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Improvement of recycled concrete aggregate properties by polymer treatments

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Abstract

The recycling of concrete, bricks and masonry rubble as concrete aggregates is an important way to contribute to a sustainable material flow. The limited reuse of recycled concrete aggregates (RCA), even partially, instead of natural aggregates, can be explained by the influence on the properties of fresh and hardened new RCA-based concretes. Experimental studies were carried out on the improvement of RCA performance, especially water absorption and fragmentation resistance. The use of polymer based treatments was applied and then the performance achieved was characterized in order to show the relevance of such polymer treatment. Beneficial effects of appropriated polymer based treatments applied on RCA were obtained especially lower water absorption and better fragmentation resistance.

Keywords: Recycled concrete aggregates; Water absorption; Water repellent polymers; Fragmentation resistance; Cement materials

1. Introduction

Decreasing natural resources of sand and gravel and increasing problems with waste management support the recycling of the accumulating waste materials. If the vision of a sustainable material flow is to be realized, the amount of recycled waste has to be increased. The building industry in particular is a major consumer of materials and at the same time a major producer of waste. One possibility is to recycle and reuse inorganic building waste as concrete aggregates. However, the composition of these aggregates can vary substantially and their properties have a significant influence on the properties of the concrete (Chen et al., 2003; Khalaf and DeVenny, 2005, 2004; Ryu, 2002; Hoffmann et al., 2012).

The reuse of RCA in concrete will contribute to valorize the construction wastes within the framework of the sustainable development. However, its application in construction field is still limited. Generally, the physical and mechanical properties of concrete made of recycled aggregates, were found to suffer compared to natural aggregate concrete (Chakradhara et al., 2011; Kou and Poon, 2011, 2009; Casuccio et al., 2008; Achtemichuk et al., 2009; Topçu and Sengel, 2004).

The physical properties of recycled aggregates depend on both adhered mortar quality and the amount of adhered mortar. The adhered mortar is a porous material; its porosity depends upon the w/c ratio of the recycled concrete employed (Etxeberria et al., 2007). The crushing procedure

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and the dimension of the recycled aggregate have an influence on the amount of adhered mortar (Nagataki, 2000; Hansen and Narud, 1983; Hansen, 1945; Sánchez de Juan and Alaejos Gutiérrez, 2009; Tam et al., 2007). The density and absorption capacity of recycled aggregates are affected by adhered mortar. The absorption capacity is one of the most significant properties which distinguishes recycled aggregate from raw/natural aggregates, and it can have an influence both on fresh and hardened concrete properties due to the presence of the porous cement mortar.

RCA properties were investigated by Sánchez de Juan and Alaejos Gutiérrez (2009) which showed the relationships between mortar content and absorption as well as mortar content and Los Angeles abrasion (LA). When attached mortar content is high, absorption increases too. The same trend is observed with regard to LA abrasion. The amount of mortar attached to fine fraction is higher to coarse fraction which showed the great heterogeneity of RCA. The main properties unfavorably affected by mortar content are absorption, density, LA and sulfate content.

The presence of RCA and the porous nature of the old cement mortar affect the bond between the RCA and cement paste when used in new concrete.

With regard to the mix design, one of the methods considered and available at present is to restrict substitution of recycled aggregates, to maintain employment of fine natural mineral additives used as partial replacement of cement and/or adding reducing agents to water (Kou and Poon, 2011; Tam et al., 2007). The poorer quality of RCA often limits its utilization.

In the literature, a number of RCA beneficiation treatments, available today, have been recently proposed to enhance the quality of RCA through reduction of the mortar present (25–70% decrease of mortar). In these treatments, one or a combination of mechanical (mechanical grinding process), thermal (microwave or conventional heating) and chemical treatments (pre-soaking or cycle soaking) are usually used to remove the attached mortar of RCA and reduce the loss of recycled aggregate properties at the present time (Sánchez de Juan and Alaejos Gutiérrez, 2009; Akbarnezhad et al., 2011; Tam Vivian et al., 2007).

In this same context, the investigation lead to the chemical treatment development which can improve the properties of RCA without removing the mortar based matrix.

The study, presented here, deals with the influence of different polymer based treatments on RCA (12–20 mm) already used in the protection of structures (grout, render...).

Polydiorganosiloxanes (also called PDMS) and alkylalkoxysilanes (also called silane) have become a very important class of materials used for water-repellent post-treatment of masonry or concrete (for example: Impregnation or sealer additive to protect structural concrete from deicing salt ingress and freeze–thaw damages) (Büttner and Raupach, 2008; Schueremans et al., 2008), additives in non load bearing concrete to control efflorescence or chloride penetration (Zhao et al., 2011), post-treatment or additives in Fiber reinforced cement boards (Lecomte et al., 2010), where durability and minimal impact on substrate appearance are important. This kind of treatment enables to decrease water absorption of porous construction materials (such as the post- treatment at the surface of the existing materials).

Since this kind of treatment is already applied on cementitious materials (both mortar and concrete), the application on crushed concrete as aggregate will be feasible in order to improve the mechanical and physical properties of aggregates.

This paper reports an experimental study to improve the properties of recycled concrete aggregates (RCA) by their impregnation with polymers. The effects of polymers applied on the water absorption, the microstructure and fragmentation resistance of the recycled aggregate concrete were evaluated.

The aim is to determine the best conditions for an efficient and sustainable polymer impregnation (PI) improving physical and mechanical RCA properties which should become closer to natural aggregates. In addition, the mode of treatment should be compatible with building yard practice.

2. Sample preparation

Natural and recycled aggregates were used as the coarse aggregate. Natural crushed aggregates are limestone type with density 2.7 g/cm^3. Recycled aggregates were crushed from ordinary concrete (OC) which was made to overcome the problem of heterogeneity due to the complexity of the mixtures of recycled aggregates. The water/cement ratio of ordinary concrete (OC) is 0.49 with cement type CPA-CEM I 52.5, the mixture proportions are reported in Table 1. Concrete specimens were prepared from a single batch. The concrete mixtures were cast in specific molds and compacted using a mechanical vibrator. After casting the specimens were stored in a room maintained at 20 °C and about 95% relative humidity (RH) for 24 h, and were cured in water at 20 °C for 90 days. The characteristics of conventional concrete are shown in Table 2. The open porosity was measured by water saturation. After 90 days of cure, the concrete was crushed in distinct granular fractions via French center. This choice allows easing the reproducibility of the tests and having “conventional

Table 1
The mix design composition of used conventional concrete.

Mix ingredients (kg/m^3)	OC
Coarse aggregate, 12–20 mm	777
Medium aggregate, 4–12 mm	415
Sand (Boulonnais), 0–5 mm	372
Sand (Seine), 0–4 mm	372
Cement CPA-CEM I 52.5	353
Total water	172
w/c	0.49

Table 2
Material properties of conventional concrete measured at 90 days.

Mechanical properties	28 days	90 days
Module of elasticity E (GPa)	22.2 ± 0.4	23.8 ± 0.5
Compressive strength f_c (MPa)	58.6 ± 2.6	70.2 ± 1.2
Open porosity measured by water saturation (%)	–	11

recycled aggregates" (CRA). Natural and recycled aggregates were graded selecting 12–20 mm fraction.

3. Set of polymer based treatments

Soluble sodium silicate which is a water soluble polymer was an industrial grade product and was used without further purification. Five commercial silicon based additives were screened. These different silicon based additives are emulsions composed of alkylalkoxysilanes (silane), polydiorganosiloxanes (siloxane) or both of them (see Fig. 1). These are silicon based polymers. These compounds are suitable water repellent polymers. These additives were supplied by Wacker chemicals and Dow Corning respectively.

Different polymer solutions were prepared with different concentrations (see Table 3). Then, RCA were soaked in these polymer solutions, which corresponds to polymer treatments. The polymer treatments were conducted under a controlled laboratory environment. The optimal concentration and combination of polymer based treatment required to improve the recycled aggregates were determined.

Polydimethylsiloxanes (illustrated in Fig. 1) are the most common siloxane used worldwide, both in terms of volume and application. Polydimethylsiloxanes are available as low or high viscosity fluids or elastomer depending on their degree of polymerization and crosslinking. Terminated by a silanol group (as in Fig. 1), they are reactive.

Low surface tension and better resistance to UV Radiation vs. organic polymer of polydimethylsiloxane are of great interest in the field of hydrophobic treatment. Silanes are molecules based on one silicon atom which bears four substituents. Alkyl trialkoxy silanes used in hydrophobic treatment (as illustrated in Fig. 1) bear an aliphatic chain (i.e. isobutyl or octyl chain) which confers the hydrophobic character to the treated substrate. Silanes with three alkoxy groups have good reactivity toward construction material (reactions during which alcohol is released as leaving groups). The "silane" present in emulsions chosen, contains

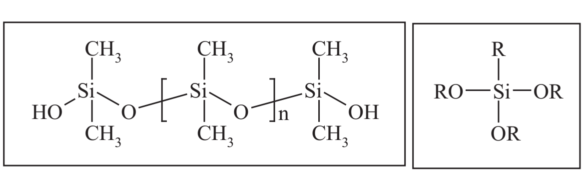


Figure 1. polydimethylsiloxane and alkyltrialkoxysilane.

three alkoxy groups. Moreover, the siloxane polymer particles are higher than silane. In fact, average diameter of silane is about 1–2 nm while that of siloxane is 5–10 nm.

The silicate gel or cross-linked polysiloxane is hydrophilic as it may still have sufficient hydroxyl groups which can attract water around the capillary wall surface and may not achieve any water repellent effect. However, it can deposit a continuous film. In addition, on the capillary wall surface, extra hydroxyl can enhance the bonding between the surface and the "siloxane". Further, sodium silicate could intensively catalyze the hydrolysis and the condensation of silane/siloxane to improve the formation of a hydrophobic thin film on the substrate wall surface. The enhancement of the water repellency of the substrate treated previously by silicate can be clearly shown. This implies that once the substrate capillary wall surface is coated with silicate, sufficient reaction between silicate and siloxane may be provided so that a satisfactory hydrophobic thin film can then be formed (Ren and Kagi, 1995; Ren, 1995).

4. Methodology of treatment process and water absorption evaluation

Before polymer aggregate treatment the water absorption test of natural and recycled aggregates was carried out according to NF EN 1097-6, this test consists of saturating the aggregates for 24 h followed by drying in ventilated oven at a temperature of 110 ± 5 °C. In the case of recycled aggregates the time of saturation is about 48 h since in previous study it has been demonstrated that longer time of saturation for recycled aggregates was obtained (>24 h) (Djerbi Tegguer, 2012). After drying process, the recycled concrete aggregate samples were treated with 2 types of impregnation process:

- Combination with a simple impregnation (also called simple combination): the aggregate samples were impregnated by each polymer solution from P1 to P6 for 5 min, then the samples were dried at room temperature maintained at 20 °C and about 50% relative humidity (RH) for 24 h, then in ventilated oven at a temperature of 50 ± 5 °C until the difference in mass during 24 h is less than 0.1%. There is no difference of mass variation between these drying steps.
- Combination with double impregnation (also called double combination) and heat treatment process: the aggregate samples were impregnated by P1 (which is soluble sodium silicate) for 3 min followed by drying for 20 h at room temperature maintained at 20 °C and 50% relative humidity (RH), then the samples were again impregnated in each polymer solution P2 to P6 for 5 min followed by drying during 24hrs in a room maintained at 20 °C and in ventilated oven at a temperature of 50 ± 5 °C until the difference in mass is less than 0.1%.

Table 3
Set of polymer based treatments.

Treatment acronyms	Names of product	Compositions	Concentration gradient	
			C_{min} (%)	C_{max} (%)
P1	Sodium silicate solution	Sodium silicate	7	30
P2	BS 2 Wacker siloxane/silane emulsion	Octyl/methyl methoxy co-oligomeric siloxane/silane	5	30
P3	IE 4 Dow Corning silane emulsion	Octyl triethoxy silane	5	40
P4	BS 3 Wacker siloxane/silane emulsion	Siloxane/propyl trimethoxy silane	5	50
P5	BS 4 Wacker siloxane/silane emulsion	Siloxane/propyl triethoxy silane	5	60
P6	BS 5 Wacker siloxane/silane emulsion	Siloxane/alkylalkoxysilane	5	40

After impregnation process, water absorption evaluation was carried out on aggregates treated for 48 h.

A plastic sieve was used for impregnation process in order to control the time of impregnation. The immersion depth is 5 cm and the ratio impregnated solution volume to aggregate sample volume is around 3. Three aggregate samples were tested for each impregnation process with each type of polymer solutions.

5. Los Angeles coefficient evaluation

NF EN 1097-2 method was used for the LA abrasion test. Test samples were over dried at 105 ± 5 °C for 24 h and then cooled to room temperature before they were tested. There are aggregate sizes grading to choose. The composition is 2/3 (in mass) from 12 to 16 mm fraction and 1/3 (in mass) from 16 to 20 mm fraction which represent 3250 g and 1750 g respectively to achieve 5000 ± 5 g.

12 steel balls were placed in a steel drum along with 5000 g mix of aggregate sample prepared previously (according to proportion). The drum was rotated 500 times at 32 ± 1 min^{-1}. Then, sample was sieved (through inferior to 1.6 mm). The residual sample is dried at 105 ± 5 °C 24 h. The final amount of material passing the sieved expressed as a percentage of the original weight was the Los Angeles loss (LA) or percentage loss.

6. Results and discussion

Water absorption measurements (EN NF 1097-6) and Abrasion resistance by Los Angeles mass loss test (EN NF 1097-2) were carried out on natural aggregate, conventional aggregate as well as conventional recycled aggregate treated in order to determine the effect of polymer treatments on recycled aggregate properties.

6.1. Comparison of water absorption between natural and recycled aggregate

Water absorption of natural and recycled aggregates was assessed in water by total immersion for 48 h. Capillary water absorption coefficients were measured before any treatment and listed in Table 3. Conventional recycled aggregate (RCA) absorbs much more water than natural aggregate and whatever granular fraction (up to 6 times higher than natural aggregates). This increase is mainly due to the presence of primary adhered mortar of recycled aggregate. The water saturation maxima of conventional aggregates were achieved for 24 h as described in EN 1097-1 while the water saturation maxima of recycled concrete aggregates were obtained after 48 h of immersion.

6.2. Effect of polymer treatment of RCA on the water absorption coefficient

Treatments with a simple or double combination of polymer solution (see section 4) were applied on different batches of RCA. A screening of polymer based treatment with concentration gradient was done and tested in order to show the impact on water absorption capacity on RCA treated. Initial water absorption (Abs (Ref)) corresponds to untreated aggregates. The final absorption of treated aggregates is noted (Abs). The ratios of Abs (Ref) per Abs were calculated for each combination of treatment. The objective of this study is to find the appropriate combination of treatment to be closer to water absorption coefficient of natural aggregates. The value is about 0.7%.

In the case of a simple polymer impregnation from P1 to P6 polymer solutions, the minimum concentration (C_{min}) or maximal (C_{max}) of polymer solution were prepared and applied on RCA.

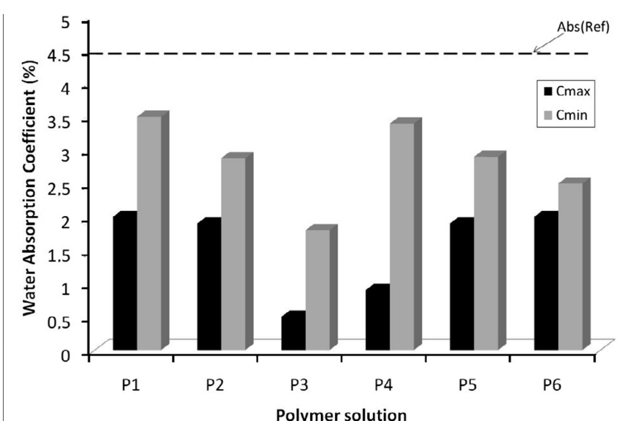
The water absorption of treated RCA was measured. The results obtained show the relevance of each treatment's type and for both polymer solution concentrations. Significant reductions were observed compared to untreated aggregates.

The use of polymer solution even with minimum concentration (C_{min}) allows reducing the water absorption capacity of RCA. The reduction noted depends on the type of polymer solution and concentration. The lowest value of water absorption coefficient is around 1.8% obtained by 5% of P3 (see Fig. 2a), instead of 4.5% which leads to a reduction ratio of 2.5 compared to the water absorption coefficient of untreated aggregates Abs (Ref) (see Fig. 2.b). In comparison with the reference (untreated RCA), the lowest reduction is obtained by 5% P1 with a reduction ratio about 1.3. This result can be explained by the type of polymer used. In fact, P1 is silicate sodium which is not water resistant polymer. This polymer fills only the RCA porous network without any hydrophobic effect.

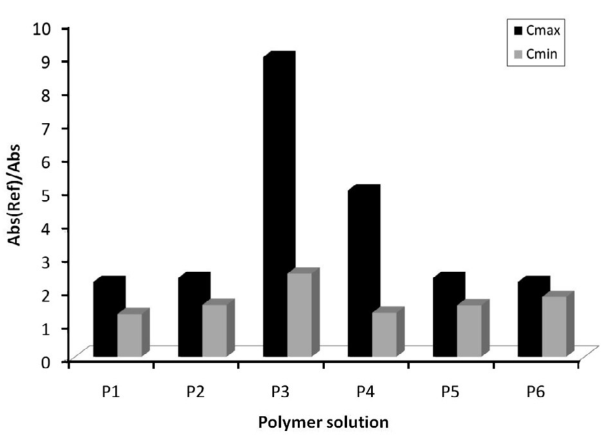
Higher concentration (also called maximal concentration (C_{max})) was applied from the selected polymers. The water absorption coefficients of treated RCA by polymer solutions (P1, P2, P5 and P6) were determined and achieved almost 2% while the water absorption coefficient value of treated RCA by polymer solutions (40% P3 or 40% P4) represents 0.5% and 0.9% respectively. These represent a reduction of water uptake which is between 2.3 and 9 times lower than the reference (untreated RCA). When 40% P3 or 40% P4 were applied on RCA, the water absorption of these treated RCA was measured. The results obtained show the relevance of each treatment's type and for both polymer solution concentrations.

Indeed, the water absorbed of RCA treated by 40% P3 or 40% P4 becomes very close to that of natural aggregates.

When these polymer solutions were applied on RCA, the polymeric particles from polymer solution are present enough to spread and diffuse into RCA's pore network. After that, polymerization occurred, polymeric film deposit is developed and transform into hydrophobic resinous which permit to decrease water uptake. Probably, the polymeric film achieved to turn up deeper in pore network with regard to this last case.



(a) Water absorption coefficient vs polymer solution



(b) Ratio of water absorption coefficient vs polymer solution

Figure 2. Effect of polymer solution treatments with simple impregnation on the water absorption coefficient of RCA.

To improve the efficiency of polymer treatment applied on RCA, Büttner and Raupach (2008), Schueremans et al. (2008), Zhao et al. (2011); Ren and Kagi (1995), Ren (1995) studies showed that the use of sodium silicate solution and siloxane based emulsion provides hydrophobic cementitious materials and reinforced. The coupled effect of sodium silicate solution (P1) and each siloxane (P2, P4, P5, P6) and/or silane (P3) based emulsion were investigated and will be discussed in the following paragraphs.

6.3. Impact of sodium silicate and siloxane-based emulsion treatment of RCA

Double impregnations were applied on RCA in order to improve RCA hydrophobic properties. Fig. 3 shows the effect of sodium silicate and siloxane based emulsion (P2, P4, P5, P6) with maximal concentration used previously on the water absorption of RCA (see section 6.2). Silicate sodium solution is fixed to 30% in concentration.

No additional positive change of the water absorption coefficient was obtained by combining (P1 and P5) or (P1 and P4). The obtained results show that the water absorption coefficient of the combination (30% P1 + 50% P4) is higher than the coefficient for simple impregnation of (50% P4).

The reduction achieved of water uptake is only due to simple P1 impregnation. The water absorption coefficient is equivalent to simple P1 impregnation. These types of combination are not efficient with P4 or P5. No compatible adhesion, between the successive polymeric films, happens.

The results showed that P1 has a good assembly with P2 and P6, the water absorption obtained is 0.7% and 1.1% respectively, while it was only 2% for simple impregnation. These combinations applied absorb less water which leads to a reduction ratio of 6.4 for the combination (30% P1 + 30% P2). With regard to the combination (30% P1 + 40% P6), the water uptake is decreased by a factor of 4 compared to the coefficient of untreated aggregates.

These results could be explained by physical and chemical interactions.

The first impregnation allows filling partially silicate sodium into pore and then the silicate film adheres on RCA pore network. After that, the 2nd impregnation provides siloxane based polymer particles which penetrate into RCA and then the particles are transformed to silanol. The silanol group reacts with the silicate group from P1 and forms organic-silicate chains.

Therefore, the formation of co-polymeric film obtained by the impregnation successively could explain the significant reduction of water uptake.

In light of the water absorption results obtained for the combination P1 and P2, concentration gradient was practiced and studied.

The following graph (see Fig. 4) shows the water absorption coefficient on recycled concrete aggregate treated versus the concentration of P2 and P1 treatments (Combination 1).

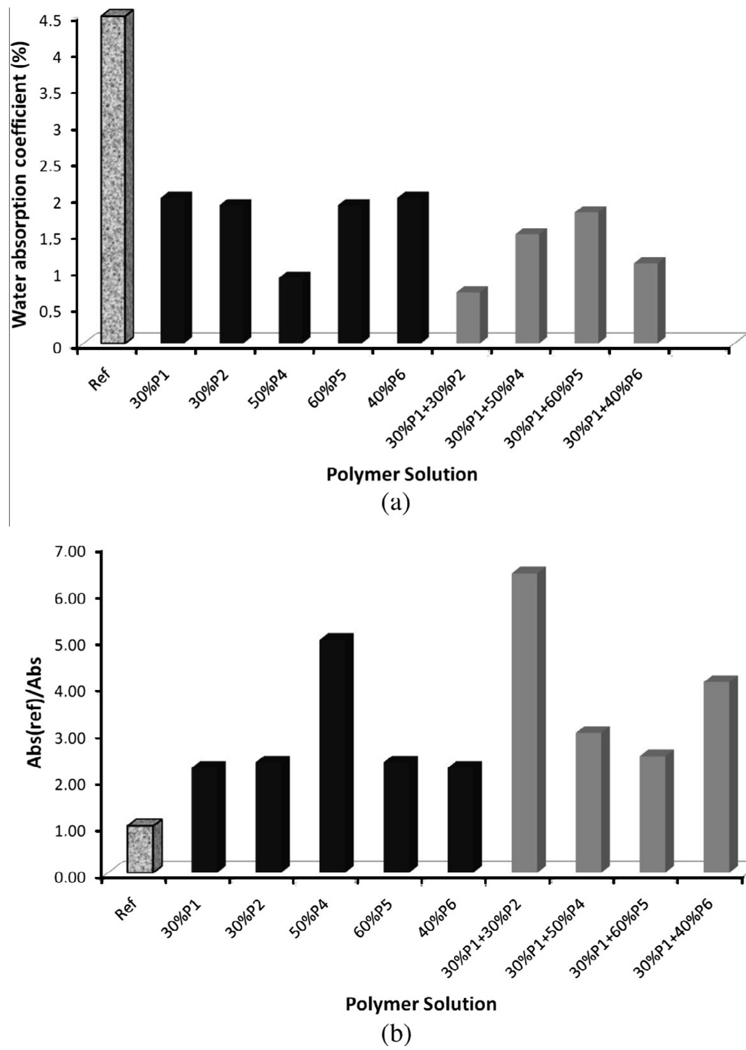


Figure 3. Effect of treatments with both impregantions on the water absorption coefficient of RCA.

Simple P1 impregnation enables to decrease the water uptake into pore network of RCA. Concentration gradient was practiced which are the following concentration values (7%, 15% and 30%).

The higher the concentration of P1 used, the more the water uptake is reduced. The same trend is noted for P2 concentration gradient (5%, 10% and 30%). The lowest value of the water absorption coefficient was obtained for 30% P2.

The water absorption coefficient of RCA, treated by double impregnation P1 (7%, 15%) and P2 (5, 10%), is inferior to simple impregnation of P1 (7%, 15%).

It can be observed that RCA treated with both impregnations by combination P1 and P2 allows reducing the water absorption coefficient of RCA, if the Cmax of P1 is used (i.e. 30% of P1). From this concentration (10% P2 in concentration) allows efficient combination which could decrease water uptake.

The coefficients of water absorption of RCA treated by P1 + P2 decrease with increasing the concentration of P2 (5%, 10% and 30%) which lead to 1.8%, 1.4% and 0.7% of water absorption respectively (Fig. 4a). The significant impact of P2 impregnation (only) can be observed up to 30% (in concentration). The ratio of initial absorption per final absorption is 6 times lower than the reference one (see Fig. 4b).

So this kind of treatment implies a significant reduction of water absorption capacity. The impact is reinforced by adding P1 treatment. These RCA treated (P1 + P2) absorb less compared with the initial water absorption of RCA untreated (reference) and represent less than 20% of water consumed for RCA untreated. As described previously (see Methodology in section 4), the RCA were first immersed in P1 solution. After dry step, the second immersion of P1-based treated RCA was done at different low P2-based concentrations. At these P2 concentrations, the combination does not work to form a new connection such as co-polymeric film. In fact, the first layer (polymeric film) formed by the first impregnation seems to be affected and even partially washed out of pore network. Normally, the first immersion allows to form an adherence layer to help fixing the second layer but the combination does not work. The

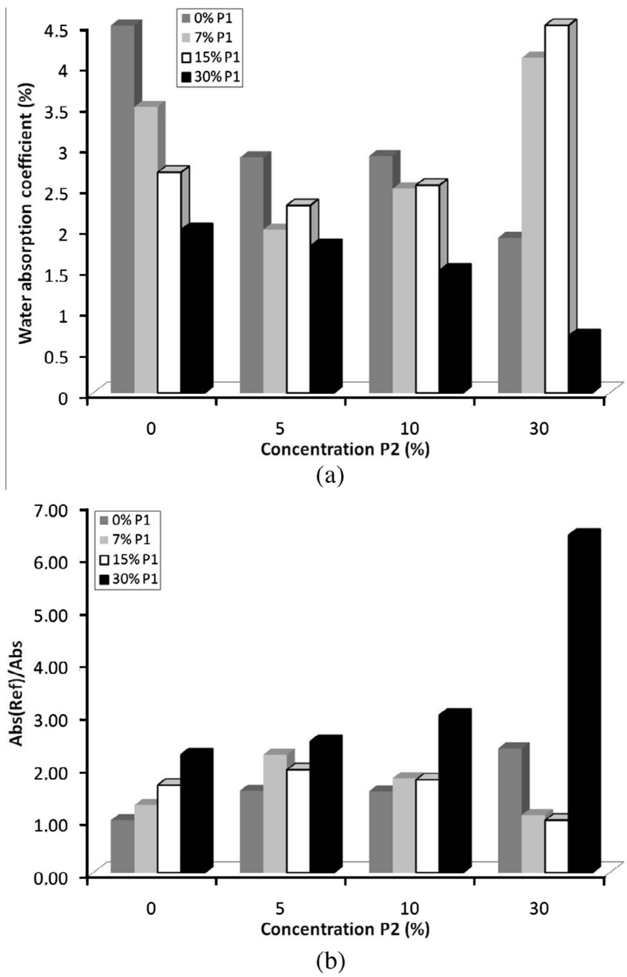


Figure 4. Water absorption coefficient of the treated recycled aggregates versus P1 and P2 concentration.

successive additions did not imply the sum of the two additions.

In order to clarify what happened, the results obtained are summed up below:

- 30% P2 = 30% P1 positive effect
- 30% P1 + 30% P2 > 30% P1 significant and positive effect
- 30% P1 + 15% P2 = negative effect
- 30% P1 + 7% P2 = very negative effect

At 30% whatever polymer solution type (P1 or P2), the polymeric film formed allows reducing the water uptake.

When double impregnations such as (30% P1 + 7% P2) were applied, very negative effect occurred because possibly the reactions involved did not allow the formation of stable co-polymeric film. The co-polymeric film generated is not strong enough and is unstable. Probably, this kind of thin film is formed but could not be fixed in pore network. It is lightly less negative when P2 concentration achieved 15%.

In addition, significant positive impact appeared for higher concentration (at 30%). In fact, the copolymerization may have occurred and the co-polymeric film formed could be more stable and stronger. Moreover, this co-polymeric seems to be resistant enough against the water uptake. The positive effect of this double combination (30% P1 + 30% P2) is higher than the sum of the simple P1 based impregnation or P2 based impregnation, respectively.

The addition of P2 solution at very low concentration (from 5% to 15%) seemed to destroy P1 based polymeric film partially.

6.4. Impact of sodium silicate and silane-based emulsion treatment RCA

Fig. 5 gives the water absorption coefficient in function of combination (P1 + P3). Polymer based treatment P3 (concentration screening) was applied on RCA. Results show clearly that RCA treated with a simple impregnation by silane-based emulsion (P3) are absorbing much less water than the reference (recycled aggregate without any treatment). The absorption coefficient of RCA decreases with increasing the concentration of P3. The coefficient is 1.84% for 5% P3, 1.47% is obtained for 15% P3 and 0.5% for 40% P3. The last value represents 90% less than RCA reference (see Fig. 4a). In spite of the second impregnation, the composition containing sodium silicate (P1) and silane emulsion (P3) has a negative effect against water penetration in their porous network compared to the compositions containing only silane agent (P3).

In order to clarify what happened, the results obtained are summed up below:

- 7% P1 + 5% P3 = 30% P3 < 7% P1: positive effect
- 30% P1 + 5% P3 < 30% P1: negative effect
- 15% P3 < 7% P1 + 15% P3: no effect
- 40% P3 < 7% P1 + 40% P3 < 30% P1 + 40% P3: very negative effect

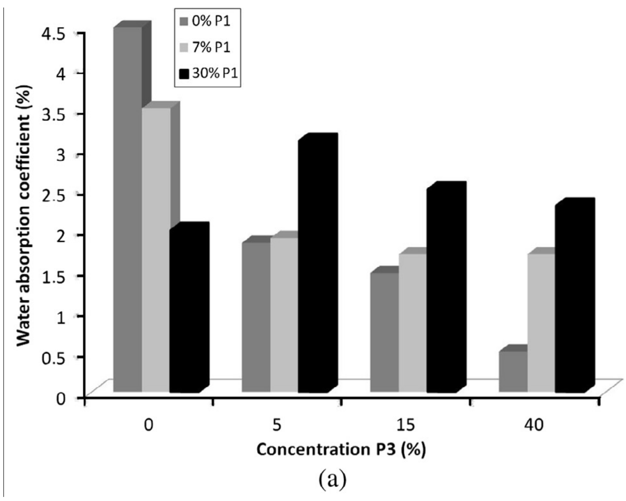
In fact, this combination appeared to be more dependent on P1 concentration (especially at 30% P1).

Higher P3 concentration is applied higher positive effect is noticed. Again, the reaction involved in pore network allowed the formation of polymeric film to be more stable and resistant enough when the P2 solution was applied. In fact, the copolymerization of (P1 + P2) might have not been occurred. So, no co-polymeric film seems to be formed. Possibly, the successive immersion enables only to superpose physically two thin polymeric layers which filled partially the pore network.

(P1 + P3) combination did not work very well. In this case, no additional impact of combining these 2 polymers based treatment (P1 + P3) compared with combination 1 (P1 + P2) (see Table 4).

The silane based emulsion (P3) applied on RCA diminishes 2.5–9 times water absorption coefficient than the reference (Fig. 5b).

Set of polymers are screening to find out an efficient chemical polymer based treatment in order to improve



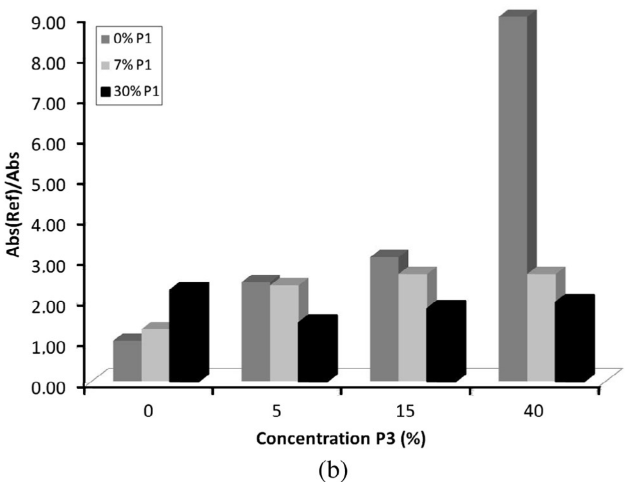


Figure 5. Water absorption coefficient of the treated recycled aggregates versus P1 and P3 concentration.

RCA properties. Impregnation of masonry with water repellent based emulsions particularly with siloxane and/or silane polymers appears to be the most successful method of protection from capillary water absorption. This kind of water repellent treatment already used as surface treatment for construction materials (Zhao et al., 2011; Lecomte et al., 2010; Ren and Kagi, 1995; Ren, 1995; Djerbi Tegguer, 2012; Spaeth et al., 2010).

A part of emulsion used was found to greatly improve the water repellent performance of the RCA. The high reactivity, the early water repellency, and the good film-forming properties of the siloxane enable the silane and/or siloxane emulsion to impart significant water repellency to various masonry substrates. In addition, the hydrolysis and condensation of siloxanes in the emulsion may not significantly affect performance and stability of the emulsion but may impart long term stabilization properties to the silane/siloxane emulsion.

Most of polymer treatments used here and applied by direct impregnation on recycled concrete aggregates allowed chemical deposit which formed polymeric protection film on surface against water uptake. After hydrolysis and condensation of siloxane, this can form a resinous or cross-linked network, embedded in the cementitious matrix (Zhao et al., 2011). This highly insoluble resinous network is modifying the tendency of the inorganic and highly hydrophilic cementitious matrix to be wetted by water, leading to a reduced absorption of water by capillarity within the interconnected pores system of the cementitious matrix (Lecomte et al, 2010).

Abrasion resistance have been implemented in particular by LA testing in order to determine whether the aggregates treated are consolidated.

6.5. Los Angeles coefficient of aggregate used

Los Angeles coefficients of natural, recycled aggregates untreated and treated were determined on 12–20 mm granular fraction and were listed in Table 5. Los Angeles coefficients were evaluated on treated RCA with two kinds of treatment; especially the P1 + P2 double combination and P3 simple combination.

The two combinations were chosen because of significant reduction of the water uptake.

The results of LA coefficient of RCA are superior to those of natural aggregates due to higher porosity of attached mortar (Table 5). There is a relationship between the LA coefficient and attached mortar for RCA. Tam Vivian et al. (2007) have shown that higher attached mortar content is, higher Los Angeles abrasion increases too. However, the treatment used in this study can improve the fragmentation resistance of RCA. With regards to the RCA treated, its LA coefficients are lower compared to untreated RCA. The lowest value was obtained for (P1 + P2) combination.

Moreover after Los Angeles test, RCA treated were sieved (#8 mm) and the amount of treated RCA with coarse fraction were determined. A Higher amount were observed (>8 mm) than that of untreated RCA. So, the granular fraction of the CRA treated batch used is higher than CRA untreated. In fact, there are still 60% and 49% of RCA treated by (P1 + P2) and P3 respectively instead of only 30% for untreated RCA (see Table 6). Indeed,

Table 4
Water absorption coefficients vs granular fraction.

Aggregates type 12–20 mm	Water absorption coefficient (%)
Natural aggregates Boulonnais	0.7 ± 0.1
Recycled concrete aggregates RCA	4.5 ± 0.2

Table 5
Los Angeles coefficients of natural aggregate, RCA and treated RCA.

Aggregates type	Los Angeles (LA) coefficients (%)
Natural aggregates	23–24
RCA	27 ± 2
RCA treated by (P1 + P2)	21 ± 1
RCA treated by P3	25 ± 2

Table 6
Granular fraction evaluation after Los Angeles test.

Aggregates type	Granular fraction (%)	
	<8 mm	>8 mm
RCA	70 ± 4	30 ± 6
RCA treated by (P1 + P2)	40 ± 2	60 ± 2
RCA treated by P3	51 ± 1	49 ± 2

the polymer treatment used enables reinforcing of RCA especially attached mortar. It appears a densified microstructure of mortar and subsequently both reduction of water absorption and improvement abrasion resistance.

LA measurements were carried out and show the impact of combination 1 on fragmentation resistance and especially on 12–20 mm granular fraction. In fact, 60% residues of RCA treated (after LA trials) are superior to 8 mm which is 2 times more than untreated RCA. The polymeric film, developed by combining two polymers based treatment (P1 + P2), should also provide an effect of consolidation on recycled concrete aggregates. In particular, this layer could change pore network especially the part of primary adhered mortar.

7. Conclusion

Different polymer treatments were tested. Concentration gradient and combination of polymer treatments were practiced and beneficial improvement were demonstrated.

From the results presented are in this paper it can be concluded:

- The polymeric film developed, by combination 1 (P1 + P2) as well as P3, supply water repellent performance by reducing significantly water absorption and reinforcing cement matrix of RCA. This means that recycled aggregates, especially adhered mortars, are protected against water penetration.
- These results show the positive effect induced by polymer treatments of water absorption capacity of RCA. In addition, the polymer treatments appear to be an appropriate treatment on RCA.
- The general trend is an improvement of the water absorption resistance. The first results are very encouraging and confirm the interest of this kind of appropriate treatment.
- These kinds of treatment emphasize the formation of polymeric film in pore network. This film allows the significant reduction of water absorption capacity.
- The film formed is efficient and resistant in alkali environment. Few amount of polymer-based treatment is necessary to achieve the water repellent performance. The polymer-based treatments are easy to prepare. This treatment should be tested on other recycled concrete aggregates and others granular fractions.

The chemical impregnation process will be presented in further article.

The study of abrasion resistance will be continued and deepened.

A study of physical and chemical interaction mechanism should be done. This kind of treatment of polymer based treatment could be very useful to the workability and water retention abilities in future mix design. In addition, the durability of polymer – impregnated based RCA (PI-RCA) and new concrete containing PI-RCA will be studied in order to show the relevance of the treatments.

The amelioration of both properties could improve the properties of Interfacial Transition Zone (ITZ), when RCA are incorporated in new RCA based concrete.

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