# Chapter 2
# Concrete with Recycled Aggregates: Experimental Investigations

**Carmine Lima, Marco Pepe, Ciro Faella and Enzo Martinelli**

**Abstract** The mechanical behaviour of Recycled Aggregate Concrete (RAC) is investigated by reporting the main results of experimental tests intended at understanding the influence of Recycled Concrete Aggregates (RCAs) on the resulting mechanical properties of concrete. The focus is placed on the higher porosity of RCAs and their higher water absorption capacity. Consequently, the role of the initial moisture conditions of RCAs at mixing is also unveiled and its consequences on both the hydration reaction and the time evolution of compressive strength are highlighted. The influence of processing procedures intended at reducing the aforementioned porosity is also discussed.

The experimental activities carried out on Recycled Aggregate Concretes have been aimed at understanding the role played by recycled aggregates in affecting the relevant properties of structural concrete. Specifically, several experimental campaigns have been performed with the scope of investigating the influence on the concrete performance of the following parameters:

- Processing procedures for RCAs;
- Initial moisture condition of coarse aggregates;
- Aggregate replacement ratio;
- Nominal water-to-cement ratio.

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## 2.1 The Influence of Processing Procedures for RCAs in RAC

The first experimental campaign described in this chapter has been mainly aimed at investigating the influence of processing procedures on the physical and mechanical performance of the resulting recycled aggregate concrete.

### *2.1.1 Materials and Methods*

All the mixtures have been produced by using “high initial strength Portland cement”, indicated as CP V ARI RS, according to the National Brazilian Standard NBR 5733:1991, characterised by a specific mass of 3100 kg/m$^3$. The grain size distribution of the Portland cement have shown that 95% of its particles are smaller than 50 μm, and 50% of the particles are smaller than 15 μm. Moreover, the polycarboxilate superplasticizer Glenium 51 was used for workability control, which is characterised by a specific mass of 1.07 kg/l and a solid concentration content of 30% (www.basf-cc.com.br).

Both natural and recycled aggregates were employed in this experimental campaign and, for natural aggregates, common crushed limestone were classified in three size classes according to the Brazilian standard (NBR 7211 2009). Meanwhile, the recycled concrete aggregates were obtained after the demolition of the hospital Clementino Fraga Filho in Rio de Janeiro (BR). The recycled aggregates were selected and analysed by the university laboratory for construction materials LABEST (PEC/COPPE—UFRJ Rio de Janeiro), and were processed as described by Pepe et al. (2014). More specifically, both NCA and RCA were

**Table 2.1** Influence of processing procedures for RCAs in RCA, natural and recycled aggregates

| Class size | Natural | | Recycled | | Recycled—CL | |
|---|---|---|---|---|---|---|
| | A (%) | γ (kg/m$^3$) | A (%) | γ (kg/m$^3$) | A (%) | γ (kg/m$^3$) |
| Sand (d < 4.75 mm) | 1.40 | 2668 | – | – | – | – |
| C1 (4.75 mm < d < 9.5 mm) | 3.39 | 2547 | 11.94 | 1946 | 5.56 | 2261 |
| C2 (9.5 mm < d < 19 mm) | 1.28 | 2634 | 4.94 | 2268 | 4.09 | 2328 |

**Table 2.2** Mixture compositions

| Mix | CEM | w | ads.w | SP | w/c | Natural | | | Recycled | | Recycled - CL | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Sand | C1 | C2 | C1 | C2 | C1 | C2 |
| | (kg/m$^3$) | | | | | (kg/m$^3$) | | | | | | |
| REF | 300 | 160 | 31.4 | 4.02 | 0.53 | 952.6 | 439.9 | 470.2 | – | – | – | – |
| RAC | | | 71.8 | | | 950.4 | – | – | 346.6 | 404.0 | – | – |
| RAC CL | | | 49.9 | | | 951.3 | – | – | – | – | 403.1 | 415.1 |

employed with the aim to analyse the effect of processing procedures on the mechanical properties of the resulting recycled aggregate concrete (Table 2.1).

Based on the results obtained so far, crushed concrete debris were processed to recycled aggregates, and three different mixtures were designed to analyse the different behaviour of concrete made with original (uncleaned) and cleaned recycled aggregates. Table 2.2 report the mix compositions of the produced concretes.

Specifically, a reference mixture, indicated as REF, was prepared with all natural components. Moreover, two additional mixtures, referred to as RAC and RAC CL, were designed with 50% (by volume) of the natural aggregates were replaced with recycled ones, with and without 15 min of autogenous cleaning, respectively (Pepe et al. 2014).

All batches were produced with 300 kg/m$^3$ cement and a w/c ratio of 0.53. To compensate the water absorption of both dry recycled and natural aggregates, additional water was poured during mixing while taking into account the water absorption tests (Table 2.1).

A slump test was performed and concrete was cast (in three steps on a vibrating table for expelling the entrapped air) in steel cylinders. After one day, specimens were demoulded and the concrete was placed in a water curing room (21 °C) up to the designated times for testing the compressive strength, elastic modulus and tensile splitting strength.

### *2.1.2 Results and Analysis*

This subsection reports a summary of the experimental results obtained from RAC samples produced as described in the previous subsection. As mentioned, three different mixtures were designed for analysing the effect of alternative processing procedure for RCAs on the mechanical properties of concretes made with them.

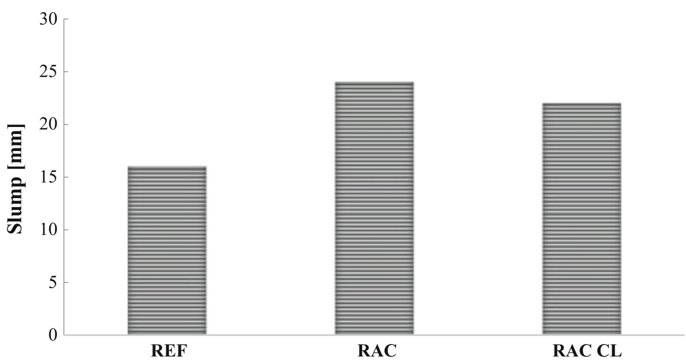



**Fig. 2.1** Slump test results

The fresh concrete properties were investigated through slump tests (EN 12350-2:2009). Results are reported in Fig. 2.1 and clearly highlight the effect autogenous cleaning has on the mix performance in the fresh state.

First of all, it is worth mentioning that a higher slump value was observed for mixtures with uncleaned recycled aggregates (RAC) with respect to the corresponding reference mix (REF). This largely depends on the fact that the same amount of superplasticizer was added for all mixtures, whereas the absorption compensation water was added on the bases of water absorption tests carried out on aggregates after 24 h of absorption time. In fact, recycled aggregates within the concrete mix cannot absorb such an amount of water in a short period time, which is equal to the mixing time. Since the mixing process only takes 10–15 min, which is much less than the absorption time used in the absorption tests (24 h), the remaining part of the water just modifies (increases) the water content in the mix (and the w/c ratio), leading to an increase in workability (and a decrease in compressive strength). Thus, such a higher amount of total mixing water available in the RAC mix, led to slump values significantly higher than those corresponding to the reference mix. Further investigations are needed to better understand the role of added water in RACs and, possibly, to achieve a sound definition of such a key parameter. The same effect is observed for the mix with cleaned aggregates (RAC CL), whose lower water absorption capacity required a lower amount of added compensation water and, led to lower slump values.

The effectiveness of autogenous cleaning of RCAs was also evaluated by conducting several tests intended at determining compressive strength, elastic modulus and tensile splitting strength. The compressive strength of the three mixtures was determined at an age of 2, 7, 14, 28 and 60 days (five tests for each curing age per

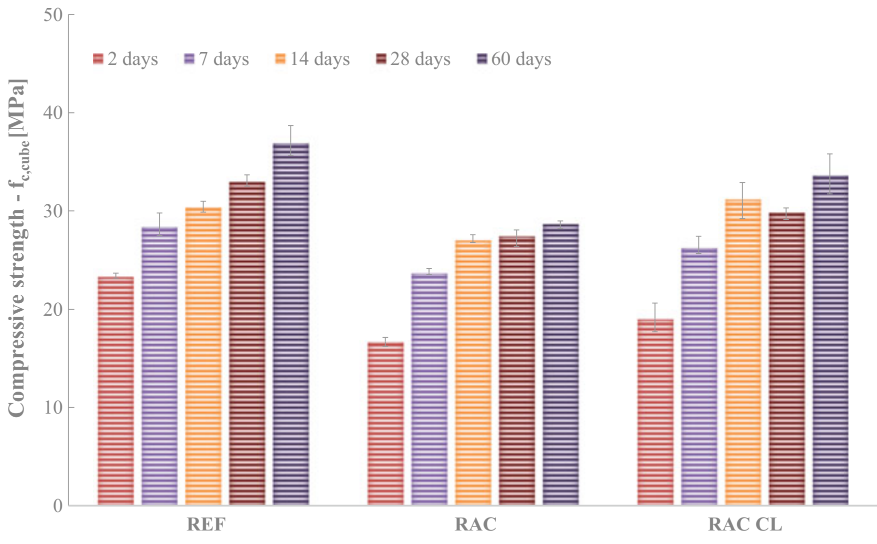



**Fig. 2.2** Compressive strength results

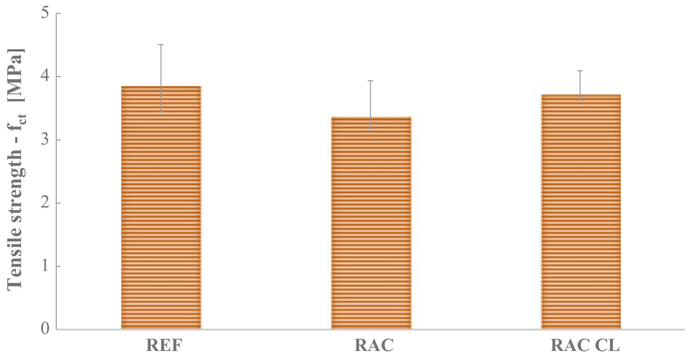



**Fig. 2.3** Tensile strength

mixture) according to the NBR 5739 (2007) on cylindrical specimens with a nominal diameter of 100 mm and a height of 200 mm.

Figure 2.2 provides the results of the compressive strength evolution. Samples of the REF mix show an average 28-day compressive strength of 33 MPa and, because of ongoing hydration, a compressive strength of 37 MPa was reached after 60 days of curing. As can be observed from the results presented in Fig. 2.2, the compressive strength of RAC concrete was reduced by about 20%. This is mainly due to a higher amount of water added for compensating absorption that increased the effective value of the w/c ratio. This effect and the change in the affective amount of free water was already observed when discussing the workability effects. However, the beneficial effect of autogenous cleaning clearly emerges when analysing the compressive strength results obtained for RAC CL, where a significantly smaller reduction was measured (8.9%).

The Brazilian tensile splitting strength was determined from cylindrical specimens (ASTM C496/C496M 2011) after 28 days of water curing (three specimens for each batch). The results show that the use of uncleaned recycled aggregates reduces the tensile splitting strength by about 13%, while autogenous cleaning has led to both higher tensile strength and a reduction in scatter (less than 4%) of the results obtained from the three tests performed on RAC CL specimens (Fig. 2.3).

## 2.2 Influence of the Initial Moisture Condition of RCAs

As recycled aggregates are characterised by water absorption capacity higher than natural ones, the initial moisture condition of RCA has an influence on the total amount of free water available in the mixture. Hence, since free water plays a key role on the evolution of the physical and mechanical properties of both hardened and fresh concrete, initial moisture conditions of RCAs are expected to have an influence on such properties.

For this reason, the experimental campaign described hereafter has investigated the changes on mechanical and physical performance of RACs by considering the possible variation of the initial moisture condition for RCAs.

### *2.2.1 Materials and Methods*

Four different concrete mixtures with 30% recycled aggregate replacement have been considered in the present study with emphasis on the relationship between the compressive strength development and the corresponding time evolution of the degree of hydration. Two key parameters, i.e. the water to cement ratio and the initial moisture condition of the recycled aggregates, respectively, have been considered in this campaign and their impact on the final concrete quality has been investigated. Specifically, their influence on both the hydration reaction and the evolution of the compressive strength of concretes made with recycled aggregates has been investigated. Therefore, two mixtures are designed with a different nominal water/cement ratio, i.e. 0.45 and 0.60. Moreover, for the recycled aggregates two different initial moisture conditions have been adopted, according to the two following definitions:

- Dry condition (DRY): the coarse aggregates have been dried for 24 h in an oven with a constant temperature of 100 °C;
- Saturated condition (SAT): the coarse aggregates have been saturated for 24 h in water and, before mixing, their surface has been dried with a cloth.

In fact, natural aggregates used in ordinary concretes have been generally characterised by a low water absorption capacity and their corresponding portion of "absorbed water" can easily be accounted for in the concrete mix design. On the contrary, a higher water absorption capacity of RCAs clearly depends on their production process. Particularly, internal damage and cracks due to demolition and crushing, results in a non-negligible influence of RCAs water absorption capacity on the concrete mix performance, in both the fresh state (in terms of actual workability and rheological properties) and the hardened state (in terms of mechanical properties). The processing of the RCAs, as considered in this study, has led to the following ranges of the grain sizes (Table 2.3):

**Table 2.3** Influence of the initial moisture condition of RCAs, natural and recycled aggregates

| Class size | Natural | | Recycled | |
|---|---|---|---|---|
| | A (%) | $\gamma$ (kg/m$^3$) | A (%) | $\gamma$ (kg/m$^3$) |
| Sand (d < 4.75 mm) | 1.2 | 2690 | – | – |
| C1 (4.75 mm < d < 9.5 mm) | 0.5 | 2690 | 6.0 | 2231 |
| C2 (9.5 mm < d < 19 mm) | 0.4 | 2690 | 3.0 | 2231 |
| C3 (19 mm < d < 9.5 mm) | 0.3 | 2690 | 1.8 | 2231 |

**Table 2.4** Influence of the initial moisture condition of RCAs, mixture composition

| Mix | CEM | w | ads. W | w/c | Natural | | | Recycled | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Sand | C1 | C2 | C2 | C3 |
| | (kg/m$^3$) | | | | (kg/m$^3$) | | | | |
| 0.45DRY | 410 | 185 | 0 | 0.45 | 760 | 130 | 300 | 100 | 400 |
| 0.45SAT | | | 21 | | | | | | |
| 0.60DRY | 310 | | 0 | 0.60 | 850 | | | | |
| 0.60SAT | | | 21 | | | | | | |

**Fig. 2.4** Insulated mould inducing semi-adiabatic boundary conditions on the curing concrete sample

- Sand, nominal size smaller than 4.75 mm;
- C1, nominal size 4.75–9.5 mm;
- C2, nominal size 9.5–19 mm;
- C3, nominal size 19–31.5 mm.

Table 2.4 describes the actual composition of the four concrete mixtures considered and differentiates between the two aforementioned values of the nominal water to cement ratios and the two initial moisture conditions.

The amount of RCAs has been kept constant to 30% of the total amount of aggregates, with a total replacement of the coarse fraction, a partial replacement of the finer fraction, and no replacement of sand.

The volume of water absorbed by the saturated aggregates is not included in the calculation of the w/c ratio. The absorbed volumes are estimated by considering the amount of the various aggregate fractions and their respective water absorption capacity, which was determined on both the natural and recycled aggregates.

Table 2.4 reports the amounts of water absorbed by recycled aggregate in saturated conditions, apart from the regular mixing water.

Finally, a common Portland cement, type CEM I 42.5 R (EN 197-1 2011), was used as a binder in all concrete mixes. For all the investigated concrete mixtures, the hydration process was monitored by measuring the temperature evolution in the centre of a concrete cube during the first seven days after casting. To this end, a cubic sample of each concrete mix was cured in semi-adiabatic conditions with the aim of measuring the temperature evolution and to use these results as input data in simulation model capable to calculating the hydration process (Martinelli et al. 2013). For this purpose, this concrete sample was cast within an insulated mould with an edge size of 150 mm (Fig. 2.4).

Four out of the six faces of the cubic sample are bounded by a thick layer (about 100 mm) of insulating material, whereas the other two faces were insulated with a significantly thinner layer (of about 40 mm). Therefore, the heat produced by the hydration reaction was supposed to be mainly dissipated through the two faces bordering with the thinner layers of insulation material. Since these two faces are placed opposite from each other (namely, the top and bottom of the system depicted in Fig. 2.4) a 1D heat flow was supposed to occur.

The evolving exothermic reaction under semi-adiabatic conditions leads to a temperature increase within the cube, which also affects the kinetics of the cement hydration reaction. The evolution of the hydration temperature inside the cube was monitored with respect to the ambient temperature using two thermocouple wires (Fig. 2.5).

Moreover, apart from the one cured within the insulated mould, ten other concrete samples for each mix were cast and cured in a water bath under isothermal conditions at a temperature $T_R$ of 22 °C. Couples of these samples were tested in compression (Fig. 2.6) after 2, 3, 7, 14 and 28 days of curing, with the aim of determining the average strength at the aforementioned curing ages.

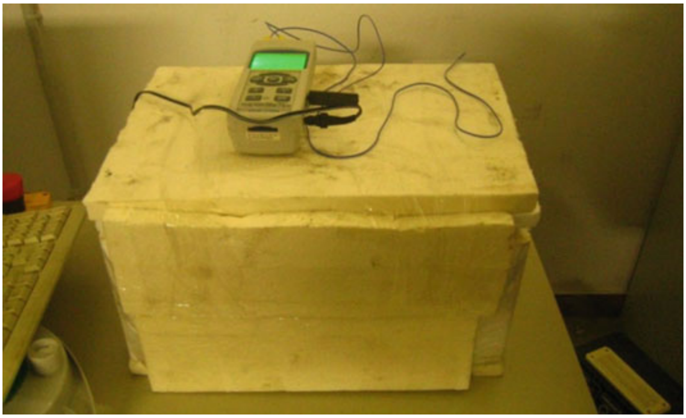
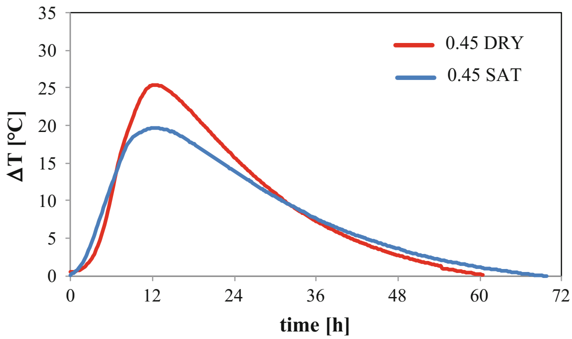


**Fig. 2.5** Temperature measurement inside insulated mould

**Fig. 2.6** Compression test

**Fig. 2.7** Time evolution of temperature on curing concrete samples (w/c = 0.45)




## 2.2.2 *Results and Analysis*

The time evolution of temperature, measured as described above, allows scrutinizing the actual influence of the mix ingredients and moisture conditions of the recycled aggregates on the resulting cement hydration reaction. Figure 2.7 shows the temperature development measured in the two concrete samples with a w/c = 0.45. It can be observed that the sample with dry aggregates reaches the highest peak value for the temperature as well as a slightly higher rate of the hydration reaction for the ascending branch. This could likely be attributed to the relatively lower amount of water in this mix with dry aggregates. In fact, the role of the w/c ratio on the hydration process is well known and this observation is basically in line with this well-established knowledge (van Breugel 1991). On the contrary, the sample with saturated recycled aggregates exhibited a slightly longer reaction period, which could likely be attributed to the higher amount of available water, and a slower temperature decay in the post-peak branch.

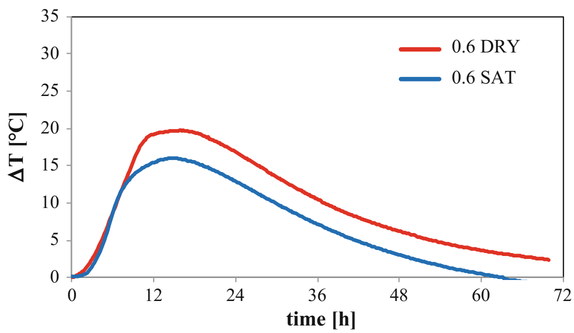



**Fig. 2.8** Time evolution of temperature on curing concrete samples (w/c = 0.60)

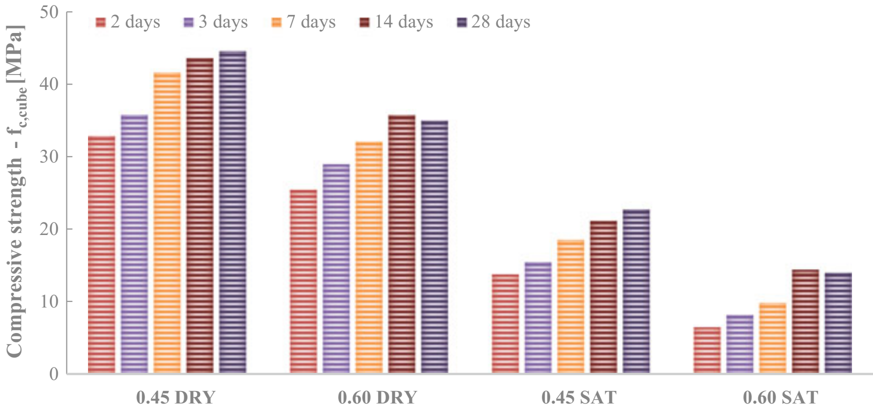



**Fig. 2.9** Time evolution of the average compressive strength on concrete samples

Similar considerations hold for the two concrete mixtures with a w/c of 0.60 (Fig. 2.8). Higher peak temperatures were reached in the concrete made with dry aggregates, but in this case the post-peak temperature decay observed in the two samples showed similar rates.

For the compressive strength evolution, the influence of the two parameters under consideration, i.e. the w/c ratio and the moisture condition of the recycled aggregates, on the hydration reaction of the four mixtures (Table 2.4) is expected to have a clear effect on the time evolution of the compressive strength.

Figure 2.9 shows the results of the compressive strength development in terms of average cube compressive strength $f_{c,cube}$, according to the procedure described in the previous subsection. The results confirm that the initial moisture content of the recycled aggregates plays an important role in the development of the compressive strength of concrete Fig. 2.9. In this respect, dry aggregates lead to higher values of $f_{c,cube}$ over the investigated time span of 28 days for both w/c ratios considered in this study. Moreover, the compressive strength of specimens denoted as 0.60DRY (namely, those with w/c = 0.6 and dry aggregates) resulted in significantly higher than the corresponding mixtures produced with initially saturated aggregates (namely, 0.60SAT). For the corresponding tests performed for the w/c ratio of 0.45 with recycled aggregates under dry and saturated conditions this reduction is about 50%. Particularly, both mixtures made with saturated aggregates were characterised by a very low compressive strength, apparently as a result of the higher total amount of water (mixing water + absorbed water) which potentially led to a higher value of the actual (local) w/c ratio, depending on the possible release of the absorbed water from the aggregates into the mix.

The correlation between the hydration processes and the resulting compressive strength can be figured out by calculating the evolution of the degree of hydration from the temperature curves as presented in Figs. 2.7 and 2.8 and by comparing the results with the strength measurements reported in Fig. 2.9. A deeper investigation towards the quantitative relationship between these hydration-related measurements and the compressive strength is proposed in the following Sect. 2.3.

## 2.3 Influence of the Aggregate Replacement and Water to Cement Ratios

Once having assessed the key role of the initial moisture condition of RCA on the resulting properties of RACs, it is important to understand how this parameter affects the nominal value of the water-to cement ratio. With this aim, the experimental campaign described in this section has considered the variation of the initial moisture condition by combining the possible variation of the aggregate replacement ratio and the water to cement ratio.

### *2.3.1 Materials and Methods*

All mixtures were produced by using a high initial strength cement, denoted as CEM I 52.5 R according to EN 197-1 (2011). Meanwhile, three different size ranges were considered for the aggregates: sand (nominal diameter smaller than

**Table 2.5** Influence of the aggregate replacement and water to cement ratios: natural and recycled aggregates properties

| Class size | Natural | | Recycled | |
|---|---|---|---|---|
| | A (%) | $\gamma$ (kg/m$^3$) | A (%) | $\gamma$ (kg/m$^3$) |
| Sand (d < 4.75 mm) | 1.20 | 2690 | – | – |
| C1 (4.75 mm < d < 9.5 mm) | 0.50 | 2690 | 8.70 | 2127 |
| C2 (9.5 mm < d < 19 mm) | 0.40 | 2690 | 6.60 | 2290 |

**Table 2.6** Influence of the aggregate replacement and water to cement ratios, mixture composition

| Mix | CEM | w | w/c | Natural | | | Recycled | |
|---|---|---|---|---|---|---|---|---|
| | | | | Sand | C1 | C2 | C1 | C2 |
| | (kg/m$^3$) | | | (kg/m$^3$) | | | | |
| 0.50NATDRY | 344 | 172 | 0.50 | 742 | 554 | 554 | – | – |
| 0.50NATSAT | | | | | 557 | 557 | – | – |
| 0.50RAC30DRY | | | | | 554 | – | – | 474 |
| 0.50RAC30SAT | | | | | 557 | – | – | 505 |
| 0.50RAC60DRY | | | | | – | – | 440 | 474 |
| 0.50RAC60SAT | | | | | – | – | 478 | 505 |
| 0.40RAC60DRY | 430 | | 0.40 | 712 | – | – | 422 | 454 |
| 0.40RAC60SAT | | | | | – | – | 458 | 484 |
| 0.60RAC60DRY | 287 | | 0.60 | 762 | – | – | 452 | 487 |
| 0.60RAC60SAT | | | | | – | – | 491 | 519 |

4.75 mm) and coarse aggregates (C1 and C2 classes already defined in the previous sections). The main physical properties of both natural and recycled aggregates employed in this study, are reported in Table 2.5, meanwhile the mixtures composition are reported in Table 2.6.

It is worth highlighting that natural sand obtained from crushing limestone rocks has been employed in this study. In fact, no recycled sand is employed, as it would have been too porous and, then, it would have had a significantly detrimental effect on the resulting concrete properties (Lima et al. 2013). Conversely, a combination of both NAs and RCAs has been employed as coarse aggregates. Ten different concrete mixtures have been produced in order to investigate the influence of the three following parameters:

- (nominal) value of the water-to-cement ratio: 0.40, 0.50 and 0.60;
- RCAs-to-NAs replacement ratio ranging from 0 to 30 to 60% relative to the total volume of fine and coarse aggregates (i.e. considering also the natural sand);
- initial moisture condition of the coarse aggregates (Koenders et al. 2014): oven-dried assured by heating the aggregates for 24 h at a temperature of 100 ± 5 °C (DRY), and saturated surface dry, obtained by submerging the aggregates in water for 24 h (SAT).

Figure 2.10 shows a schematic synopsis of the tests, while Table 2.6 describes into detail the mix compositions. In all mixtures, the fine fractions (i.e., sand) represented 40% (by volume) of the total amount of aggregates, while the remaining 60% is equally divided into two fractions of coarse aggregates (i.e., C1 and C2).

The first two reference mixtures described in Table 2.6 were obtained with only natural aggregates (NAT in the mixture labels), a nominal water-cement ratio of 0.50 (also mentioned in the labels) and two alternative initial moisture conditions of the coarse aggregates (i.e., DRY and SAT).

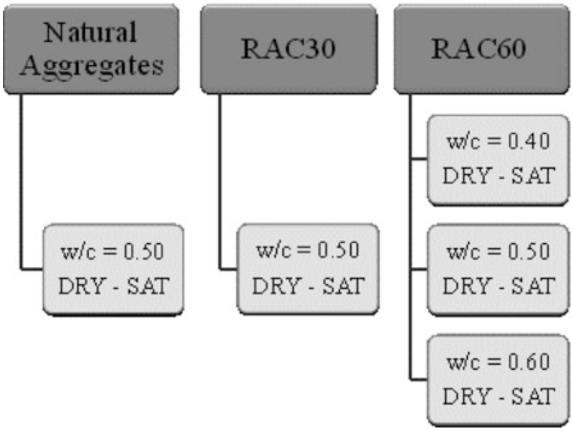



**Fig. 2.10** Experimental campaign

Therefore, a RCAs-to-NAs coarse aggregate replacement of 30% was obtained via a complete replacement of the coarse fraction (namely class C2) with the corresponding ones made of RCAs, whereas 60% was achieved by replacing both fractions C1 and C2 of the NAs with the corresponding fractions of RCAs. Hence, the two mixtures denoted as 0.50RAC30DRY and 0.50RAC30SAT were derived from 0.50NATDRY and 0.50NATSAT, by fully replacing the C2 fraction with an equal volume of RACs. Similarly, the two mixtures, denoted as 0.50RAC60DRY and 0.50RAC60SAT, were obtained from the reference ones by replacing all the coarse aggregates (i.e. classes C1 and C2).

Finally, the last four rows refer to the composition of the two mixtures obtained by either reducing to 0.40 or raising to 0.60 the nominal w/c ratio. For each mixture, nine compressive strength tests were performed on cubic specimens according EN 12390-3:2009 after 1, 3 and 28 days of curing in a water bath under isothermal conditions at a temperature 20 ± 2 °C. Moreover, the time development of temperature was measured in the centre of the cubes, prepared for all concrete mixtures and cured in semi-adiabatic conditions so that an indirect monitoring of the hydration process could be registered and applied to the numerical procedure as recently proposed in the scientific literature (Martinelli et al. 2013). However, the concrete specimens tested in compression have been cured in isothermal conditions, at room temperature. However, due to the small size of such specimens and due to the quick dissipation of the reaction heat to the environment, no significant temperature enhancement could be measured. Therefore, a special insulated mould was designed to measure the evolution of the hydration temperature inside a cube such that a significant temperature enhancement was monitored with respect to the room temperature, using two thermocouple wires (as already described in the previous section).

### 2.3.2 Results and Analysis

Figures 2.11 and 2.12 show the time evolution of compressive strength and temperature during the first 28 days of hardening.

The analysis of these results clearly show that the use of RCAs in concrete, as well as their initial moisture condition, affects the resulting concrete performance.

First, when comparing the compressive strength results of the concrete mixes characterised by equal nominal water-to-cement ratio and the same initial moisture condition (i.e., w/c = 0.5, DRY and SAT) it turns out that with increasing the aggregate replacement ratio, the 28 day compressive strength is decreasing. This effect becomes even more pronounced whenever employing saturated initial moisture conditions (SAT). This result can be explained by the higher porosity of recycled aggregates. In fact, when a SAT condition is employed, the aggregates tend to release accumulated water into the mixture and consequently to change the

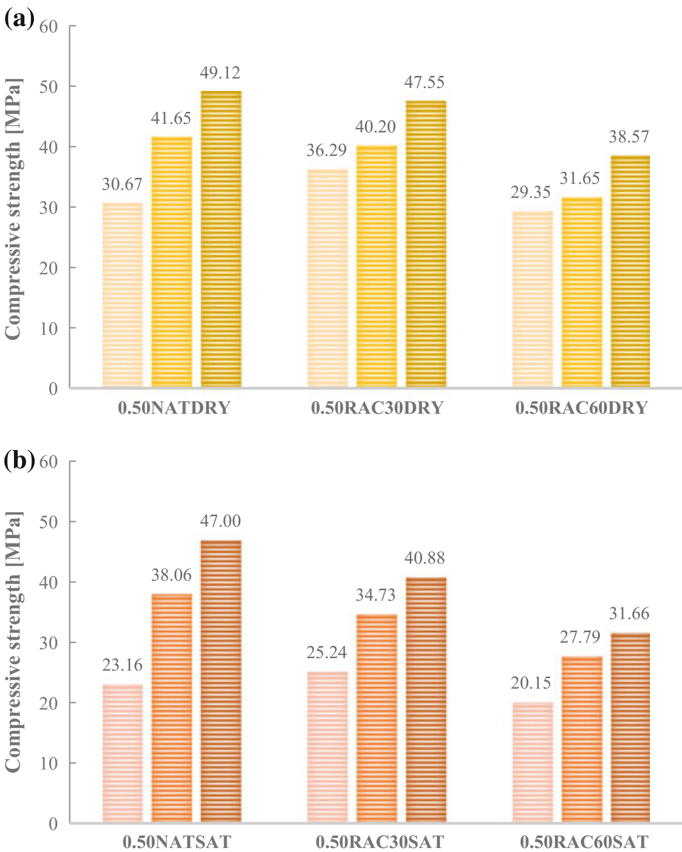



**Fig. 2.11** Time-evolution of compressive strength

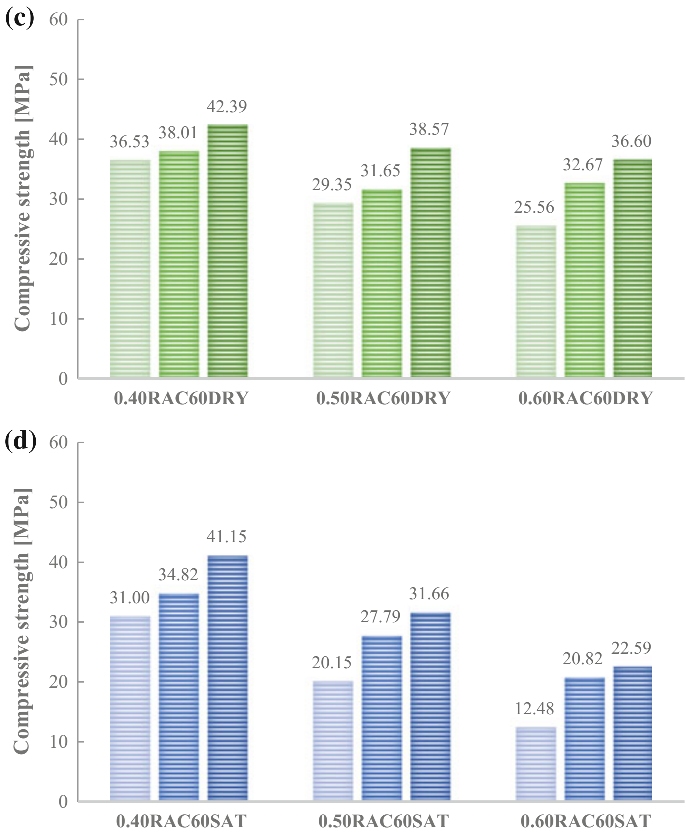



**Fig. 2.11** (continued)

water-to-cement ratio. On the contrary, when DRY conditions are adopted, the aggregates tend to absorb part of the mixing water and, then, reduce the actual water-to-cement ratio. This phenomenon is less evident when natural aggregates are used because of their lower absorption capacity and, consequently, the amount of water, potentially released or absorbed into a mixture is negligible compared to the total amount of mixing water. On the other hand, analysis of the compressive strength results of those mixtures characterised by the same aggregate replacement ratio (i.e., RAC60), but with different nominal water-to-cement ratios (i.e., moving from 0.40 to 0.50 to 0.60), highlights the key impact of the w/c ratio on the final strength of concrete, as already known from literature. It is worth mentioning that also in this case, the initial moisture condition plays an important role. In fact, the gap (in terms of compressive strength at 28 days) between DRY and SAT mixtures also increases with increasing the nominal water-to-cement ratio.

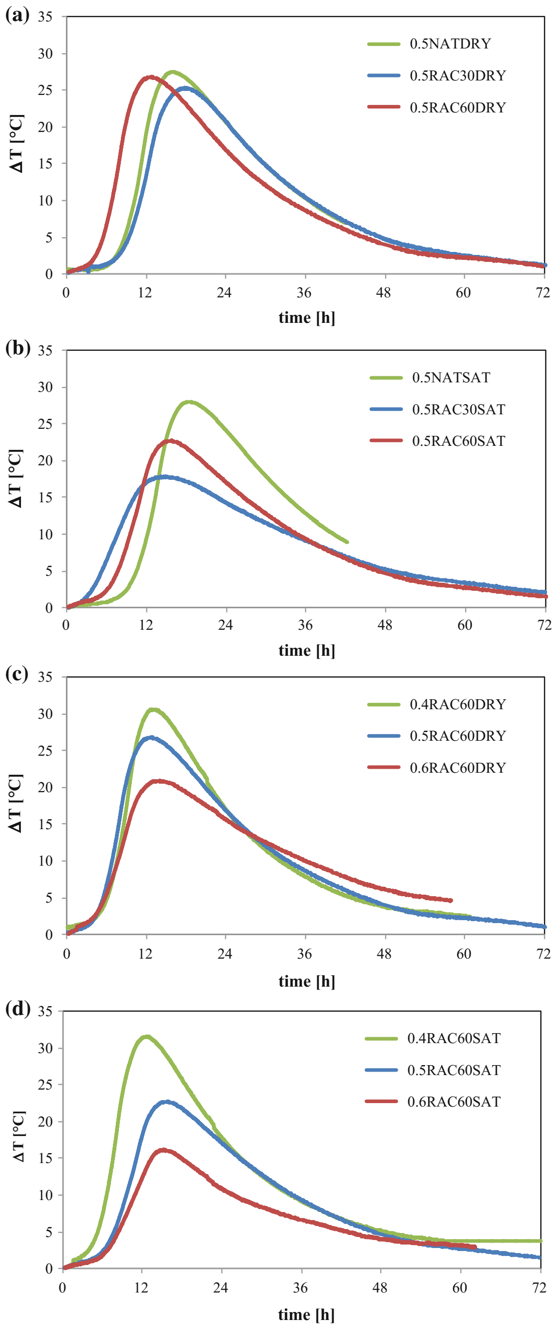



**Fig. 2.12** Temperature-time evolution

A more fundamental analysis can be performed by considering the differences of the temperature measurements in time, as reported in Fig. 2.12. Experimental results highlight that a lower w/c ratio results in a faster acceleration of temperature. A similar effect was observed by enhancing aggregate replacement ratio or in case of DRY aggregates.

Based on the above considerations and the analysis of results, it is clear that the initial moisture condition and the aggregate porosity tend to modify the nominal water-to-cement ratio and, hence, an effective value, taking into account both the initial moisture condition and the aggregate porosity, can be defined as follows:

$$\left(\frac{w}{c}\right)_{eff} = \frac{w}{c} + \frac{w_{add}}{c} - \delta \cdot \left(\sum_{i=1}^{n} \frac{p_i \cdot P_i}{c}\right) \tag{2.1}$$

where w/c is the nominal water-to-cement ratio, $w_{add}$ is the extra water added to the mix from the (partially or totally) soaked the aggregates, $p_i$ and $P_i$ represent the absorption capacity and the weight in the mixture of the ith aggregate fraction, and $\delta$ is a parameter that takes into account the initial moisture condition of the aggregates and is zero in SAT conditions and 0.5 in DRY ones. The calibration $\delta = 0.5$ for DRY condition is that during mixing and casting it turned out that the aggregates are able to absorb an amount of water equivalent to 50% of their 24 h capacity.

## 2.4 Concluding Remarks

The experimental results summarised in this section highlight that:

- the presence of RCAs in the concrete mixtures modifies their fundamental properties, as even the cement hydration reaction is affected by replacing ordinary aggregates with recycled ones;
- RCAs are significantly more porous than NAs and this is the main reason behind the difference in the observed behaviour of ordinary concrete and RACs;
- moreover, the initial moisture condition of aggregates at mixing plays a significant role, as it modify the actual amount of water (and, hence, the water-cement ratio) available for the hydration process;
- cleaning of RCAs may be an option to modify porosity (and, hence, water absorption capacity) in RCAs and, hence, reduce the difference between RCAs and NAs.

Finally, three main parameters are supposed to control the behaviour of RACs (namely, water-cement ratio, aggregate replacement ratio and initial moisture conditions): their influence may be condensed by defining an “effective” water-cement ratio that can be employed in a generalised Abrams’ law capable to predict compressive strength of RAC, as will be explained in Chap. 6.

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