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# Mechanical and durability properties of concrete using contaminated recycled aggregates

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ABSTRACT

The degradation of concrete structures due to chlorides and sulphates penetration is of obvious importance in civil engineering as having major impact on structural durability. In this paper, the results of an investigation on the effect of contaminated crushed concrete aggregates on mechanical properties and durability of recycled concrete are presented. Natural aggregates concrete (NC) slabs were cured in water, sea water, chloride solutions or sulphate solutions and then crushed to obtain virgin and contaminated (polluted) recycled aggregates. The properties of natural (NA) and recycled aggregates (RA) and the mechanical properties and durability performances of a new concrete made from 100% of RA are analysed. The results show that contaminated RA are much sensitive to chlorides than sulphates and are rapidly leached when soaked into water. Significant differences were observed between the properties of original and new concrete and the results clearly show the necessity of taking these contaminations into account.



## 1. Introduction

The use of construction and demolition (C&D) waste as a source of aggregates for the production of a new concrete has become more common in the recent decade. From 3 billion tonnes of wastes of all kinds annually produced in the European Union, about 31% are coming from C&D area [1]; they are mainly composed of concrete, asphalt and masonry [2].

The reuse techniques for C&D wastes are now going out of laboratories and more and more used in industries as an alternative solution. Hendricks [3] stated that current production and use of RA resulting from concrete and bricks in Europe are close to 11% and 10%, respectively, and estimates that these quantities will increase up to 15% and 14% in 2015. Moreover, new standards and guidelines are now issued and applied in most western countries, due to severe environmental regulations and natural aggregates production increasing costs [4–6].

However, concrete that has to be recycled can be damaged or polluted in specific environments. In practice, RA can be contaminated (polluted) by various sources of aggressive ions like chlorides and sulphates from deicing salts, sewage plants or seawater. These contaminants may affect the properties of recycled concrete at fresh and/or hardened states and accelerate its own degradation process. Therefore, it is important to understand the effect of RA properties on the intrinsic characteristics of recycled concrete such as permeability and diffusivity. Many research studies are carried out on the use of RA in concrete in order to determine the properties of recycled aggregates concrete (RC); however, most of these studies are focused only on the mechanical properties and do not take into account the possible contamination of recycled aggregates [5,6].

That is the reason why a research program has been defined to study and analyse the influence of these types of aggression on the mechanical performances and the durability of concrete made with 100% of contaminated recycled aggregates. In this experimentation, the natural and recycled (virgin and contaminated) aggregates are physically, chemically and mechanically characterised. Compressive and flexural strengths as well as elasticity modulus are evaluated and compared at 28 days of age. Oxygen permeability, capillary absorption, porosity, freeze–thawing resistance and corrosion are measured and analysed.

## 2. Experimental work

### 2.1. Materials

An industrial Portland cement type CEM I 52.5 N from Belgium, with Blaine fineness of 385 $m^2/kg$, a density of 3130 $kg/m^3$ and an

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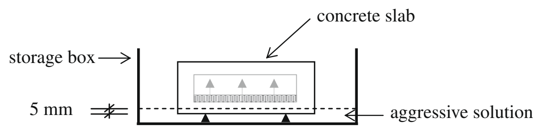


**Fig. 1.** Contamination of natural concrete slabs.

average compressive strength at 28 days of 64 MPa, was used for all concrete mixtures.

Four NA fractions (coarse natural aggregates (NG): 2/7 mm, 7/14 mm and 14/20 mm and fine natural aggregates (NS): 0/2 mm) of limestone's crushed rock are used for concrete mix design. Small (365 × 265 × 100 mm) natural concrete slabs (with 100% of coarse and fine NA) manufactured in laboratory, are semi-immerged into contaminated water solution and exposed to capillary absorption; three aggressive solutions (Chlorides: NaCl-5% (Cl), Sulphates: $MgSO_4{\cdot}7H_2O$-5% (Su), and sea water[1] (Sw)) have been prepared. After 1 year of ageing, slabs are crushed to produce virgin (VRA) or contaminated (CRA) recycled aggregates, respectively.

The mode of ageing (contamination) of concrete is by capillary absorption through immersion into solution containing aggressive agents that simulate the situation one can observe in structures and in road infrastructures (Fig. 1). The phenomenon is accelerated by regular reversal of the slabs (once per month). The mixing water used for the different mixes is tap drinking water, free of impurities with a pH equal to 7.9.

After using a jaw crusher for a primary crushing and another with percussion for a secondary crushing, three other fractions (coarse recycled aggregates (RG): 4/14 mm and 14/20 mm and fine recycled aggregates (RS): 0/4 mm) of RA are obtained and used for recycled concrete mix design.

### 2.2. Mix design

Based on the same granular skeleton and the same quantity of cement, five concrete types (Fig. 2) have been tested. The fine and coarse NA are used for producing reference NC. All the NA are replaced with VRA or CRA (RA-Cl, RA-Su or RA-Sw) to produce recycled concrete with virgin recycled aggregates (RC-VRA) or recycled concrete with contaminated recycled aggregates (RC-Cl: RC with RA contaminated by chlorides, RC-Su: RC with RA contaminated by sulphates and RC-Sw: RC with RA contaminated by sea water), respectively (Fig. 2).

The NC mix was based on the granular mix design developed by the Research Centre on Cement Industry (CRIC) in Belgium [5] and the RC mix was prepared according to Dreux mix design [7]. In order to limit the number of mixes and to be able to compare them on a common basis, a constant slump of 60–80 mm was imposed for the different mixes and the water content was consequently adapted. Coarse aggregates should not absorb any water because the mix design method used is based on Saturated Surface Dry coarse aggregates (SSD): they were hence soaked into water or contaminated solution (Cl, Su or Sw) for 24 h before use. Table 1 summarizes all the mixes used. The RC mixing procedure is summarized in Table 2 with a total mixing time of 5 min.

### 2.3. Tests procedures

Mechanical and physical properties of fresh and hardened concretes are determined according to local and European standards (Table 3). The chloride and sulphate ion concentration are evaluated respectively by the potentiometric titration and gravimetric methods according to Belgian standards NBN B 15-257, NBN B 61-201 and NBN B 15-256.

Before demoulding, the specimens are stored in laboratory conditions (25 ± 5 °C and 55 ± 5% RH) and covered with plastic film in order to avoid evaporation of water. After 24 h, they are demoulded and stored (28 days for strength and elastic modulus specimens and 8 months for the others) in climatic room (20 ± 2 °C and 95 ± 5% RH). Each test was carried out on three specimens.

The permeability test is performed with a constant head CEMBUREAU permeameter: an apparent coefficient of permeability ($K_{app}$) is measured and, according to Klinkenberg concept, the intrinsic coefficient of gas permeability ($K_{int}$) is calculated [5].

Water absorption test system is presented in Fig. 3. The lower side of the specimen is placed into water and periodically removed and weighed. Initial absorption (kg/m$^2$) is defined as a quantity of water absorbed after 1 h and sorptivity (kg/m$^2$ h$^{0.5}$) as the slope of the curve "quantity of water absorbed by a unit of surface versus square root of the elapsed time" from 1 to 24 h [5]. The porosity of concrete is evaluated on the base of total immersion test in water, with sample preparation under vacuum.

Corrosion sensitivity is analysed by means of a so-called electrochemical technique "half-cell potential". The test consists in taking various measurements of potentials between ordinary portable half-cell, made up of reference electrode copper-sulphate/copper ($Cu/CuSO_4$) placed on one longitudinal surface (preferably moulded) of the reinforced concrete beam, and the steel bar located inside concrete (Fig. 4). Sensitivity is evaluated through potential ($V$) values.

In order to evaluate the resistance to freezing, the specimens previously saturated into water are subjected to 14 freeze–thaw cycles (24 h cycle from −15° to +15 °C). The evaluation of the specimens after ageing is carried out on the base of visual inspection and loss of mass.

## 3. Results and discussion

### 3.1. Physical and mechanical characteristics of aggregates

Aggregates size distribution curves of NA and RA are presented in Fig. 5 and their physical and mechanical properties are summarized in Table 4.

The grain size distribution of coarse NA and RA is comparable but the recycled sand appears coarser than the natural one and consists mostly of coarse sand and a low proportion of medium sand (Fig. 5). However, the percentage of fines (<80 μm) is higher for NS than RS. RA present relatively lower bulk density and higher water absorption in comparison with NA. The higher water absorption of RA is due to the mortar gangue. The RA are less hard than the NA but values of Los-Angeles (35% on average) remain acceptable with regards to the allowable 40% limit usually required. The shape of RA is very irregular. Visual observations show that RA presents a rough cracked surface compared to a smoother surface for NA: this confirms the high porosity of RA [5]. The coefficient of cubicity is higher for NA than for RA.

### 3.2. Contaminated aggregate properties

After 1 year of storage in contact with aggressive solutions (chlorides, sulphates or sea water), the rate of contamination by chlorides (% Cl) and sulphates (% Su) of the concrete slabs is presented in Table 5. The results obtained confirm that the concrete is highly polluted. Initially the natural concrete (NC) presents a non-negligible level of chlorides and sulphates. The reason is probably the nature of natural aggregates (NA) and the presence of cement mortar. European standard EN 206:2001 [8] limits the

[1] Composition of 1 l of artificial sea water: 1000 g of distilled water, 30 g of NaCl, 6 g of $MgCl_2{\cdot}6H_2O$, 5 g of $MgSO_4{\cdot}7H_2O$, 1.5 g of Ca $SO_4{\cdot}2H_2O$ and 0.2 g of $KHCO_3$.

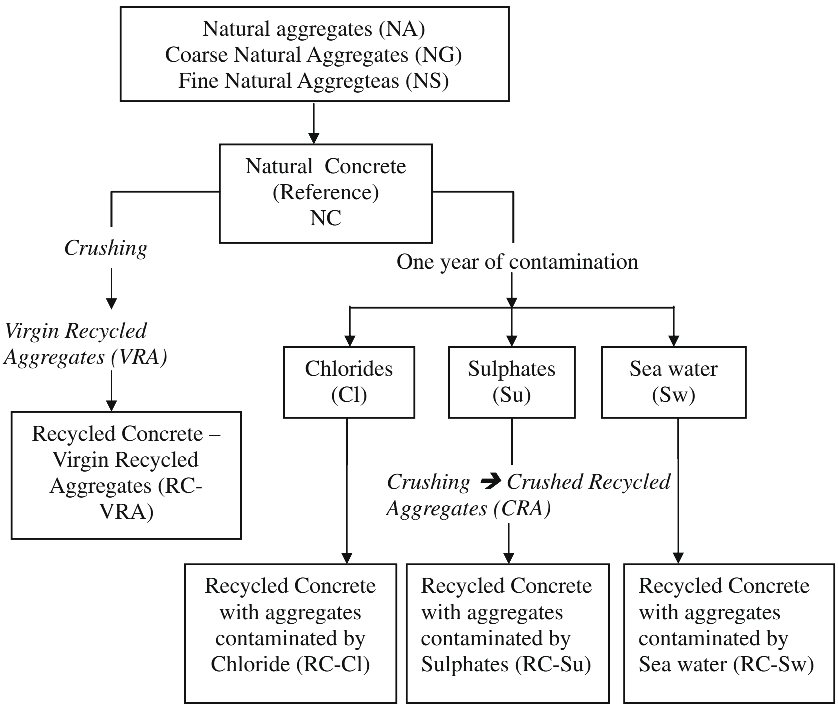


**Fig. 2.** Production of recycled aggregates (RA) and recycled concretes (RC).

**Table 1**
Mix proportion.

| | $W/C_{eff.}$ | Constituents (kg/$m^3$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Cement | NS | NG | | | RS | RG | |
| | | | | 2/7 | 7/14 | 14/20 | | 4/14 | 14/20 |
| NC | 0.63 | 300 | 696 | 213 | 676 | 349 | – | – | – |
| RC | 0.65 | 300 | – | – | – | – | 786 | 840 | 329 |

maximal content in chloride to 1%, 0.4% and 0.2%, respectively, in concrete, reinforced concrete and prestressed concrete. The Swiss recommendation (SIA 162/4) imposes the limits of 0.12% (mass of the primary concrete) for reinforced concrete and 0.03% for prestressed concrete [2].

Table 6 summarizes the chlorides and sulphates contents in NA, VRA and CRA. These values correspond to average measurements on two samples (approximately 200 g of aggregates by sample).

We can observe significant chlorides content in CRA, while the sulphates content is comparable to that measured on VRA. The chlorides and sulphates contents measured on fine aggregates are higher than those for coarse aggregates. This is probably due to the presence of large quantity of old mortar and fine cementitious particles in sand.

According to some standards, the maximal content in chloride in RA is limited to 0.06% [9,10]. French standard (NF P 18-541) [11] and RILEM recommendations and the specifications of European Committee for Standardization [12,3] limit the maximal content in sulphates (expressed by mass of $SO_3$) in RA, respectively, to 0.15% and 1%.

**Table 3**
Tests identification.

| Tests | Specimens ($mm^3$) | Standard |
|---|---|---|
| Slump | Abrams cone | EN 12350-2 |
| Compressive strength and elastic modulus | Cylinder (Ø160, h320) | NBN B 15-203 |
| Splitting tensile strength | Cylinder (Ø160, h320) | NBN B 15-218 |
| Oxygen permeability | Disk (Ø150, h50) | AFPC-AFREM |
| Capillary absorption | Core (Ø80, h100) | EN 13057 |
| Porosity | Prism (100 × 100 × 100) | AFPC-AFREM<br>NBN B 15-215<br>NBN B 24-213 |
| Freeze–thaw resistance | Prism (100 × 100 × 100) | NBN B 05-203 |
| Corrosion | Beam (140 × 100 × 600) | ASTM C 876-09 |

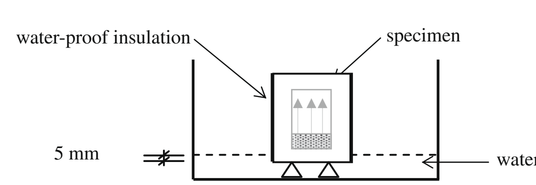


**Fig. 3.** Capillary water absorption.

Usually, RA resulting from structural concrete, road concrete, masonry and building wastes, contain a quantity of sulphates (0.3–0.8% by mass of $SO_3$) from which the greatest part is combined with and in hydrated microstructure of cement and does not produce any significant expansion of mortar or concrete [13].

**Table 2**
Mixing procedure for RC.

| Time | $t_0 - 4'$ | $t_0 - 2'$ | $t_0 - 1'$ | $t_0$ | $t_0 + 30''$ | $t_0 + 2'$ | $t_0 + 5'$ | $t_0 + 5'30''$ |
|---|---|---|---|---|---|---|---|---|
| Additions | RG + RS + ½W | | Cement | | ½W | | | |
| Mixing | Mixing | Rest | Mixing | Rest | Mixing | Rest | Mixing | Rest |

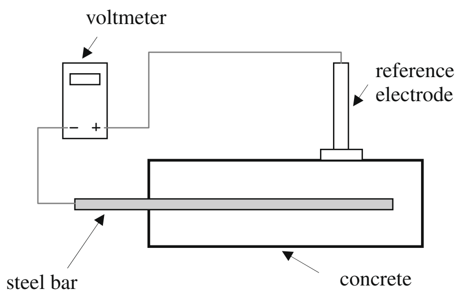


**Fig. 4.** Measurement of corrosion potential per half-cell.

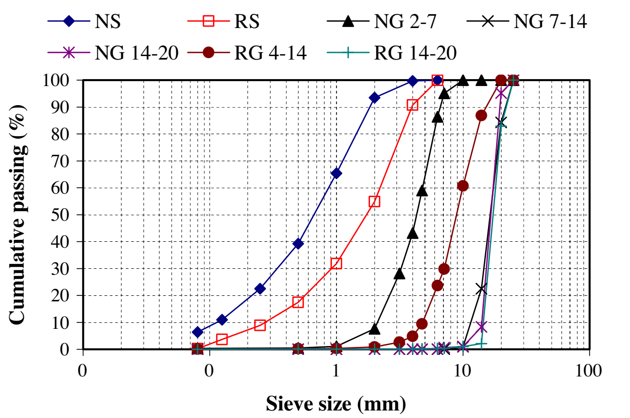


**Fig. 5.** Grading of natural and recycled aggregates (S = sand, G = coarse aggregates).

For chlorides, we had the confirmation that they were not linked or fixed to the hardened cement structure. This observation is of prime importance because the leakage of chloride ions means potential corrosion of reinforced concrete steel rebars due to ions diffusion. Indeed, after 15 days of total immersion into water, the coarse RA resulting from the contamination of concrete by chlorides, lose up to 96% of their chlorides (Fig. 6); the final content becomes comparable with that of NA. These chlorides are thus free chlorides and not bounded chlorides and hence can go out of concrete after an adequate leaching. It is consequently obvious that chloride content measurement is a property to be checked before using recycled aggregates. Moreover, after a good washing or a total immersion into water during at least 2 weeks, leaching of chloride can leave clean RA that can be used in concrete and even in reinforced or prestressed concrete without any risk of corrosion.

This leaching is observed if aggregates are stored into water. In order to keep contamination level into aggregates, it was decided to saturate RA before batching recycled concrete not in water but in the same solutions used for contamination. This also allowed us to have less dispersion in contamination level for each aggregate.

### 3.3. Concrete properties

#### 3.3.1. Fresh concrete

Densities are lower for RC (up to 7%) than for NC (reference). Moreover, for time of mixing exceeding 30 s, segregation is observed for RC. It may be due to the excess of water induced by soaking aggregates before mixing.

#### 3.3.2. Mechanical performances

Fig. 7 shows the variation of compressive strength (Rc), splitting tensile strength (Rt) and elasticity modulus ($E$). Mechanical properties of RC are lower (40% for Rc, 19% for Rt and 38% for $E$) than for reference (NC) concrete. These results are comparable to results of other researchers [9,14,15] who found about 24–35% of decrease in mechanical properties of recycled concrete with 100% of recycled aggregates. The contamination of the RA does not seem to have a significant effect on these properties up to 28 days of age.

#### 3.3.3. Physical characteristics of hardened concrete

*3.3.3.1. Oxygen permeability.* The results confirmed that RC is more permeable to oxygen than NC but, even if this permeability is close to double that of NC and remains constant for all RC, it is relatively low. This result is in agreement with that of Wainwright et al. [16]. Quebaud [17] found also on oxygen permeability for RC close to that of NC, but it doubles when the percentage of recycled fine

**Table 4**
Physical and mechanical properties of natural and recycled aggregates.

| Properties | NS | RS | NG | | | RG | | Norm |
|---|---|---|---|---|---|---|---|---|
| | 0–2 | 0–4 | 2–7 | 7–14 | 14–20 | 4–14 | 14–20 | |
| Specific weight (kg/m$^3$) | 2707 | 2309 | 2670 | 2691 | 2757 | 2329 | 2319 | NBN B 11-255 |
| Bulk density (kg/m$^3$) | 1510 | 1364 | 1326 | 1312 | 1319 | 1164 | 1022 | NBN B 11-255 |
| Water absorption (%) | 0.28 | 9.20 | 1.20 | 0.37 | 0.36 | 4.92 | 6.00 | NBN B 11-255 |
| Sand equivalent | 78.8 | 84 | – | – | – | – | – | NF P 18-598 |
| Fineness modulus | 2.72 | 3.33 | – | – | – | – | – | NF P 18-598 |
| Impurities (%) | – | – | 0.27 | 0.60 | 0.24 | 0.52 | 0.93 | NF P 18-598 |
| Los-Angeles (%) | – | – | 25 | 22 | 24 | 34 | 36 | NF P 18-573 |
| Cubicity (%) | – | – | 71 | | | 55 | | BS 812 :1 |
| Cement of old mortar (%) | – | 14 | – | – | – | 13 | 13 | NBN B 15-256 |

**Table 5**
Average content in chlorides and sulphates in concrete slabs after contamination.

| | 0 days virgin specimen | | 30 days | | 90 days | | 365 days | |
|---|---|---|---|---|---|---|---|---|
| | %[a] Cl | % Su | % Cl | % Su | % Cl | % Su | % Cl | % Su |
| NC | 0.104 | 4.472 | – | – | – | – | – | – |
| NC-Cl | – | – | 0.432 | – | 0.968 | – | 2.632 | – |
| NC-Su | – | – | – | 4.128 | – | 4.768 | – | 4.608 |
| NC-Sw | – | – | 0.208 | 4.856 | 1.240 | 4.512 | 3.640 | 5.504 |

[a] % Brought back at cement mass.

**Table 6**
Chlorides and sulphates content in the aggregates.

| | NS 0/2 RS 0/4 | | 2/7 mm | | 4/14 mm | | 7/14 mm | | 14/20 mm | |
|---|---|---|---|---|---|---|---|---|---|---|
| | % Cl | % Su | % Cl | % Su | % Cl | % Su | % Cl | % Su | % Cl | % Su |
| NA | 0.073 | 0.845 | 0.033 | 0.669 | – | – | 0.064 | 0.510 | 0.157 | 0.471 |
| VRA | 0.099 | 4.172 | – | – | 0.083 | 3.439 | – | – | 0.083 | 3.229 |
| CRA-Cl | 3.079 | – | – | – | 4.246 | – | – | – | 4.629 | – |
| CRA-Su | – | 5.814 | – | – | – | 4.365 | – | – | – | 4.321 |
| CRA-Sw | 1.105 | 5.691 | – | – | 2.234 | 3.274 | – | – | 3.256 | 4.405 |

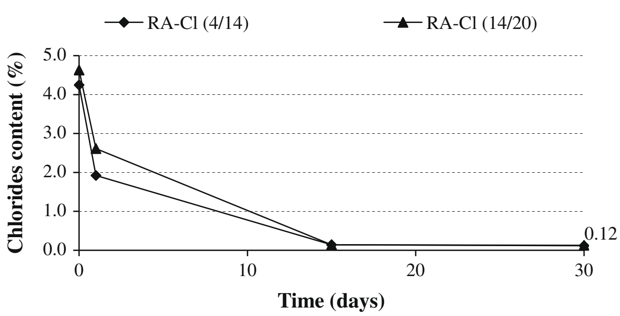


**Fig. 6.** Chlorides content in coarse RA soaked in water (leaching of coarse RA rich in chlorides).

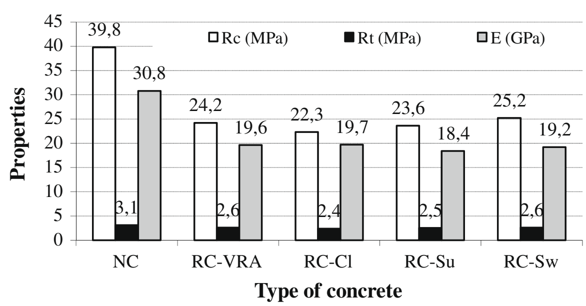


**Fig. 7.** Compressive strength, tensile strength and elasticity modulus of concrete.

aggregates exceeds 46%. This result allows us to conclude that, in our case, the increase in oxygen permeability for the RC is undoubtedly due to the high percentage (100%) of recycled sand. The type of contamination of the RA however does not apparently change the oxygen permeability values. Oxygen permeability of RC is more influenced by the porous texture of concrete, and specifically the cement paste, than by the chemical content of the recycled aggregates.

*3.3.3.2. Water absorption.* The experimental results of water absorption and initial absorption show that the process of water absorption is similar for RC and NC. However, RC presents a higher water absorption rate than NC: that is due to the high (100%) percentage of RA and, especially, the great capacity for water absorption of the recycled fine aggregates. The fine aggregates induce moreover a porous structure whose absorption capacities are significant. The initial absorption of the RC is 10 times higher than for NC. These results confirm the importance of early water absorption to evaluate the porosity of concrete surface and, even, of the RC.

*3.3.3.3. Porosity.* According to the porosity results, the RC is extremely porous (approximately two times) in comparison with the NC. This is probably due to the higher porosity of the RA and, specifically here with their high percentage of substitution (100%). Similar results were found by Katz [14]. The mode of ageing of the RA seems however not to have any significant effect on the porosity of the RC: all the RC presents a similar average porosity of 25%.

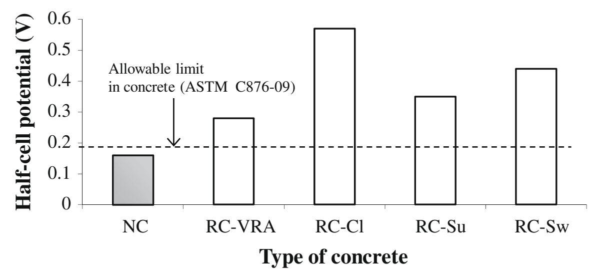


**Fig. 8.** Half-cell potential of recycled reinforced concrete beams.

*3.3.3.4. Sensitivity to corrosion.* It is generally admitted that chloride content, reported to the cement weight, between 0.3% and 0.5% and even below these values, can generate a risk of corrosion [18]. Fig. 8 shows measurements of half-cell potential on recycled reinforced concrete beams. The reinforced concrete with 100% of coarse and fine aggregates contaminated by chlorides (RC-Cl), sulphates (RC-Su) and sea water (RC-Sw), presented values of potential of 0.57, 0.35 and 0.44 V. Respectively with regard to the limits imposed by ASTM C 876-80 standards, the probability of corrosion of steel rebars in reinforced concrete with 100% of CRA by chlorides and/or sulphates is more than 90%.

*3.3.3.5. Freeze–thaw resistance.* After 14 freeze–thaw cycles, the visual specimen's examination did not allow to detect any significant deterioration for all the concretes. The correlation between the loss of mass and the water absorption showed that the loss of mass of RC does not exceed 1% in any case. These concretes thus have a very good resistance in winter severe climate, in spite of a higher porosity. This result was confirmed by Québaud et al. [19].

## 4. Conclusions

The following conclusions may be drawn from the present investigation:

1. The recycled aggregates are lighter, absorb more water and contain a significant quantity of old mortar.
2. The recycled aggregates contaminated by chlorides are leached if they are soaked into water. After a good washing or a total immersion into water during at least 2 weeks, leaching of chloride can leave clean recycled aggregates that can be used in concrete and even in reinforced or prestressed concrete without any risk of corrosion.
3. Mechanical performances seems not to be influenced by contamination up to 28 days of age.

4. Durability of the recycled aggregates concrete can be strongly affected by the porosity and the high water absorption of the recycled aggregates.
5. The type of contamination of recycled aggregates does not have a significant effect on porosity and permeability of the recycled aggregates concrete. The use of recycled aggregates induces however an increase of initial absorption and porosity, independently of the type of contamination.
6. In spite of a higher porosity, concrete containing only recycled aggregates has a good resistance to freeze–thaw cycles.
7. Contamination with chlorides has however a significant impact on concrete durability and, specifically, on reinforcement corrosion.

The use of contaminated aggregates consequently needs a specific approach in order to guarantee a sufficiently low value of chloride or sulphate ions concentration. The leaching into water can be a solution in order to avoid such situation: because these ions are not linked to cementitious microstructure, and hence easy to take out of concrete by means of a simple water leaching. But it remains that precautions and specific measurements are needed to be taken, especially with aggregates from hazardous or critical origin such as sewage water plants, road infrastructures or buildings under marine environments. Further research is needed with regards to sulphate contamination and possible secondary ettringite formation as this is could be a potential danger.

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