Performance Approach to Recycled Aggregate Incorporation in Design of Steam-cured SCC for Precast Use

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Abstract: Managing the waste resulting from precast concrete activities is a challenge for the industry. This paper addresses the problem by providing potential applications involving the use of recycled crushed concrete as aggregates. For precast applications, the main properties of the material should be high reactivity at an early age (1 day), optimal performance at 28 days, and enhanced long-term durability. This study presents a systematic comparison between the properties of a control self-compacting concrete (SCC-0%) blended only with natural aggregates (NA) and SCC blended with 10% recycled aggregate (RA) as a partial replacement for NA (SCC-10%). For steam-cured SCC for precast use, fresh state properties (slump and segregation resistance), mechanical compressive strength and durability indicators (water porosity, water absorption, permeability and carbonation) were measured. The results showed that replacing NA with RA at a rate of 10% by mass did not affect the properties of the material in the fresh and hardened states in comparison with the control concrete (SCC-0%). This result leads to solid environmental benefits: recycling concrete waste can induce a reduced use of landfill space and slows down the consumption of valuable natural resources.

Key words: Precast industry, recycled aggregates, performance-based approach, steam-cured SCC.

Nomenclature

\[ S = \text{Sorptivity (kg·m}^{-2}·\text{h}^{-1/2}) \]
\[ t = \text{Time (h)} \]
\[ \sigma = \text{Surface tension (N·m}^{-1}) \]
\[ r = \text{Average radius of capillary pores (m)} \]
\[ \theta = \text{Connecting angle (°)} \]
\[ \mu = \text{Water viscosity (Pa}·\text{s)} \]
\[ p_n = \text{Porosity (%)} \]
\[ \rho_0 = \text{Absorbed fluid density (water)} \]
\[ \text{Cte} = \text{Constant} = f(\sigma, \theta, \mu, \rho_0) \]
\[ k_a = \text{Apparent permeability (m}^2) \]
\[ \beta = \text{Klinkenberg coefficient} \]
\[ k_{int} = \text{Intrinsic permeability (m}^2) \]
\[ P_m = \text{Average pressure (P_t+P_{atm}/2) (N·m}^{-2}) \]
\[ C_{fp} = \text{Carbonation degradation depth (mm)} \]
\[ K = \text{Rate of carbonation (mm·d}^{-1/2}) \]
\[ t = \text{Time (d)} \]

1. Introduction

The precast industry is booming. Due to its many advantages, such as reduction of building time, product selection, enhanced quality with certified performance levels, cost optimization and so on, it currently represents 20% of concrete production worldwide. In the precast industry, the use of SCC is increasing and it is expected to replace vibrated concrete in many applications because of its various advantages, including the reduction of harmful effects of noise in urban environments, the possibility of pouring in congested reinforced areas or complex geometry, and a reduction in industrial process costs.
These benefits concern two key issues, both of which are crucial in Europe and particularly in France:

Constituents and concrete must comply with the specifications of standards EN 206-1 [1] and EN 13369 [2] which are based on a performance approach;

Concrete producers are becoming increasingly concerned with preserving natural resources and the environment.

This research programme is part of the development project of a precast company that manufactures pretensioned, prestressed beams for structural elements cast in horizontal moulds [3] (Figs. 1a and b) and cured in steam conditions in order to ensure production in one day.

The precast process is based on a specific SCC, the properties of which are clearly defined in its specifications:

In the fresh state, a low yield stress and adequate viscosity are required to achieve flow under gravity alone and with limited segregation;

In the hardened state, a minimum 1-day compressive strength value of 30 MPa is necessary to reduce the pre-tensioning time of the cable, and satisfactory strength is required at 28 days for concrete quality control (at least 60 MPa).

The specifications presented above are achieved through the following design rules:

Correct placing requires a high volume of paste (typically 330-400 l m$^{-3}$), a high fines content (about 500 kg m$^{-3}$), a continuous particle size distribution for the granular skeleton, a gravel/sand ratio of about 1 and a water/equivalent binder ratio by mass, W/B, between 0.35 and 0.45 [4];

Mechanical specifications are satisfied by means of a reactive high-strength cement (CEMI 52.5R), an optimized granular skeleton regarding packing and intrinsic strength, a water-reducing admixture, a limited W/B ratio and accelerated maturation [5].

Now, the design of concrete should evolve in the context of sustainable development, the essential features of which are preservation of the environment and conservation of rapidly diminishing natural resources. In addition, continuous industrial development poses serious problems of construction and demolition waste disposal [6]. Accordingly, on the one hand, there is a critical shortage of natural aggregates for new concrete production and, on the other hand, the enormous amounts of waste concrete resulting from the demolition of deteriorated and obsolete structures are creating severe ecological problems [7].

For practical purposes, recycled aggregates (RA) from concrete waste can be used as a substitute for natural aggregates (NA). For the time being, RA is mainly used in road construction [8-10], where the most common practice is a partial substitution of coarse NA by RA [8].

The incorporation of RA in concrete design for building structures is being studied [11]. The NA substitution by RA or the RA incorporation can adversely affect the flow properties in the fresh state.
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[12], the mechanical strength [13-15] and the durability of concrete [16, 17].

The more important parameters affecting the properties of concrete are the fine content of RA [18], the replacement level of RA [19, 20] and the water saturation rate of RA [12, 18, 21].

In the precast industry context, the incorporation of RA in concrete design is rather limited by the partial nonconformity of RA to the standards on concrete aggregates and the lack of available durability data [22, 23].

Accordingly, few studies on this issue are available in literature. This study, supported by the French precast company SEAC Gf, is a performance-based approach relative to steam-cured concrete. Here, the use of RA in SCC is considered. The objective of this paper is to assess the influence of RA incorporation on the properties of an SCC (including fresh state characteristics, mechanical strength and durability indicators) for prestressed beams, in comparison with the properties of the reference concrete mix currently employed in a precast plant using NA only. The variation in properties of concrete incorporating RA is then analyzed by the means of physical and chemical investigations.

2. Materials and Methods

2.1 Raw Materials

2.1.1 Binder Cement (C), Limestone Filler (LF) and Chemical Admixtures (SP)

To ensure everyday profitability, the precast industry generally uses CEM I 52.5R cement (EN 196-1) [24] for both its reactivity at early age (R) and its good strength at 28 days (52.5 MPa). The CEM I cement was composed of 95% clinker, 5% mineral admixture (limestone filler) and 5.6% gypsum, by weight. Its density was 3.14 g cm⁻³ and Blaine fineness was 4,015 cm² g⁻¹.

For SCC design, limestone filler (98.5% calcium carbonate) was employed. Its density was 2.71 g/cm³, its Blaine fineness was 4,800 cm² g⁻¹ and the activity index was 0.751 according to the EN 196-1 standard. A water-reducing admixture SP was an acrylic copolymer, of relative density 1.06 with 30% solid content by weight.

2.1.2 Granular Phase, Natural Aggregates (NS and NG) and Recycled Aggregates (RS and RG)

The granular skeleton was composed of natural sand (NS) and natural fine gravel (NG). The main characteristics of NS and NG are provided in Table 1 and their size distribution is given in Fig. 2.

The recycled aggregate RA was produced from the waste of precast concrete used by SEAC Gf in Vilette d’Anthon, France, a company that is committed to recycling (Fig. 3).

These concretes used for manufacturing beams, hollow core slabs and floor joists, are considered as good quality concrete (C50 to C70 according to standards EN 206-1, EN 13369). The waste is the excess concrete at the end of the formwork or comes from non-compliant elements. In the latter case, the crushing phase is carried out in such a way that components such as gypsum, plastic or heavy metal do.
not pollute the waste, ensuring good traceability of this co-product.

Two types of aggregate result from the crushing phase; recycled sand and recycled gravel. The main properties and grading curves of RA (RS and RG) are shown in Table 1 and Fig. 2, respectively. The results of preliminary testing determined the conformity of RA to the Standards for concrete aggregates [25-28] (Table 2).

2.2 Self-compacting Concrete Designs

SCC-0% is the reference SCC and SCC-10% is the concrete incorporating RA with a replacement rate of 10% by mass of granular phase (65% RS + 35% RG), see Table 3. This replacement rate was the maximum limit authorized by the previous version of the EN 206-1 Standard (2005) in the precast industry context.

Several comments can be made on the designs presented in Table 3.

Cement, limestone filler and superplasticizer contents were kept constant in both designs. They corresponded to an optimized binder (best performance) which was determined from experience in this factory.

A slight increase in the amount of water was needed due to the high water demand of RA (see absorption coefficients in Table 1). The superplasticizer SP was used to keep the consistency constant.

The proportions used in the concretes were based on the performance-based approach of the European Standard (EN 206-1) and specifications of the standard for precast concrete (EN 13369).

However, the current version (2012) of Standard EN 206-1 implies that RA is no longer considered as a normalized concrete raw material in the precast industry. Accordingly, SCC-10% design, developed before 2012, does not comply with the standard. Nevertheless, the following results obtained via a performance approach point out the interest of replacing natural aggregates with recycled ones in terms of fresh state behavior, mechanical and durability properties.

2.3 Mixing and Placing in Real Conditions

After development in laboratory, the mix was used in full-scale production trials at the plant. Mixing and placing conditions were consistent for both concretes.

### Table 1 Properties of natural and recycled aggregates.

<table>
<thead>
<tr>
<th></th>
<th>Natural Sand (NS)</th>
<th>Natural Gravel (NG)</th>
<th>Recycled Sand (RS)</th>
<th>Recycled Gravel (RG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrography</td>
<td>Hard calcareous</td>
<td>Hard calcareous</td>
<td>Crushed concrete</td>
<td>Crushed concrete</td>
</tr>
<tr>
<td>Density (kg m⁻³)</td>
<td>2650</td>
<td>2600</td>
<td>2400</td>
<td>2600</td>
</tr>
<tr>
<td>Absorption (%)</td>
<td>0.6</td>
<td>0.9</td>
<td>9.3</td>
<td>6.1</td>
</tr>
<tr>
<td>Flow time (s)</td>
<td>12 / 17 /</td>
<td>/</td>
<td>17</td>
<td>/</td>
</tr>
</tbody>
</table>

### Table 2 Conformity of recycled aggregates (RA) according to related standards.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Standard</th>
<th>Values</th>
<th>Conformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>NF EN 1097-2 [25]</td>
<td>37.5%</td>
<td>Ok</td>
</tr>
<tr>
<td>Prohibitive impurity</td>
<td>XP P18-545 [26]</td>
<td>0.023%</td>
<td>Ok</td>
</tr>
<tr>
<td>Total chloride content</td>
<td>EN 1744-1 (Art.8) [27]</td>
<td>0.009%</td>
<td>Ok</td>
</tr>
<tr>
<td>Total sulfur (S)</td>
<td>EN 1744-1 (Art.11) [27]</td>
<td>0.22%</td>
<td>Ok</td>
</tr>
<tr>
<td>Soluble sulfate (SO₃)</td>
<td>EN 1744-1 (Art.12) [27]</td>
<td>0.55%</td>
<td>Ok</td>
</tr>
<tr>
<td>Alkali reactivity</td>
<td>XP P18-594 [28]</td>
<td>0.27%</td>
<td>Ok</td>
</tr>
</tbody>
</table>

### Table 3 Designs of precast self-compacting concrete (kg/m³) incorporating RA or not.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Cement</th>
<th>Filler</th>
<th>NS</th>
<th>NG</th>
<th>RG</th>
<th>RS</th>
<th>SP</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC-0%</td>
<td>390.0</td>
<td>120.0</td>
<td>860.0</td>
<td>800.0</td>
<td>0.0</td>
<td>0.0</td>
<td>3.2</td>
<td>165.0</td>
</tr>
<tr>
<td>SCC-10%</td>
<td>390.0</td>
<td>120.0</td>
<td>775.0</td>
<td>725.0</td>
<td>60.0</td>
<td>110.0</td>
<td>3.2</td>
<td>170.0</td>
</tr>
</tbody>
</table>
For a given composition, a batch was prepared using a plant mixer with 1.5 m$^3$ maximum capacity. The mixing sequence began by granular phase introduction (NS, RS, NG and RG), followed by the introduction of the binder phase (cement, limestone filler) and, finally, the liquid phase (water, SP). The mixing time was 3.5 minutes. After placing in cylindrical moulds (Ø11 cm × H22 cm and Ø15 cm × H30 cm), the specimens were sealed with cling film.

### 2.4 Steam Curing, Maturation and Conservation

To achieve high performance at early age, the SCC was steam cured. This thermal treatment in the plant was made possible by a water network under horizontal formwork, equipped with a boiler. The cycle (pre-setting 30 °C for 2 h, constant increase of 12 °C h$^{-1}$, temperature stabilization at 57 °C for 6.5 h and 5-hour decrease in ambient atmosphere) was equivalent to one daily shift in the plant. Immediately after the thermal treatment, the samples were demoulded and immersed in water (20 °C ± 1 °C) up to the time of testing.

#### 2.5 Tests

The two steam cured concretes were compared at various stages, from the fresh state to the hardened state (Table 4). The corresponding European/French recommendations or the standards for material characterization tests [29-32] are also given in Table 4.

The characterization in the fresh state was carried out directly in the factory. The specimens subjected to the steam curing cycle were then transported to the laboratory so that the compressive strength and the durability indicators could be measured (Fig. 4).

### Table 4  Synopsis of the tests performed at the different stages.

<table>
<thead>
<tr>
<th>Fresh state</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump (cm)</td>
<td>EN 206-9 [29]</td>
</tr>
<tr>
<td>Sieve stability at $t_0$+15min</td>
<td>AFGC (2008) [30]</td>
</tr>
<tr>
<td><strong>Hardened state</strong></td>
<td></td>
</tr>
<tr>
<td>Compressive strength at 1, 7, 28 days (MPa)</td>
<td>EN 12350-2 [31]</td>
</tr>
<tr>
<td>Durability (tests starting from 35 days)</td>
<td></td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>AFPC-AFREM (1997) [32]</td>
</tr>
<tr>
<td>Water absorption by immersion (kg m$^{-2}$)</td>
<td>EN 13369 [2]</td>
</tr>
<tr>
<td>Absorption kinetics (kg.m$^{-2}$/√t)</td>
<td>AFPC-AFREM (1997) [32]</td>
</tr>
<tr>
<td>Oxygen permeability (m²)</td>
<td>AFPC-AFREM (1997) [32]</td>
</tr>
<tr>
<td>Accelerated carbonation test (mm)</td>
<td>AFPC-AFREM (1997) [32]</td>
</tr>
</tbody>
</table>

Fig. 4a  Carbonation resistance test.  
Fig. 4b  Cembureau permeameter.  
Fig. 4  Tests concerning durability indicators [32].
3. Results and discussion

3.1 Fresh State Characterization

The test results at the fresh state, obtained on SCC-0% and SCC-10%, are shown in Table 5.

It is clear from Table 5 that the slump flow diameter decreased slightly when RA was incorporated into the SCC. This result can obviously be attributed to the high water absorption capacity of RA, compared to that of NA. Even though more water was added into the concrete mix to compensate for the higher water absorption of the RA (Table 3), the decrease in the flow was really due to the initial hydric state of the RA. Here, they were incorporated in air-dried conditions during mixing, which is probably the worst condition for obtaining unchanged flow behavior. This experiment shows that a consistent method needs to be found for establishing a reliable relationship between the absorption coefficient of RA and a presaturated state before mixing. The small alteration of the flowability when SCC incorporated RA did not modify the resistance to static segregation, as shown by the results of the sieve stability tests. In both cases, the laitance percentage was significantly less than the limit criterion for SCC acceptance (15%) according to standard EN 206-9 [29] and AFGC-2008 [30].

3.2 Mechanical Performance

Compressive strength values according to the time of testing are shown in Fig. 5.

At all test ages, the RA concrete (SCC-10%) performance was lower than that of the reference concrete (SCC-0%). Nevertheless, except at 7 days of age, differences were not significant. Specific investigations on the paste-aggregate interface should be carried out in order to assess the structuring of the interfacial transition zone when RA is used. The nature and arrangement of hydration products close to RA may modify the paste-aggregate bond and the strength of the whole material. In any case, as shown in Fig. 5, these results are not alarming in this experimental context because the strength of SCC-10% is higher than the minimum strength value required at 1 day of age (strand release phase corresponding to the pretensioning of the beams) and at 28 days of age (quality control). In the precast context, it can be concluded that the 10% mass-for-mass replacement of NA by RA is really feasible and leads to sufficiently high strength at key times (1 and 28 days).

3.3 Durability Indicators

Diffusion, absorption and permeation are accepted to be the main physical processes promoting the transport of aggressive agents into concrete. The tests performed on these processes make it possible to characterize the durability of concrete by measuring the penetration potential of species.

3.3.1 Water Porosity

The water porosity results are presented in Table 6. Water porosity is slightly higher (+2% relative variation) for the SCC with RA (15.9%) than for the reference SCC (15.6%) on average, but differences are not significant. The small increase in the global pore

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Results at the fresh state.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spread (cm)</td>
<td>Sieve stability test (%)</td>
</tr>
<tr>
<td>SCC-0%</td>
<td>72.5 ± 2.0</td>
</tr>
<tr>
<td>SCC-10%</td>
<td>67.5 ± 2.0</td>
</tr>
<tr>
<td>Criterion [29] (65-75 cm)</td>
<td>&lt; 15%</td>
</tr>
</tbody>
</table>

Fig. 5 Compressive strength vs. time: SCC-0% and SCC-10%.

in Fig. 5, these results are not alarming in this experimental context because the strength of SCC-10% is higher than the minimum strength value required at 1 day of age (strand release phase corresponding to the pretensioning of the beams) and at 28 days of age (quality control). In the precast context, it can be concluded that the 10% mass-for-mass replacement of NA by RA is really feasible and leads to sufficiently high strength at key times (1 and 28 days).
volume of concrete is certainly related to the intrinsic higher open porosity for RA than for NA.

3.3.2 Water Absorption: Standard Value and Kinetics

Table 6 also presents the results of water absorption by total immersion obtained according to the procedures defined in the European Standard for precast concrete (EN 13369, 2004). The partial replacement of NA with RA does not induce a variation in the total water absorption value by immersion. In both cases, the specifications of the standard are satisfied (< 6%).

Furthermore, the sorptivity (S), relative to absorption kinetics, is calculated as the slope of the water capillary absorption versus the square root of time (Fig. 6).

The sorptivity was equivalent for SCC-0% and SCC-10% (0.46 and 0.48 kg m$^{-2}$/√h, respectively, in Table 6). Accordingly, the same kinetics of absorption was observed with NA or RA in SCC. Equivalence in the porous network can explain the similarity of water absorption properties and porosity for SCC-0% and SCC-10%.

The lack of variation in the porous network when RA is incorporated can be supported by the Washburn equations for impregnation dynamics (Eqs. 1 and 2) [33], which express the sorptivity S according to several parameters such as porosity $p_w$ and average pore radius $r$. The mean radius can be derived from Eq.1 and expressed in Eq. 2.

$$S \times \sqrt{t} = \frac{\sigma \times r \times \cos \theta \times t}{2 \times \mu} \times p_w \times \rho_0$$  \hspace{2cm} (1)

$$r = Cte \left( \frac{S}{p_w} \right)^2$$  \hspace{2cm} (2)

The mean radii ratio $r_{0\% \text{RA}} / r_{10\% \text{RA}}$ can be calculated from Eq. 2 and is equal to 0.954 indicating that the incorporation of RA slightly increases the mean pore size at 35 days of age. This is a non-significant difference according to the similar compressive strength values at 28 days of age (Fig. 5).

3.3.3 Oxygen Permeability

The results of the oxygen permeability test were obtained from four test pressures $P_i$ applied to dried material (5 cm × 11 cm cylindrical specimens). Although the draining of the porous network does not represent concrete in normal conditions of use, it

<table>
<thead>
<tr>
<th>Water porosity $p_w$ (%)</th>
<th>SCC-0%</th>
<th>SCC-10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water absorption Standard val. (%)</td>
<td>4.18 ± 0.17</td>
<td>4.12 ± 0.16</td>
</tr>
<tr>
<td>Abs24h (kg m$^{-2}$/h)</td>
<td>2.14 ± 0.13</td>
<td>2.22 ± 0.11</td>
</tr>
<tr>
<td>Sorptivity S (kg m$^{-2}$/√h)</td>
<td>0.46</td>
<td>0.48</td>
</tr>
<tr>
<td>Oxygen permeability Intrinsic permeability $k_{int}$ (10$^{-18}$ m$^2$)</td>
<td>7.88 ± 0.46</td>
<td>8.64 ± 2.11</td>
</tr>
<tr>
<td>Klinkemb erg coefficient $\beta$</td>
<td>4.37 ± 0.27</td>
<td>4.01 ± 0.61</td>
</tr>
<tr>
<td>Carbonation degradation Carbonation depth at 28 d of degradation (mm)</td>
<td>14.6 ± 1.0</td>
<td>14.0 ± 1.0</td>
</tr>
<tr>
<td>Rate of carbonation (mm.d$^{-1/2}$)</td>
<td>2.57</td>
<td>2.50</td>
</tr>
</tbody>
</table>
enables the interconnectivity of the pores to be evaluated.

Fig. 7 presents the evolution of the apparent oxygen permeability as a function of the inverse of the average pressure between the upstream and downstream faces of the dried sample.

According to Klinkemberg’s theory [34], other information concerning the porous path can be extracted from the oxygen permeability test. The Klinkemb inger coefficient (β in Eq. 3) and intrinsic permeability (k_{int} in Eq. 3) offer an indication of the non-viscous part of the flow (molecular flow) of a fluid inside the porous network, which is related to the fine participating porosity of concrete.

\[
k_a = k_{int} \times \left[ 1 + \frac{\beta}{P_m} \right] \tag{3}
\]

As shown in Table 6, intrinsic oxygen permeability values are similar for both SCCs, as are the β values, considering the experimental scatter but mostly the order of magnitude [35].

It is well-known that permeability is controlled by the percolation path resulting from the connectivity and the tortuosity of the porous network. However, based on the measurements, no indication can be given as to whether or not pore connectivity and tortuosity are unchanged. It is only possible to conclude that the incorporation of RA does not significantly modify the oxygen permeability.

3.3.4 Carbonation

Fig. 8 presents the carbonated depth as a function of the square root of time. The test was done under accelerated conditions of carbonation (50% CO₂ and 65%RH).

As shown on Fig. 8, after 28 days’ accelerated degradation, depths leached by carbonation were similar for both SCCs (14.63 mm for control and 14.00 mm for SCC-10%). In the experimental context, the carbonated depths remained small, i.e. less than 25 mm, which would be reached after 40 years in natural conditions [36].

Moreover, the rate of carbonation (K) was determined from Fick’s first law of diffusion of carbon dioxide into concrete (Eq. 4) [37].

\[
C_{fp} = K \times \sqrt{t} \tag{4}
\]

As shown in Table 6, the results for the kinetics of carbonation degradation were similar for SCC-0% (2.57 mm/√d) and SCC-10% (2.50 mm/√d). In this case, equivalent kinetics of carbonation for both SCCs is consistent with the results of water absorption and oxygen permeability (Table 6).

3.4 Understanding Study: Physical and Chemical Investigations

The slight variations of performances (mechanical and physical aspects) observed above can be explained by chemical (anhydrous phase supply) and physical (packing variation) considerations.
3.4.1 Anhydrous Phase Supply

The first hypothesis is based on the additional supply of anhydrous phases from recycled aggregates (fines and wrap of mortar surrounding gravels). It is well known that the degree of hydration of common concrete is between 80% and 90%; Cassagnabère et al. [5] found 87.4% for this kind of concrete in the context of the precast industry. When recycled aggregates are incorporated, anhydrous phases (silicate of calcium C₃S and especially C₂S slower to hydrate than C₃S) are supplied. XRD analysis (Fig. 9), carried out on a crushed sample (65% RS+35% RG) passing through a 100 μm sieve, shows, in addition to typical phases of sand and gravel (quartz, dolomite, calcite), the presence of Alite (C₃S) and Belite (C₂S). These anhydrous phases can be re-usable to product a more important amount of hydration products [38].

3.4.2 Packing Increase

Second assumption is based on a physical effect associated with a packing increase of the granular skeleton. This effect is discussed according to three aspects. Firstly, the amount of fine particles for the RA and especially for RS is significantly greater than the one for NS (+78 % in the grain size less than 100 μm). These additional fines contribute to reinforce the compactness of the mixture [39]. Secondly, recycled gravels are intrinsically less resistant than natural ones (LOS = 37.5% and MDE = 23.5% for RG, LOS = 28% and MDE = 18% for NG). Then, particles of RA will tend to split up more easily during the mixing phase. This fragmentation of the RA particles and the associated generation of fines will enhance also the compactness. The third aspect is linked to the stability with time of the filler effect because a part of these fine particles can present an interesting intrinsic resistance. Indeed, Fig. 10 presents results of thermal analysis obtained on recycled aggregates (crushed sample (65% RS+35% RG) passing through a 100μm sieve). The presence of calcium carbonate (from granular phase of the old concrete) and C-S-H (resistant hydrates from the matrix of the old concrete) are observed. Incorporation of C-S-H phases into the new concrete can even develop sites of homogeneous germination [40, 41] that further promote the densification of the matrix. On the other hand, the absence of Portlandite is positive regarding some pathology aspects such as carbonation and chloride penetration.

4. Conclusion

The partial replacement of natural aggregate NA (natural sand NS and natural gravel NG) by recycled aggregate RA (recycled sand RS and recycled aggregate RA) produced from precast concrete wastes at a substitution rate of 10% by mass was studied in steam-cured self-compacting concrete SCC. With the
The aim of assessing the effects of such replacement on properties in the fresh and hardened states, a reference concrete containing no RA was made. The following results could be noted. The basic properties in the fresh state, such as slump flow and segregation resistance, were not significantly changed. A slight but not significant decrease in compressive strength was observed at 1 day and 28 days of age. However, it is important to note that specifications at 1 day of age (30 MPa for pre-stressed application) and 28 days of age (60 MPa for quality control) were still satisfied. Durability indicators such as water porosity, water absorption, oxygen permeability, and carbonation degradation were also unchanged. Hence, it appears that the replacement of a part of NA with RA does not significantly affect the properties studied.

In order to explain the above observations, two assumptions have been presented: The first hypothesis is based on the supply of the anhydrous phase (silicate of calcium C₃S and especially C₂S slower to hydrate than C₃S) coming from the incorporation of the recycled aggregates (fines and wrap of mortar surrounding gravels), that can be reused to produce a more important quantity of hydration products. The second concerns a physical effect related to a packing increase of the granular skeleton, which enhances not only the mechanical resistance but also the durability of the structure.

Although RA is not currently considered as a normalized aggregate by the European Standard (EN 206-1), the performance levels of SCC incorporating up to 10% RA are similar to or better than those of the concrete containing only NA. The results obtained in this performance-based approach should encourage the standard committees to consider this type of aggregates again.

Furthermore, the incorporation of RA can provide a new generation of concretes that have a lower environmental impact and can be used right now in the precast industry. The results presented in this study are promising for precast concrete manufacturers who are concerned about preserving the environment and sustainable development.

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