 minutes/ *Densitatea şi rezistența mecanică a betoanelor preparate cu agregat natural (NA), agregat de beton concasat (RCA) şi RCA supus tratamentului termomecanic la 400°C şi 700°C timp de 10 minute*

Indicative	NA	RCA	RCA-TM 400	RCA-TM 700
Density / *Densitate/* (kg/m³)	2377	2317	2359	2366
Compressive strength / *Rezistența la compresiune* (N/mm²)	40.5	32.4	38.1	39.7

These values are in good corelation with those previosly presented i.e. the higher efficiency of the mechanic treatment was recorded for bigger RCA grains (4/8 mm, 8/16 mm and 16/32 mm).

The value of density of the concrete made with crushed aggregate (RCA) is slightly smaller as compared with the original concrete with natural aggregate (NA), which justifies to some extent the application of thermo-mechanical treatment (Table 4). The values of density of concrete prepared with thermo-mechanic treated RCA (RCA-TM) are close to those determined on original concrete (with NA), which shows the efficiency of the applied treatment.

An improvement of compressive strength values of the concrete prepared with RCA-TM as compared with the one prepared with RCA can be also noticed (Table 4). The compressive strength of the concrete prepared with RCA is about 20% smaller than the one of original concrete (with NA) and concrete prepared with RCA subjected to thermo-mechanical treatment (RCA -TM).

Nevertheless, it has to be mentioned that RCA used in this study was obtained by removing the crust of a class C20/25 concrete pieces, which usually do not happen in practice, where there is not a concrete provenience control.

4. Conclusions

The thermo-mechanic treatment of RCA, applied in this study, for the removal of cement paste/mortar adhered to natural aggregate grains, is a possible solution for the improvement of these aggregates quality.

Thermal treatment is more efficient for the smaller grains (fraction 2/4 mm), due to the larger volume of the superficial cement paste/mortar layer heated with respect to the aggregate grains volume. The heating of cement paste/mortar layer followed by rapid cooling increases the friability of this material and facilitate its removal.

The mechanic treatment has a more important effect on the bigger aggregate grains (fraction 4/8 mm, 8/16 mm and 16/32 mm) due to the higher amount of cement paste/mortar adhered on their surface. The applied mechanical treatment (autogenous grinding in Los Angeles machine) simulates the conditions specific for a rotary kiln.

It is to be expected that simultaneous thermal and mechanic treatments (in a rotary kiln) will give better results because of the continuous removal of the heated layer of cement paste/mortar from the surface of RCA grains. Also, the depth of heated layer of cement paste/mortar will be higher in a rotary kiln.

The thermo-mechanic treatment of RCA applied in this study improved considerably the quality of RCA grains; the values of apparent density of RCA grains increased after the treatment i.e. a higher amount of cement paste/mortar layer was removed. Also, the compressive strength values of new concretes prepared with thermo-mechanical treated RCA are higher (approximately 20%) as compared with those of the concrete with non-treated RCA.

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