MECHANICAL AND DURABILITY PERFORMANCE OF SUSTAINABLE STRUCTURAL CONCRETES: AN EXPERIMENTAL STUDY

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ABSTRACT

This study reports the results of a wide experimental campaign intended at investigating the mechanical and durability performance of structural concretes made with Recycled Concrete Aggregates (RCAs) and coal Fly Ash (FA). To this end, twelve mixtures were designed by replacing part of the ordinary constituents (i.e. cement, sand and coarse aggregates) of a reference one with RCAs and FA. Samples of these mixtures were subjected to various tests aimed at assessing both their structural properties and durability performance. As for the former, time evolution of compressive strength was monitored at various curing times up to 365 days, and the splitting strength was determined at 28 days. Moreover, the expected durability performance of the aforementioned concrete mixtures was scrutinised by measuring some relevant physical quantities, such as water permeability, carbonation depth and chloride-ions ingress at various curing ages.

The results obtained from these tests are often not self-evident, as they unveil the synergistic effect of combining both RCAs and FA on the resulting physical and mechanical properties of "green" concrete. Moreover, they demonstrate that the current code restrictions on the use of both RCAs and FA for structural concrete might be significantly relaxed, especially if the delayed binder effect, induced by the latter, is duly taken into account and, hence, concrete properties are measured at curing times longer than the conventional 28 days.

KEYWORDS: Recycled Aggregate Concrete; Fly Ash; Durability; Water permeability; Chloride-ion penetration; Carbonation.

1 INTRODUCTION

With a global production of around 10.000 million tons per year [1], concrete is certainly the most used construction material. Consequently, the concrete production requests huge amounts of energy and raw materials, resulting in a significant depletion of natural resources [2]; moreover, it is also responsible for a significant share of the global greenhouse gas emissions, mainly due to cement production processes [3].

Therefore, nowadays several organisations and, consequently, research groups are committed to formulating more sustainable materials and processes intended at “greening” the concrete industry [4]. A possible solution for achieving this objective is based on adopting alternative binders (often obtained from industrial by-products) as a partial replacement of Portland cement [5], with possible positive consequences, not only on sustainability, but also in terms of durability [6]. Furthermore, replacing ordinary aggregates with recycled ones is another viable solution [7]: in the literature, the concrete produced with recycled aggregates is often referred to as Recycled Aggregate Concrete (RAC) [8].

The huge amount of Construction and Demolition Waste (CDW) produced in Europe [8][9] is a potential source for producing recycled aggregates: in fact, despites the huge production of CDW (Figure 1), its recycled percentage is often very low (Figure 2). Moreover, the current regulations about structural concrete [10-14], with their restrictions to the use of recycled aggregates, represent a further hurdle for RAC to be more commonly employed in construction, at least when ordinary mechanical properties are requested and mild environmental exposure conditions are expected.

However, several recent researches demonstrated that a limited use of recycled aggregates derived from CDW has negligible consequences on the mechanical performance required in structural applications in terms of technological aspects [15], fundamental behavior (i.e. in terms of cement reaction development) [16][17] and resulting stress-strain response [18].

The present study focuses on the combined use of recycled aggregates derived from demolished concrete members ("Recycled Concrete Aggregates", RCAs) and coal Fly Ash (FA), which places several concerns about the resulting mechanical and durability performance of concrete.

In fact, since RCAs can be seen as the combination of two main phases, such as original natural aggregates and paste attached to them (usually referred to as Attached Mortar, AM [19]), they are generally characterised by higher porosity and, hence, water absorption capacity, with respect to the "ordinary" natural aggregates. This is the key motivation for developing a dedicated mix-design procedure capable of predicting the effects of RCAs on the resulting compressive strength of RAC [20]. Moreover, the presence of RCAs can seriously affect both workability at the fresh state [21] and durability performance of RAC [22].

However, the use of FA in partial substitution of Portland cement and fine aggregate can also be considered, in order to mitigate the drawbacks induced by using RCAs in structural concrete and, at same time, promoting a further greening practice in the concrete industry [23]. As widely demonstrated in the literature, a limited use of FA, either as a filler or as a possible cement replacement, can have beneficial effects on RAC in terms of fresh state workability [24], mechanical performance at the hardened state [25][26] and long-term behaviour [27]. As for the latter, experimental results already demonstrate the positive effects of FA [28][29][30] in terms of resistance to chloride-ion penetration [31], water permeability [32] and durability against the exposure to chemical agents and adverse environmental conditions [33].

This paper is specifically intended at unveiling the consequences of using both RCAs and FA in concrete. It reports the results of a wide experimental campaign, performed at the Laboratory of Material and Structures (LMS) of the University of Salerno (Italy) and at the research laboratory of General Admixtures SpA (www.gageneral.com). Particularly, twelve concrete mixtures were designed and produced by replacing part of the ordinary constituents of a reference one with RCAs and FA, being the latter considered in substitution of both/either Portland cement and/or fine aggregates.

Finally, it is worth highlighting that, since the performance of the concrete mixtures under investigation were already analysed in terms of workability and compressive strength [34], the present study focuses more on durability-related aspects. In fact, the short review of the current state of knowledge, proposed in the first part of this section and based on relevant studies published in very recent time, demonstrates that investigating the durability performance of RAC with FA is indeed a subject of current relevance, as few experimental results are already available in the literature on this material, which represents a promising solution for a significant “greening” of concrete industry.

2 MATERIALS AND METHODS

2.1 Materials

The concrete mixtures under investigation were produced by using Portland cement, labelled CEM I 42.4R, according to EN 197-1 [35]. Moreover, class F coal FA [36] was used for partially replacing Portland cement and natural sand: it was produced in a thermo-electrical power plant and was compliant with the EN 450-1 [37]. Table 1 summarises chemical composition and physical properties of both Portland cement and Fly Ash.

Moreover, both Natural Aggregates (NAs) and Recycled Concrete Aggregates (RCAs) were used in this study. More specifically, crushed limestone particles were employed as NAs, whereas RCAs were obtained by crushing rubbles obtained from demolishing of existing concrete structures.

Both recycled and natural aggregates were selected, cleaned and sieved in laboratory. As for qualification, the supplier company certified RCAs according to EN 13242 [38], whereas their characterisation as aggregates for concrete was carried out in laboratory according to EN 12620 [39]; moreover, ASTM C127 [40] and ASTM C128 [41] provisions were followed for determining water absorption (at 24 hours) in coarse and fine aggregates, respectively. Table 2 summarises main properties of aggregates: water absorption is a weighted average of the values obtained for the four size fractions described in the following:

- Class N3, characterised by a nominal diameter of the aggregate particles ranging between 20 mm and 31.5 mm;
- Class N2, characterised by a nominal diameter of the aggregate particles ranging between 10 mm and 20 mm;
- Class N1, characterised by a nominal diameter of the aggregate particles ranging between 2 mm and 10 mm;

- Sand, characterised by a nominal diameter of the aggregate particles smaller than 2 mm.

The results of Table 2 are further detailed in Table 3 reporting both particle density and water absorption capacity for each size class; as it is well-known in the literature [19], RCAs are characterised by both lower particle density and higher water absorption capacity in comparison with natural ones.

Finally, a chemical admixture based on polycarboxylic polymers, labelled "PR*i*MIUM RM28" and produced by General Admixtures SpA, was used in order to control workability at the fresh state.

2.2 Mixture design and specimens geometry

As already mentioned, a total of thirteen different concrete mixtures were produced: the first mixture, assumed as a reference, was realised by using only ordinary aggregates and Portland cement; conversely, the other twelve ones were obtained by partly replacing aggregates and Portland cements with RCAs and FA.

Table 4 describes the composition of the aforementioned mixtures. The first column of the table reports a label, consisting of the following symbols:

- letters *L*, *M* and *H* indicate, respectively, a low (80 kg/m^3), medium (220 kg/m^3) or high (255 kg/m^3) content of FA;
- letter *N* indicates those concretes made of only natural aggregates;
- letter *R* denotes mixtures with RCAs in substitution of NAs: the following number (namely, 30, 60 or 100) represents the total replacement percentage, in volume.

For instance, the mixture *LR30* is made with 80 kg/m^3 of FA and an amount of RCAs equal to 30% of NAs considered in the mixture *LN*. Table 4 also reports further information, such as the amount of cement, fly ash and water per unit volume of concrete, the percentage of RCAs.

As for water, due to the higher porosity of RCAs, it is clear that its dosage is expected to affect significantly the resulting properties of concrete. In this study, the nominal amount of free water was kept constant (i.e. w_{free}=150 kg/m^3) in all mixtures. Since NAs and RCAs were dried in oven before mixing, an "extra" quantity w_{add} of water was added, which is supposed to saturate the whole aggregates of each mixture, based on the values of water-absorption capacity (at 24 hours) determined in laboratory and reported in Table 3 for each size fraction of NAs and RCAs.

The first row of Table 4 describes the composition of the reference concrete mix (*N*); it was designed with the aim to meet the requirements of EN 206 [42] for an environmental exposure class XC2: maximum water-to-cement ratio w/c=0.60, minimum cement content C_{min}=280 kg/m^3, and minimum target strength class C25/30.

Based on EN 206 [42] provisions, the minimum cement content C_{min} may be reduced down to a quantity $C=C_{min}-\Delta C$, with:

$$\Delta C = (C_{min} - 200) \cdot \rho \tag{1}$$

and FA can be used as supplementary cementitious material with the following limitation:

$$\frac{FA}{C} \leq 0.33 (\text{by mass}) \cdot \tag{2}$$

Coefficient ρ in eq. (1) is a sort of "*cementing efficiency index*" of FA: in the case it replaces CEM-I 42.5, ρ is set to 0.4 [37].

Moreover, the following restriction should be met:

$$C + FA = (C_{min} - \Delta C) + FA \geq C_{min} \tag{3}$$

The mixtures denoted by the initial L were obtained by assuming ΔC=30 kg/m^3 (and, hence, C=250 kg/m^3) based on eq. (1), and FA=80 kg/m^3, according to the limitations expressed by eqs. (2) and (3). According to EN 450-1 [37], further amount of FA, actually adopted in mixtures M and H, have to be considered as "inert" filler, which can be considered as replacement for the finer fraction of NAs (namely, sand).

Table 4 also describes the actual composition of the concrete mixtures obtained by replacing RACs and FAs from the reference one. Moreover, it reports the free water-binder ratio w_{free}/b defined as follows, according to the limitation given by eq. (2):

$$\frac{w_{free}}{b} = \frac{w_{free}}{C + \rho \cdot \min\{FA; 0.33 \cdot C_{min}\}} \quad (4)$$

The following consideration can be drawn by observing the cement and FA contents reported in Table 4:

- the mixture *LN* fully agrees with the current code provisions in terms of Portland cement replacement with FA;

- the mixture *MN* was produced by using 220 kg/m^3 of FA and 250 kg/m^3 of cement: therefore, according to eq. (2), around 140 kg/m^3 of FA cannot be considered as a binder, but only as a replacement of fine aggregates (i.e., the sand), whose content was actually adjusted for volume balance;

- the mixture *HN* is characterised by an even lower cement C=200 kg/m^3 and 255 kg/m^3 FA were considered with the aim to keep the total amount of binder, defined by eq. (3), equal to the *MN* mixture.

As for replacement of NAs, all the mixtures the amount RCAs do not meet the restrictions in terms of aggregate replacement for structural concrete, according to most of the codes currently in force in Europe [10-14].

Moreover, as regards water, it is worth highlighting that in various mixtures the water-to-binder ratio reported in Table 4 is higher than the corresponding maximum value provided by EN 206 for environmental exposure class X2 (namely, w/c=0.60).

Cubic and cylindrical samples were cast in polyurethane moulds in order to obtain the specimens for tests at hardened state. Particularly, after 36 hours samples were removed from moulds and cured at 20°C with 100% humidity up to 28 days after casting. Further information about the mixtures under investigation are reported in a previously published paper [34].

2.3 Testing methods

The whole experimental programme realised as part of this study was aimed at investigating the mechanical behaviour and determining some physical properties of relevance for durability. Since the former were already documented in a previous paper [34], only the tests carried out to determine the latter are described in the following subsections.

2.3.1 Water Permeability tests

The water permeability test, carried out according to EN 12390-8 [43], aims at determining the depth of penetration of water under pressure. More specifically, cubic samples are subjected to a water pressure of 0.5 MPa for 72 h: Figure 4 shows the experimental setup and one specimen after testing.

At the end of the test, each specimen was split into two halves and the average depth h_m of the wet profile of water penetration is measured: as well-known, higher values of h_m correspond to higher permeability and, hence, less durable concretes.

2.3.2 Rapid chloride penetrability tests

Rapid Chloride Penetration test (RCPT) measures the amount of electric charge passing through a concrete specimen and allow estimating the resistance to chloride-ion penetration.

According to ASTM C1202 [44], RCPTs were carried out on two different concrete cylinders (102 mm in height and 51 mm in diameter) at 90 days and 365 days. The two ends of each concrete specimen were immersed in a sodium chloride solution and in a sodium hydroxide solution, respectively, before exposing the concrete sample to a potential difference of 60 V for 6 hours (Figure 5). The total charge passed through the concrete specimen was considered for evaluating the chloride permeability of each sample: a qualitative correlation between the electric charge, expressed in coulombs, and the expected sensitivity to chloride diffusion is reported in Table 5.

2.3.3 Carbonation test

Carbonation is a major cause of deterioration in concrete structures: although it is not a detrimental phenomenon for the concrete itself, it is recognised for triggering corrosion in steel reinforcement [45][46].

According to EN 14630 [47], carbonation tests were performed. on standard concrete cubes (150 mm in edge): two specimens per mixture were cast and cured at controlled conditions (in water at 20±2°C) for 28 days. Consequently, the cubes were placed outside at environmental conditions and tested at 90 and 365 days. Each specimen was split into two parts, where a phenolphthalein solution (1% phenolphthalein in isopropyl alcohol) was applied. Then, the carbonation depth D was evaluated as follows [47]:

$$D = \frac{A_1 + A_2 + B_1 + B_2 + C_1 + C_2 + D_1 + D_2}{8} \tag{5}$$

whose symbols, corresponding to the so-called “affected depths”, are defined in Figure 6.

2.4 Experimental test matrix

Experimental tests intended at estimating the mechanical properties were performed on either cubic (150 mm edge) or cylindrical (150 mm x 300 mm) specimens. More specifically, the following mechanical tests were carried out for each one of the thirteen concrete mixtures [34]:

- 14 compression tests on cubic specimens at 2, 7, 28, 60, 90 and 365 days of curing (2 tests at 2 days, 1 at 7 days, 6 at 28 days, 2 at 60 days, 1 at 90 days and 2 at 365 days);
- 2 splitting tests on cylindrical samples at 28 days, for evaluating the concrete tensile strength.

Moreover, 4 standard cubes and 1 cylindrical sample (102 mm in diameter and 300 mm in height) were prepared per each concrete mixture, in order to determine durability-related physical quantities. Particularly, the following tests were performed at 90 and 365 days for each mixture:

- 1+1 water-penetration tests on cubic specimens;
- 1+1 carbonation tests on cubic samples;

- 2+2 chloride-ion penetration tests carried out on 102 x 51 mm^2 cylinders obtained by cutting the central portion of the above-mentioned 102 mm x 300 mm cylinders into four parts (Figure 3).

Therefore, 104 “durability tests” were actually performed in this research: 26 water permeability tests, 26 carbonation tests and 52 rapid chloride-ion penetrability tests.

3 RESULTS AND ANALYSIS

This section reports the experimental obtained results. Particularly, the consequences of a combined use of RCAs and FA on the resulting durability-related quantities are specifically analysed, along with the main mechanical properties already discussed in a previous paper [34].

3.1 Physical characterisation: mass density

The average values of mass density were determined at 28 days of curing: six standard (150 mm edge) cubes were weighted per each concrete mixture before performing the compressive strength tests: Figure 7 plots the average density vs. the RCAs replacement ratio for the three series of mixtures L, M and H; the density obtained for the N mixture is also dashed as a reference.

As expected, density is lower in concretes with higher amount of RCAs, being the latter significantly more porous that the ordinary ones [15]: a maximum reduction of around 20% is observed in one of the mixtures with all aggregates replaced by RCAs.

Conversely, the influence of FA emerging from Figure 7 is less self-evident. On the one hand, the comparison of mixtures *L* and *M* and *H* shows that the former are slightly light-weighted than the latter: this can be explained by considering that the total volume of aggregates in mixtures *M* and *H* is lower than in the *L* mixtures, as a part of fine aggregates is replaced by FA. Therefore, the influence of aggregate replacement is less pronounced in the mixtures *M* and *H* than *L* mixtures: this even leads to mixture *HR100,* characterised by the higher amount of FA, to have an average density higher than *MR100*.

3.2 Mechanical properties

3.2.1 Time evolution of compressive strength

Figure 8 to Figure 10 highlight the time evolution of compressive strength: they report the average values measured at 2, 7, 28, 60, 90 and 365 days of curing. The plotted results point out the concurrent role played by both FAs and RCAs.

First of all, as for the former, it is apparent that before 28 days of curing, the strength of mixtures with FA is lower than the control mixture *N*: more specifically, none of them achieved the 28-day strength of the control mixture. Conversely, after a sufficiently longer curing time, these mixtures reach compressive strength values even higher than those achieved by the reference concrete, whose strength keeps almost constant after the conventional 28 day curing duration. This result is mainly due to the delayed binder properties of FA, which are exploited in a time longer than Portland cement [27]. Therefore, the compressive strength obtained for concrete mixtures produced with FAs and natural aggregate only (i.e., mixtures *LN*, *MN* and *HN*) is higher than the reference values and, although in *MN* and *HN* mixtures part of the FA was initially considered as an inert filler, it actually contributes to the resulting mechanical property at long curing age. These observations are a clue for claiming that the restrictions to using FA in concrete mixtures currently adopted by EN 450-1 [37] might be relaxed, if strength for this class of concrete is measured at sixty (or more) days of curing.

Moreover, with regards to the role of RCAs in concrete, Figure 8 to Figure 10 highlight that the use of RCA in concrete significantly affects its compressive strength. This effect can certainly be attributed to the higher porosity of RCA, as it results in a weaker structure in the solid skeleton of the concrete matrix. Nevertheless, recent studies demonstrated that this decay in strength is mainly due to an alteration of the "effective" free water actually available for cement hydration [15]: in fact, the effective water is not generally equal to the "nominal" one, as the higher water adsorption capacity of RCAs and their initial moisture condition can significantly affect free water. Since structural concrete mixtures are generally produced by using initially dry aggregates and adding water for their full saturation (considering their water absorption capacity at 24h), when this procedure is applied to RACs, the higher water absorption capacity of RCAs significantly modifies the total amount of water in the mixture and, hence, the effective water-to-cement (or, more generally, -binder) ratio. Based on experimental observations, Pepe [20] suggests defining this "effective" free water by adding 50% of the added water w_{add} to the nominally free one w_{free} (Table 4).

Therefore, the analysis proposed in the following are based upon the following generalised definition of the effective water-to-binder ratio $(w/b)_{eff}$ reported below:

$$\left(\frac{w}{b}\right)_{eff} = \frac{w + 0.5 \cdot w_{add}}{C + \rho \cdot FA} \quad (6)$$

Figure 11 shows that this $(w/b)_{eff}$ values and the corresponding compressive strength ones R_{cm} are closely correlated, especially for long curing time. As a matter of fact, the points group around a curve resembling the Abrams' law, widely accepted for expressing the relationship between w/c and R_{cm} in ordinary concrete. Therefore, this observation confirms the sound definition of the ratio $(w/b)_{eff}$, intended at generalising the concept of w/c for taking into account the various peculiarities of the concrete mixtures under consideration, such as the effect of FA, the initial moisture condition and the actual water absorption capacity of RCAs.

3.2.2 Tensile splitting strength

Figure 12 reports the mean values of the average tensile splitting strength f_{ctm} determined on cylindrical specimens at 28 days of curing. These results demonstrate that, at the conventional curing time, the concrete mixtures made with natural aggregates and FA exhibit a tensile strength higher than the control one. However, the actual content of FA does not affect significantly the tensile strength of the concretes under consideration. Moreover, as well as in the case of compressive strength, the tensile strengths progressively decrease by increasing the replacement ratio of NAs with RCAs.

3.3 Durability-related properties

3.3.1 Water permeability tests

Figure 13 depicts the contour lines typically describing the wet surface resulting at the end of some of these permeability tests, carried out at both 90 and 365 days of curing on two different samples of the thirteen mixtures under investigation.

Figure 14 reports the values of average water penetration depth h_m (defined in Section 2) obtained from the aforementioned tests. Unfortunately, the results of tests performed on cubic samples made of mixture *LR100* are not available, as they failed under the water pressure. The following considerations can be drawn out from the results plotted in Figure 14:

- concrete mixtures produced with RCAs and FA generally exhibit lower water penetration depth in comparison with the reference mixture, both at 90 and 365 days of curing;
- except for the reference mixture, the difference in water penetration measured on specimens cured for 90 and 365 days are in the order of magnitude of the dispersion usually affecting experimental observations of physical properties in concrete;
- concrete permeability significantly decreases by adding FA to the concrete mixture; however, this decrease is quantitatively significant when FA is added in replacement of cement for mixtures L and it is still appreciable when part fine aggregates of mixtures L are replaced by FA in mixture M; conversely, no further reduction are observed for higher amounts of FA;
- concrete permeability appears not to be significantly influenced by the total amount of RCAs.

A predominant role of FA clearly emerges from these experimental results and comments, as mixtures containing higher amounts of FA are characterised by lower water permeability. As already observed in the scientific literature [23][27][49], this is because FA, due to its small diameter particles, influences the microstructure of paste and enhances water tightness in concrete: in the mixtures under considerations, FA is even capable to counterbalance the possible increase in porosity and, hence, water permeability expectedly induced by RCAs: in fact, Figure 14 shows that mixtures with higher aggregate replacement percentage have generally lower water permeability than the reference ones with only FA.

Moreover, the influence of FA is further highlighted by Figure 15, which “aggregates” the results of water penetration h_m for the three groups of mixtures. It shows that the increase in FA, characterising the *M* mixtures with respect of the *L* ones, results in a significant reduction in water penetration. However, further increasing the amount of FA (as from M to H mixtures) does not have any quantitatively relevant effects. Therefore, a threshold behaviour is highlighted for the FA content with respect to the resulting reduction in water permeability.

3.3.2 Rapid chloride-ion penetrability tests

Figure 16 reports the electric charge (in Coulombs) passing through each cylinder, in 6 hours. The results reported therein demonstrate that a significant attenuation of the chloride-ion penetration phenomenon can be achieved by adding FA to the concrete mixtures. Conversely, the higher the percentage of RCAs, the lower the resistance to chloride-ion penetration.

Furthermore, all the concrete mixtures containing FA exhibit resistances to the chloride-ion penetration at 365 days remarkably lower than the corresponding value achieved at 90 days of curing. This can be attributed to the slower reaction of FA, which contributes to make concrete mortar less permeable to chlorides.

Finally, the obtained experimental results clearly indicate that water permeability results cannot be correlated to resistance to the chloride-ion penetration, especially when RCAs are used in concrete (Figure 17). As already documented in the literature [50], this lack of correlation between two supposedly similar phenomena may be explained by the different transport mechanisms developing in the two phenomena.

3.3.3 Carbonation tests

Figure 18 depicts the obtained carbonation depths, determined by means of equation (5), based on the experimental observations.

First of all, as expected, the results confirm that carbonation is higher for concrete specimens tested after 365 than 90 days of curing. Secondly, all the mixtures realised with RCAs and FAs were generally affected by a higher value of carbonation depth with respect to the control mixture *N*. Moreover, the presence of RCAs significantly reduces carbonation resistance in all the three specimens series.

Since carbonation is mainly controlled by the chemical, physical and mechanical characteristics of concrete paste, it is interesting to analyse the experimental values of D in connection with the corresponding effective water-to-binder ratio defined by equation (6). Figure 19 reports the values $(w/b)_{eff}$ and the corresponding estimates of D: it points out that higher values of the former result in deeper carbonation layers. This analysis highlights that, as well as for water permeability, carbonation is more influenced by paste than aggregates. In fact, the mixtures with high percentage of RCAs show higher values of D, as they are also characterised by the higher water/binder ratios.

Moreover, as well know from the literature [51], the carbonation depth D can be correlated with time through the following equation:

$$D = k_c \cdot \sqrt{t} \tag{7}$$

where k_c is the carbonation factor and t is the air exposure time.

Figure 20 confirms that, also for the concrete mixtures under investigation, a liner relationship between D and the square root of the time can be determined. Moreover, for deeper investigating the role of FA and RCA on the carbonation mechanism diffusion, the k_c factor variation is plotted in Figure 21. The trends observed in the figure confirm the fact that both the presence of FA and RCA accelerates the carbonation process in comparison with the reference *N* mixture. In fact, the highest values of the carbonation factor are registered for the *H* mixtures, characterised by the higher amount of FA and, an higher amount of RCA causes an increasing in the carbonation factor. On the other hand, the *L* mixtures present higher values of carbonation factor in comparison with the *M* mixtures, despite the latter were produced with an higher amount of FA. This evidence can be explained, again, by considering the effective water-to-binder ratio values (Table 4): the *L* mixtures are characterised by a significantly more porous matrix (being higher the effective water-to-binder ratio) in comparison with the *M* and this can, certainly, explain the unexpected trend observed in Figure 21.

4 CONCLUSIONS

This paper analysed mechanical performance and durability-related properties of sustainable structural concrete produced with recycled concrete aggregates and fly ash. The following conclusion can be drawn out:

- the results presented herein demonstrate the feasibility of using recycled constituents for producing a durable sustainable concrete mixtures, suited for structural applications, at least for constructions that are not exposed to severe environmental conditions;

- the lower mechanical and durability performance of RAC, generally induced by the high porosity of RCAs, can be compensated by the presence of FA;

- the chloride ions penetration is affected by the presence of RCA in concrete, but, at the same time, FA enhances the resistance to chloride-ion penetration;

- the carbonation depth is mainly controlled by the paste characteristics: it is higher for higher values of the effective water-to-binder ratio defined in this study;

- overall, the results obtained in this study demonstrate that the limitations to the use of FA (EN 206 [42]) and RCAs ([13]) as constituents in structural concrete might be significantly relaxed, especially in the case of a combined use of both, and in cases of no special requirements in terms of strength and durability.

Finally, the results reported herein, along with the other ones recently published in the international scientific literature, can contribute at assembling a database of experimental information needed to formulate and calibrate models capable to predict mechanical and durability-related phenomena, which control the resulting properties of the sustainable concrete considered in this research.

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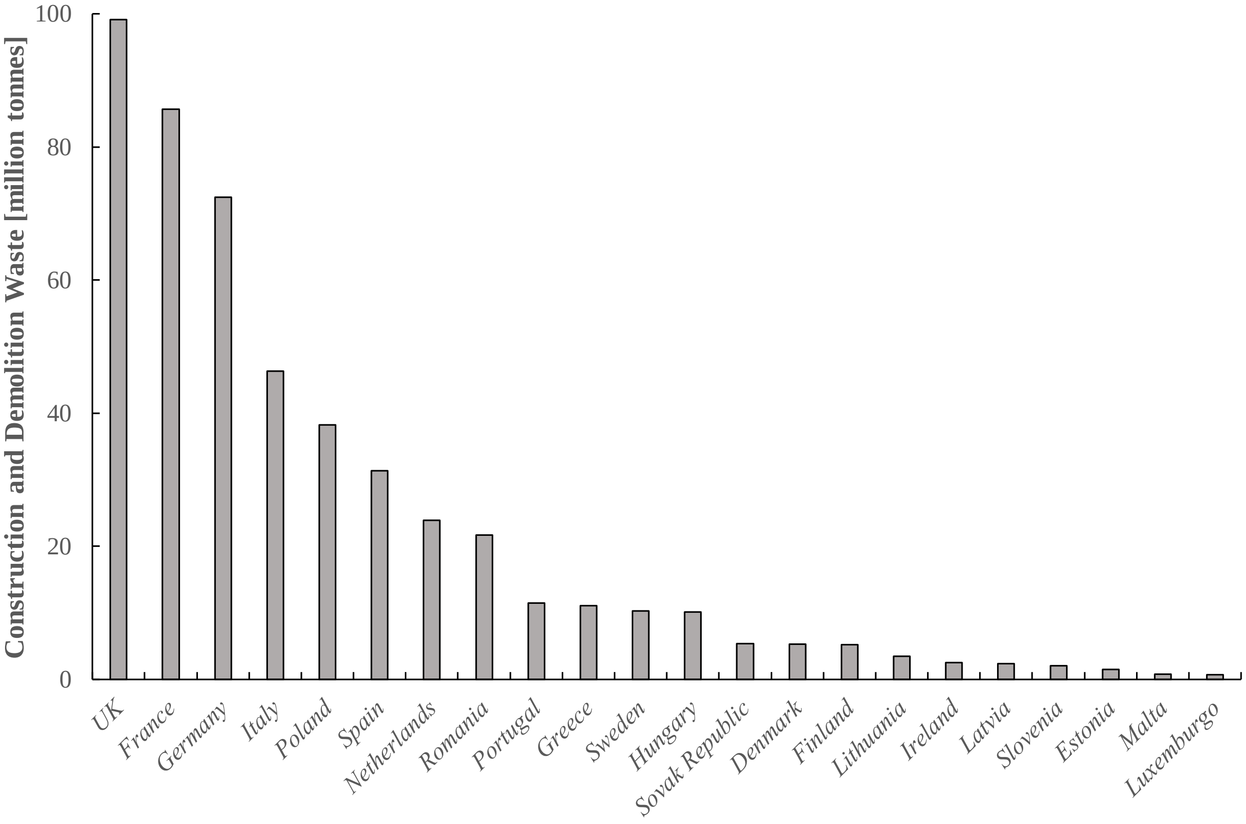


Figure 1: Annual production of Construction and Demolition Waste in Europe [9].

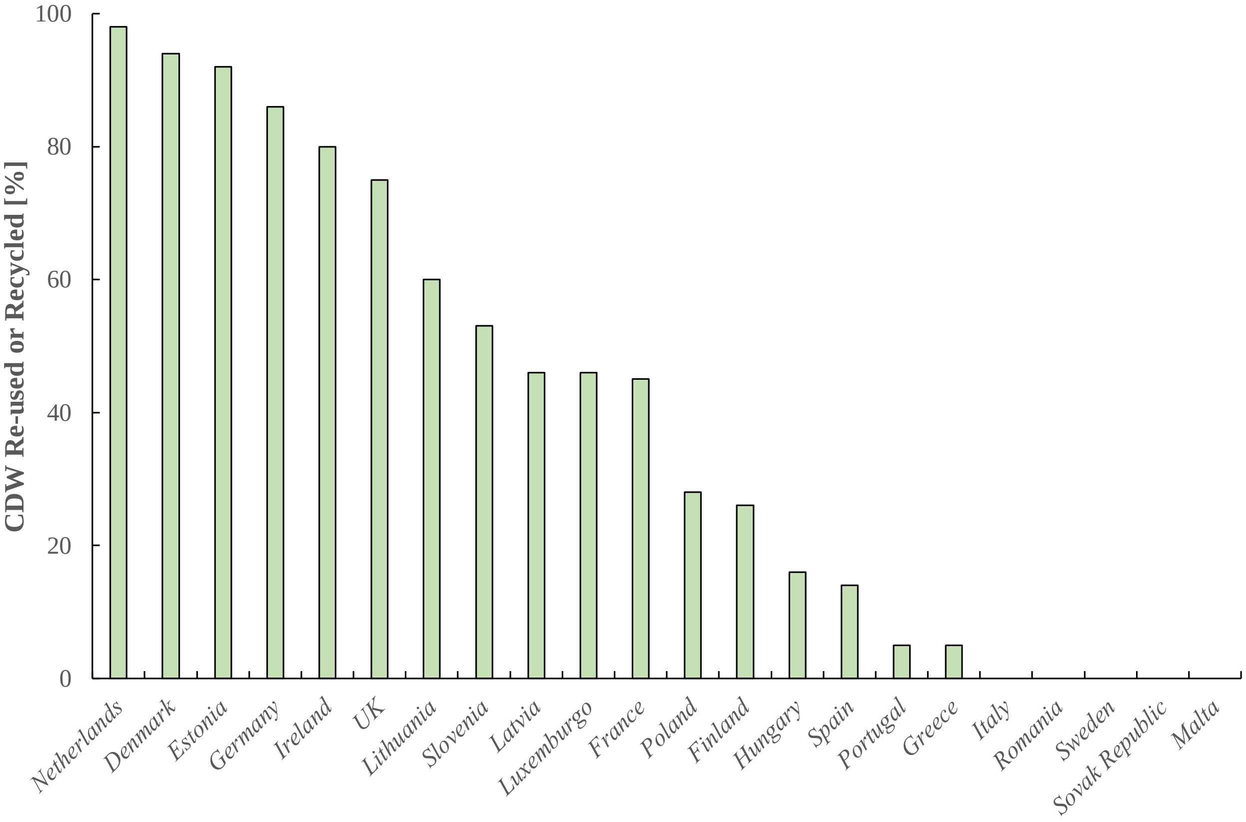
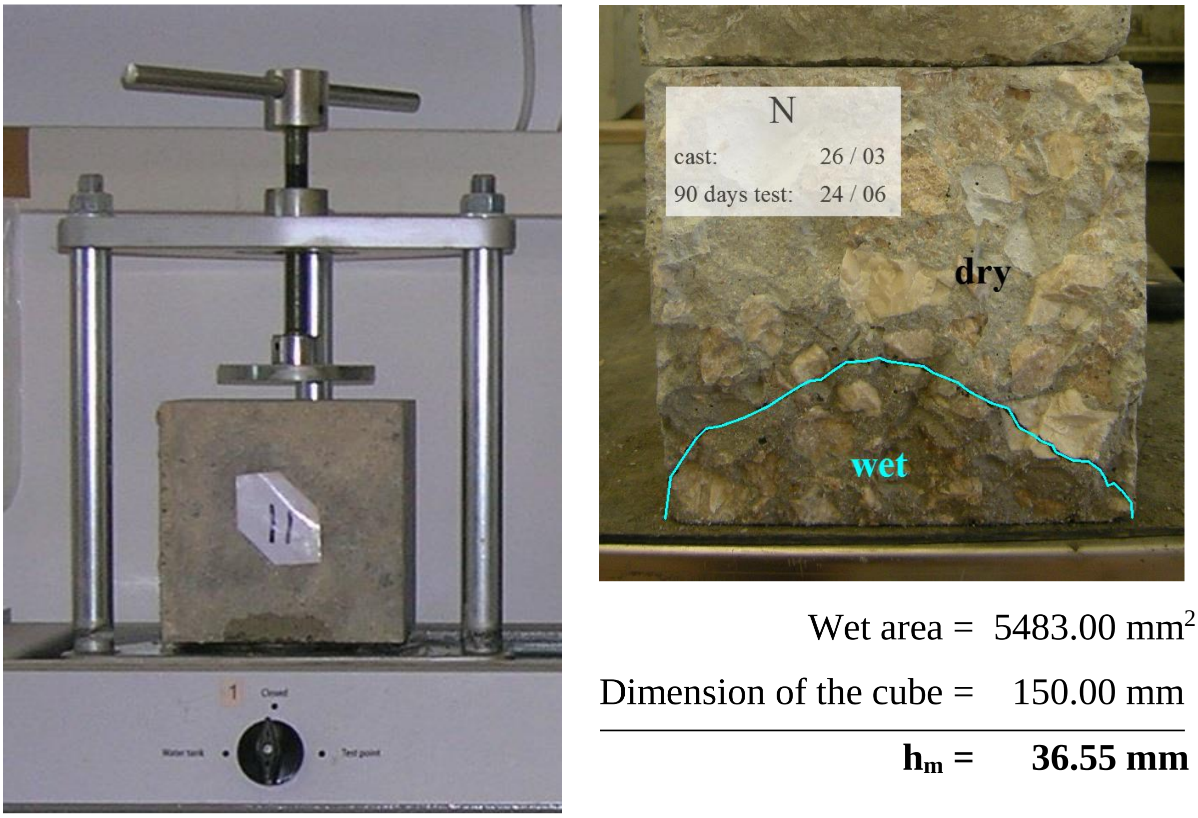


Figure 2: Re-use and Recycling of Construction and Demolition Waste in Europe [9].

Figure 3: Concrete cylinders used for chloride-ion penetration tests.



Wet area = 5483.00 mm^2

Dimension of the cube = 150.00 mm

h_m = 36.55 mm

Figure 4: Water permeability tests.

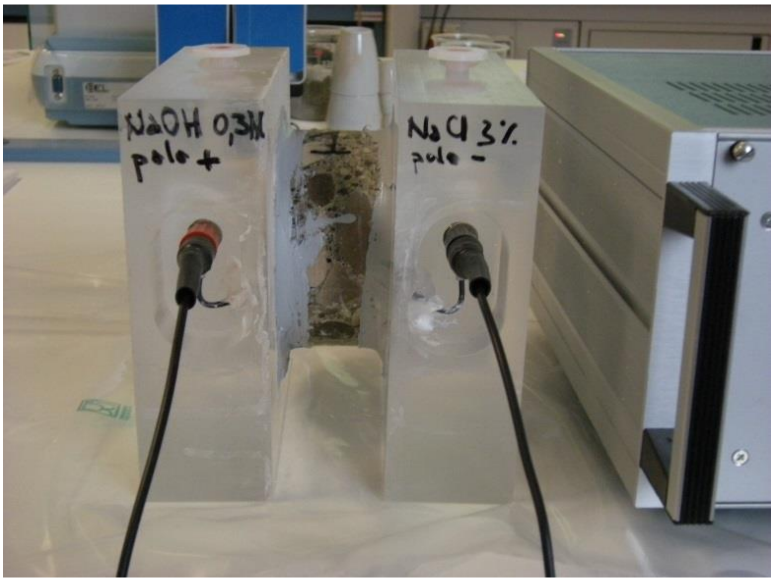


Figure 5: Chloride-ion penetration tests.

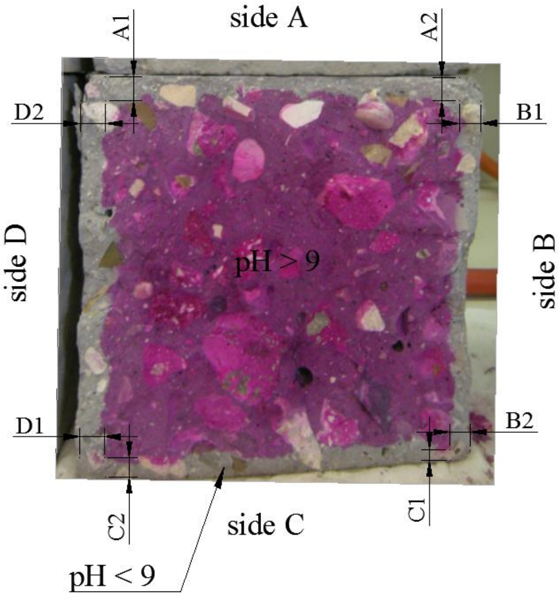


Figure 6: Carbonation test.

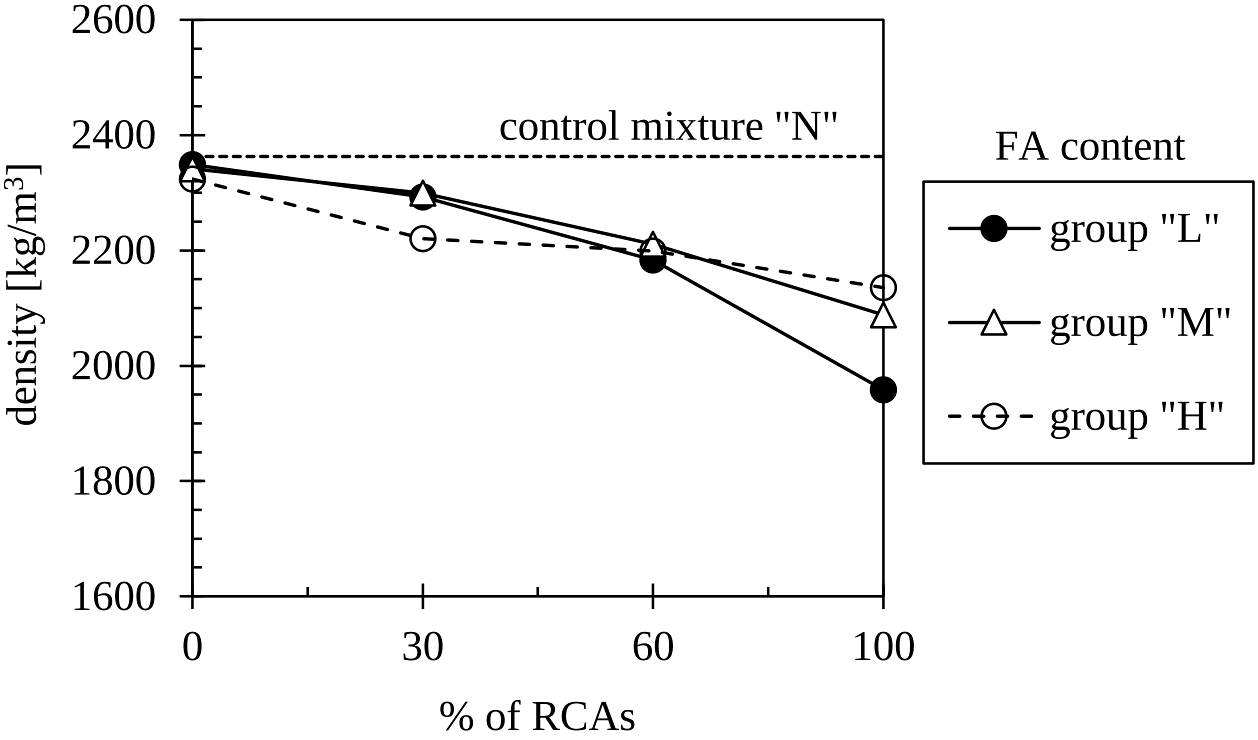


Figure 7: Density of concrete mixtures.

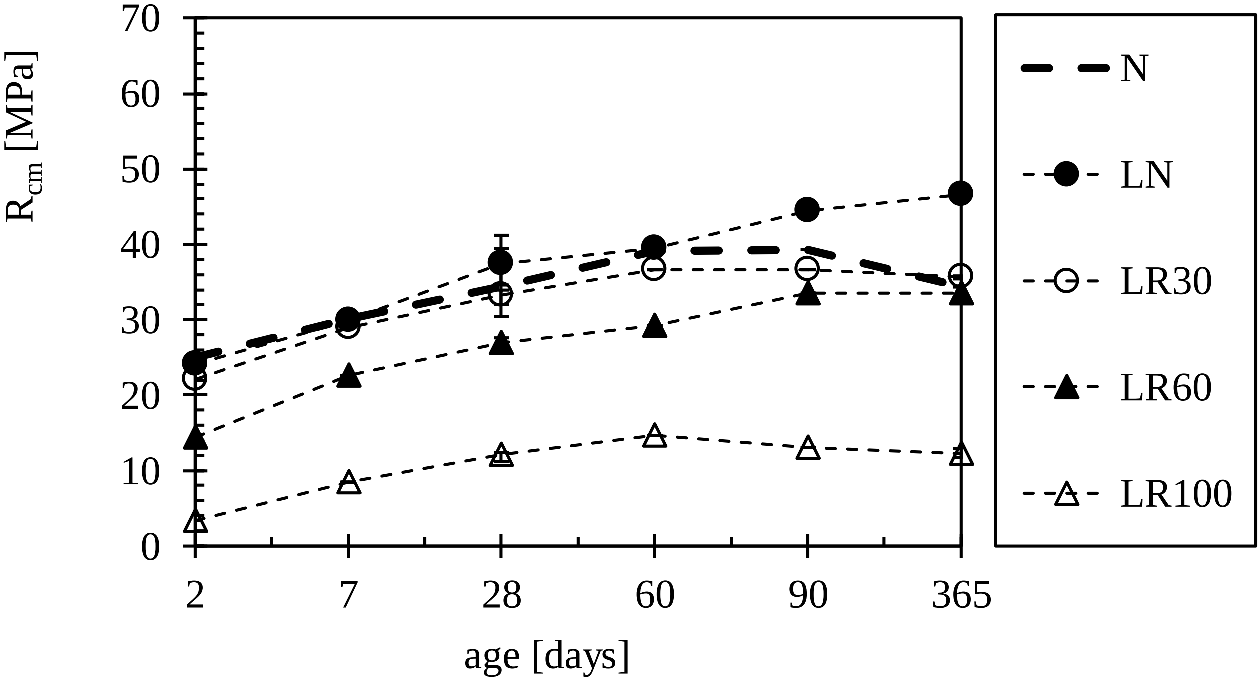


Figure 8: Compressive strength of NAC and RAC with low content of FA.

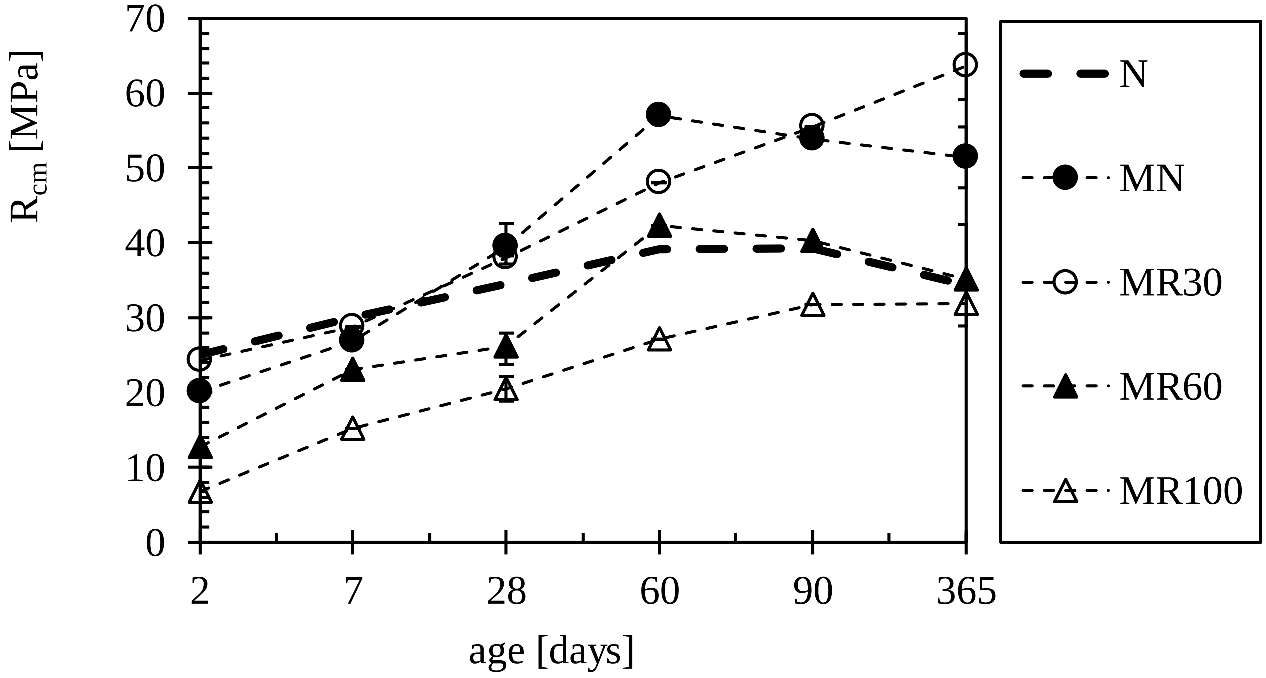


Figure 9: Compressive strength of NAC and RAC with medium content of FA.

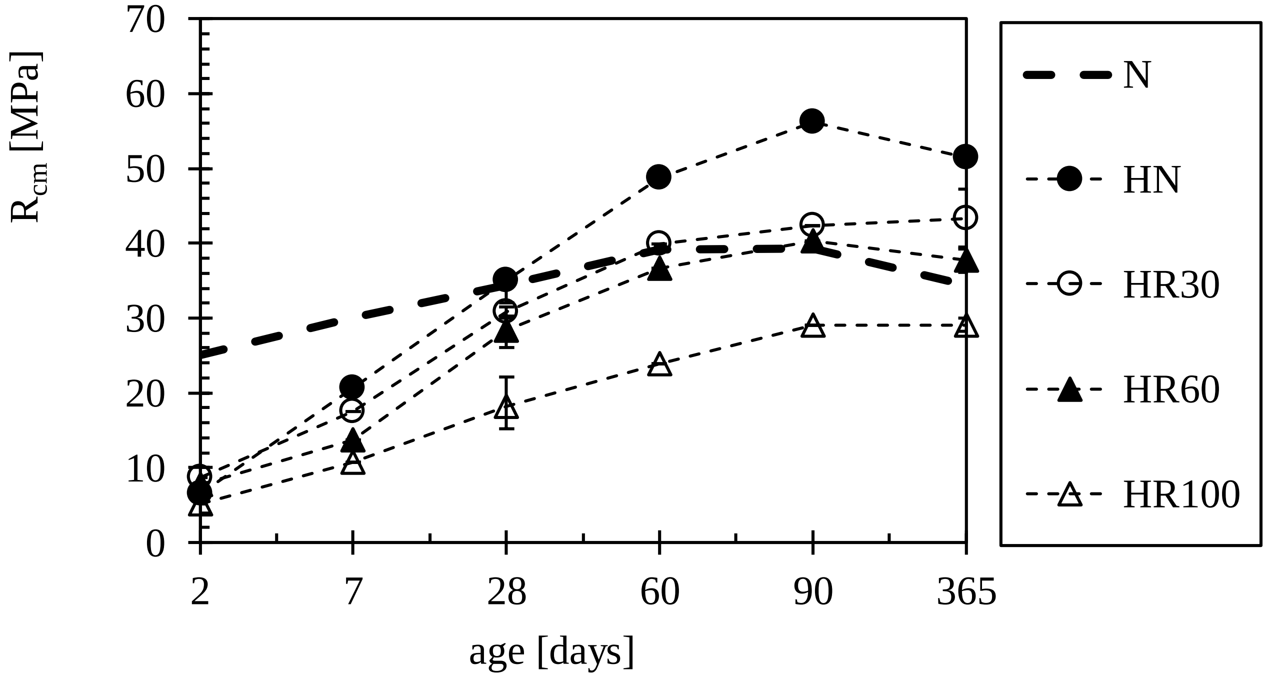


Figure 10: Compressive strength of NAC and RAC with high content of FA.

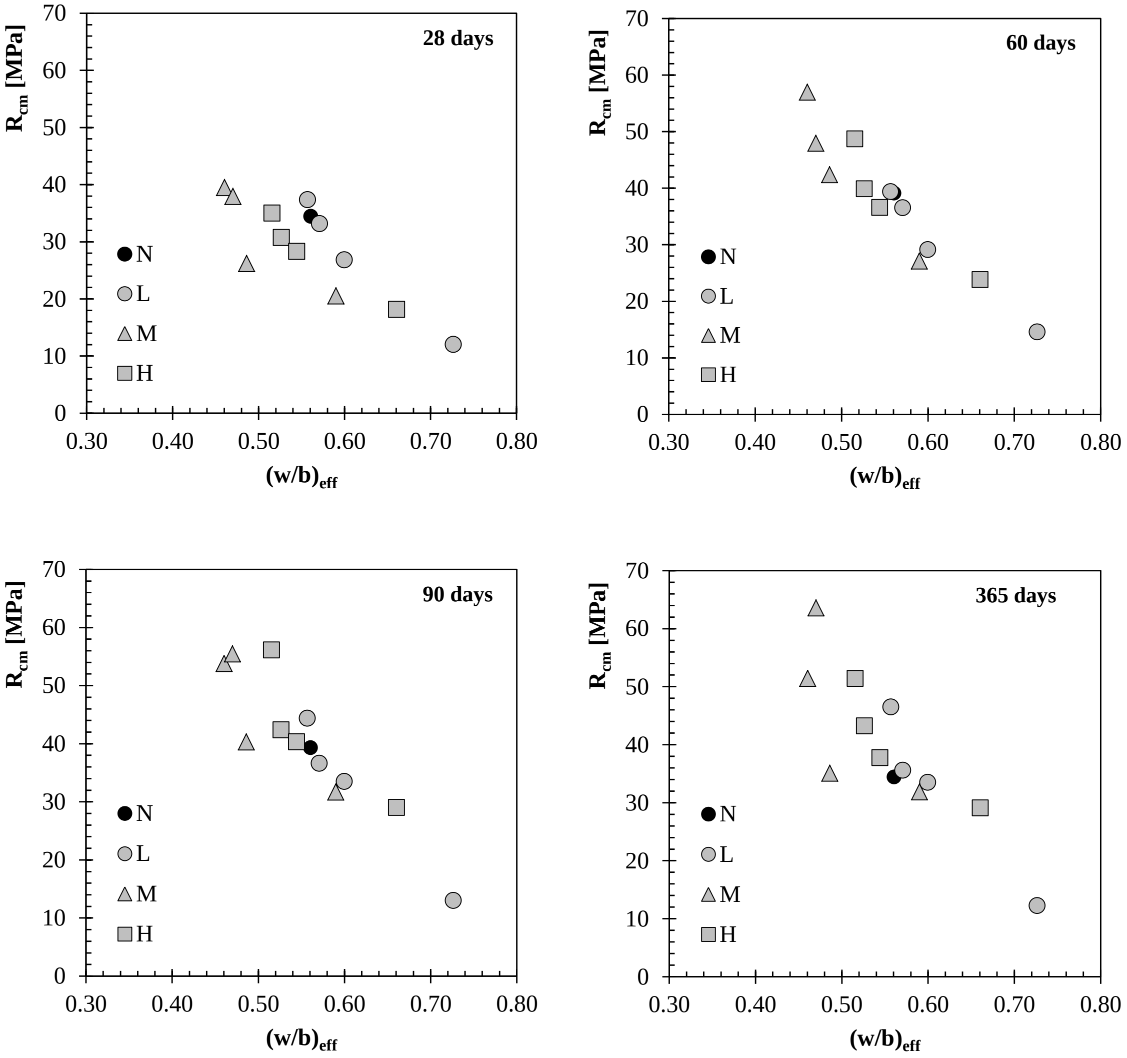


Figure 11: Compressive strength vs effective water-to-binder ratio.

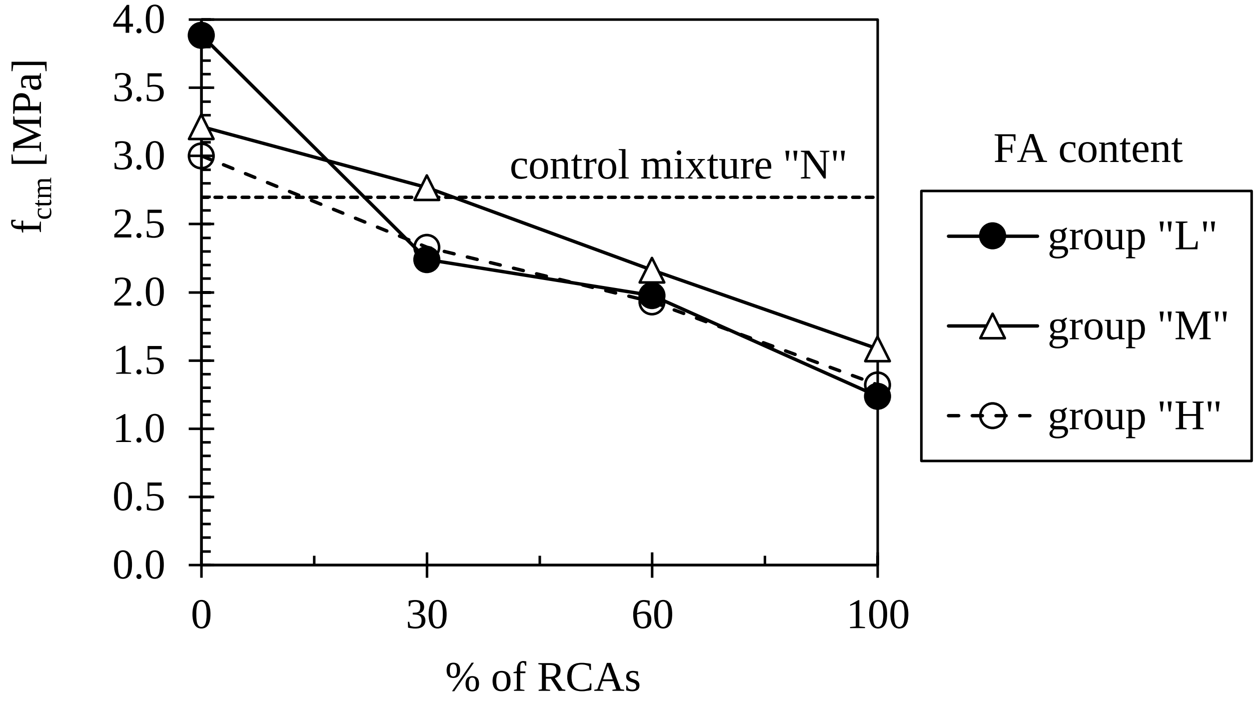


Figure 12: Splitting tensile strength of concrete mixtures at 28 days.

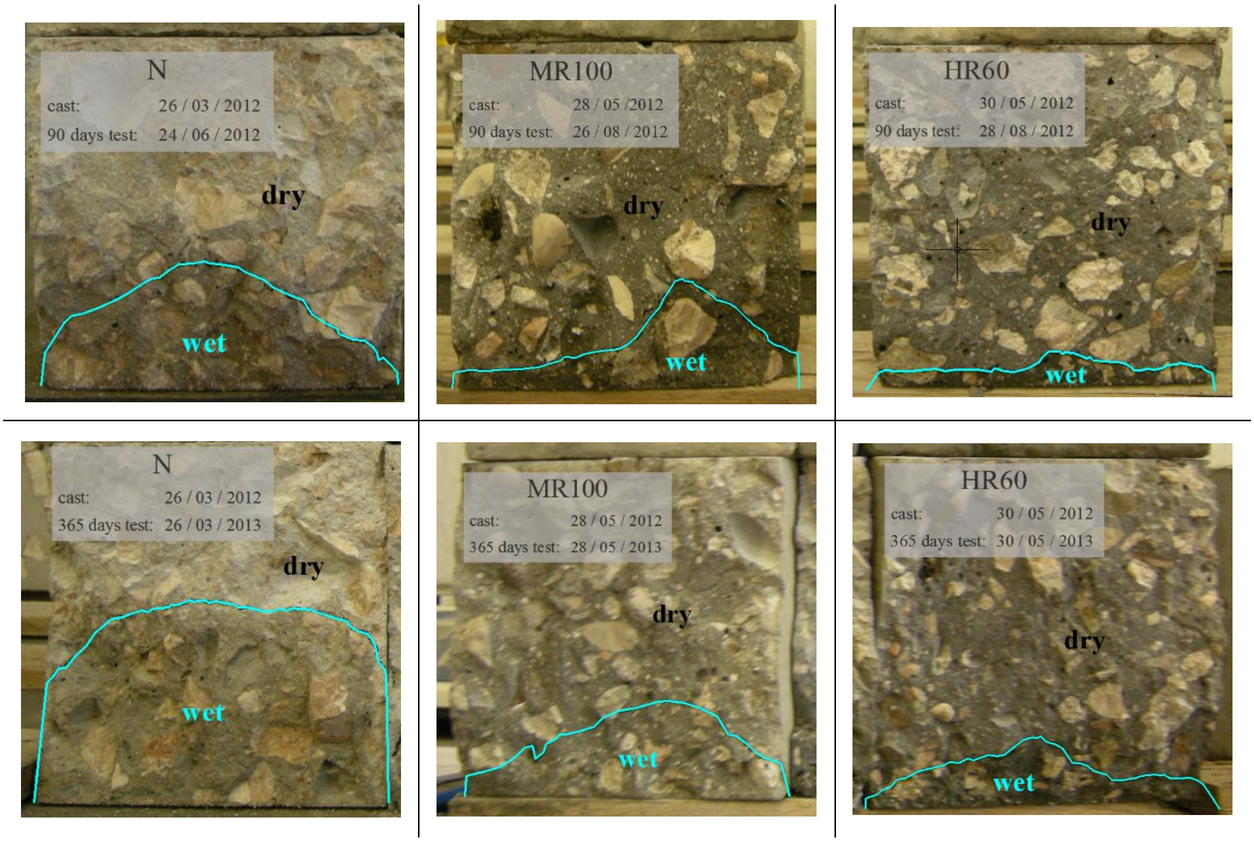
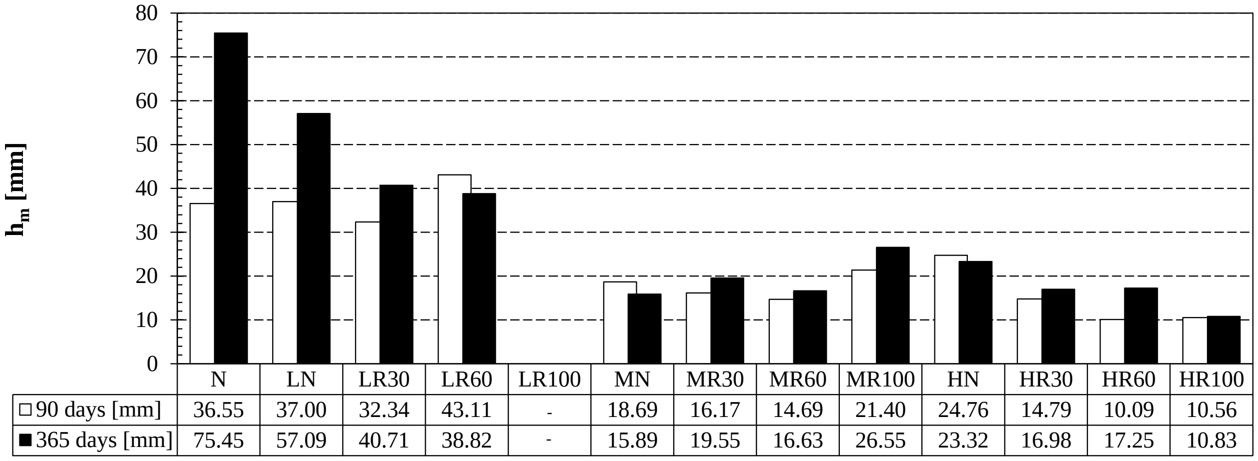


Figure 13: Some results from water permeability tests.



	N	LN	LR30	LR60	LR100	MN	MR30	MR60	MR100	HN	HR30	HR60	HR100
□ 90 days [mm]	36.55	37.00	32.34	43.11	-	18.69	16.17	14.69	21.40	24.76	14.79	10.09	10.56
■ 365 days [mm]	75.45	57.09	40.71	38.82	-	15.89	19.55	16.63	26.55	23.32	16.98	17.25	10.83

Figure 14: Experimental values of the water penetration depth tests.

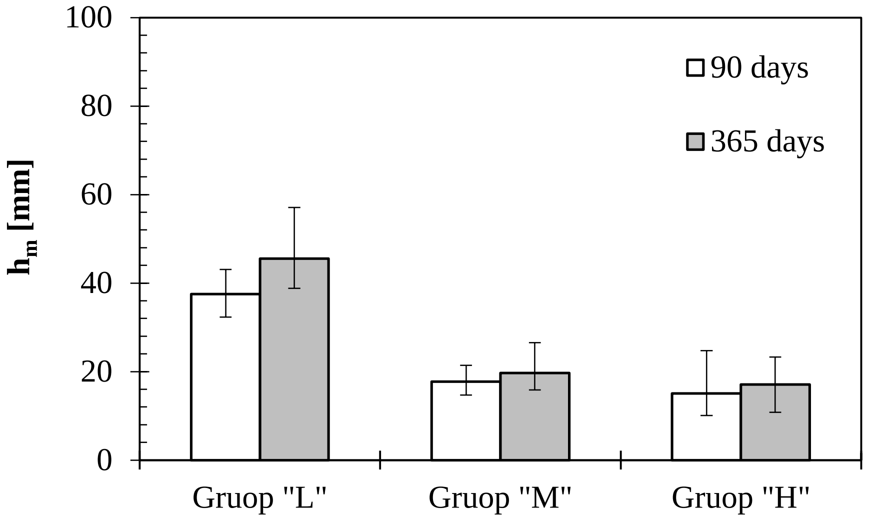
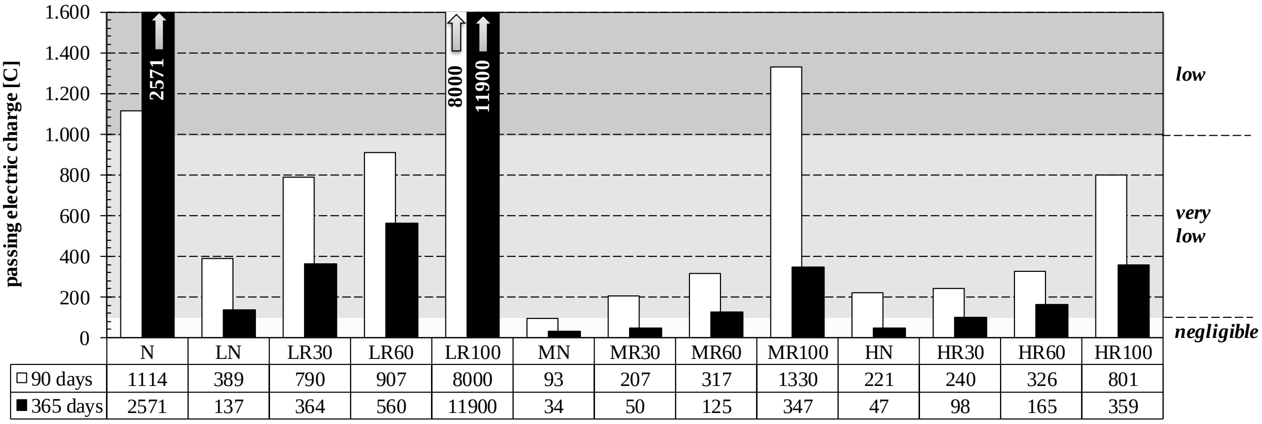


Figure 15: The infleuce of RCAs and FAs on water penetration depth for concrete.



	N	LN	LR30	LR60	LR100	MN	MR30	MR60	MR100	HN	HR30	HR60	HR100
□ 90 days	1114	389	790	907	8000	93	207	317	1330	221	240	326	801
■ 365 days	2571	137	364	560	11900	34	50	125	347	47	98	165	359

Figure 16: Results of chloride ion penetration tests.

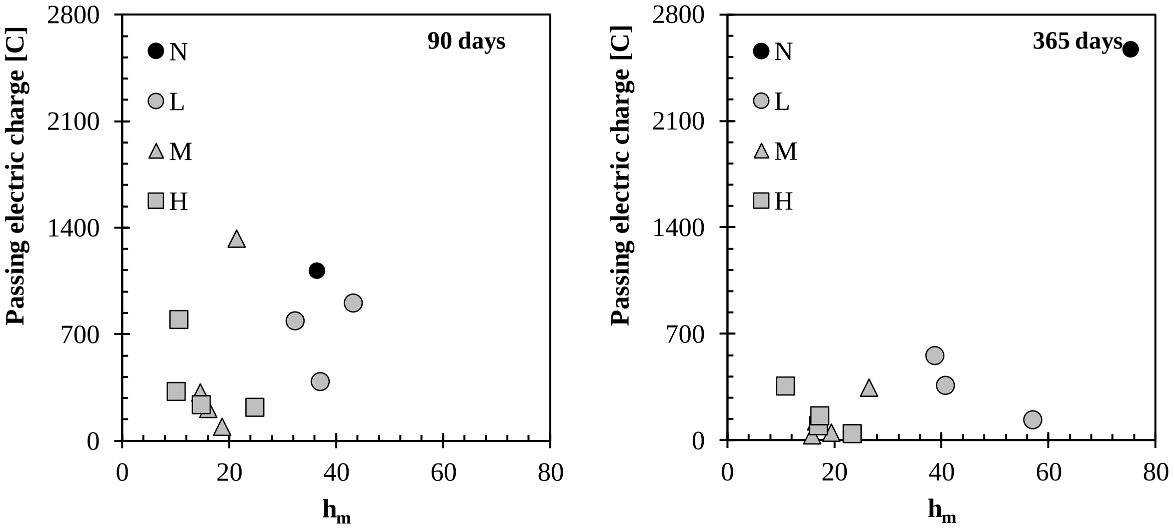
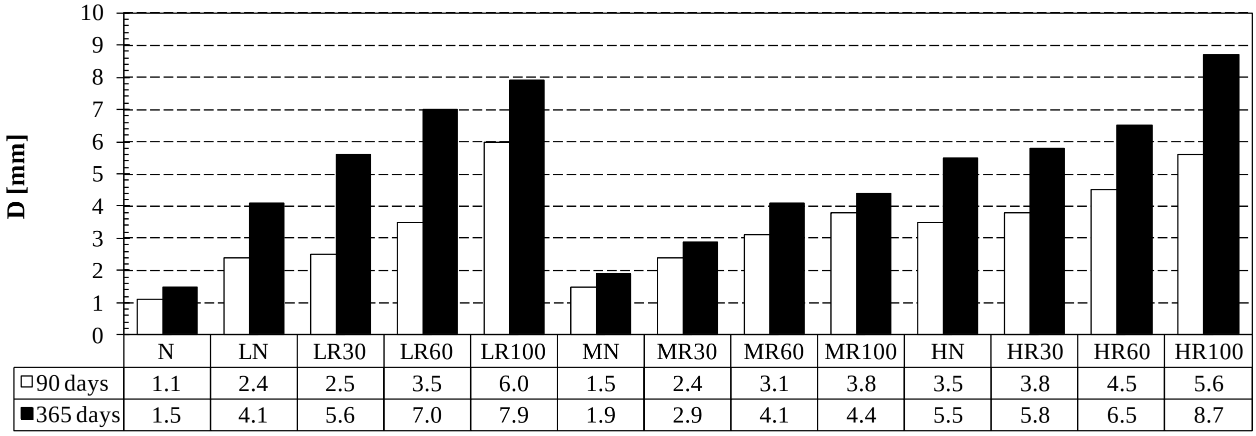


Figure 17: Water penetration depth – Passed charge.



	N	LN	LR30	LR60	LR100	MN	MR30	MR60	MR100	HN	HR30	HR60	HR100
□90 days	1.1	2.4	2.5	3.5	6.0	1.5	2.4	3.1	3.8	3.5	3.8	4.5	5.6
■365 days	1.5	4.1	5.6	7.0	7.9	1.9	2.9	4.1	4.4	5.5	5.8	6.5	8.7

Figure 18: Carbonation depths of all concrete specimens.

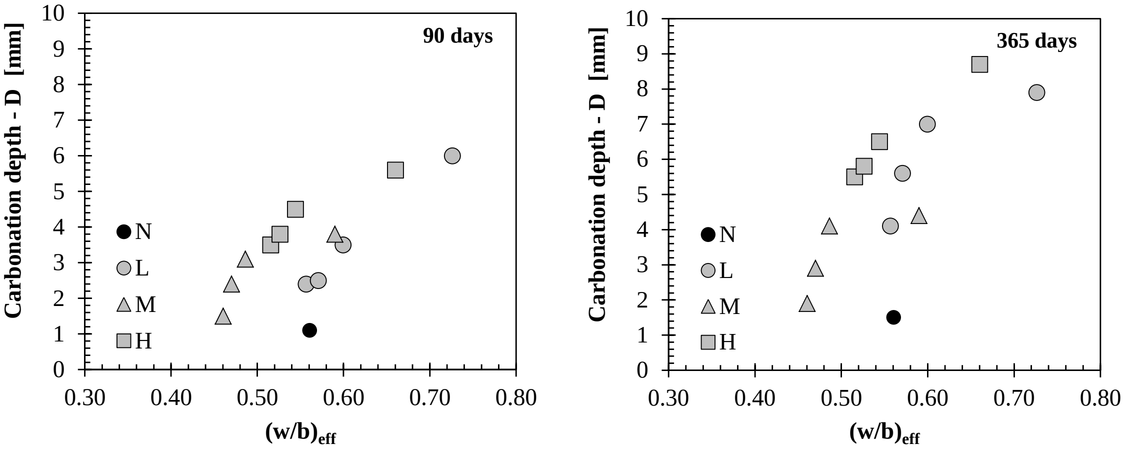


Figure 19: The influence of the effective water-to-binder ratio on carbonation depth for sustainable concrete.

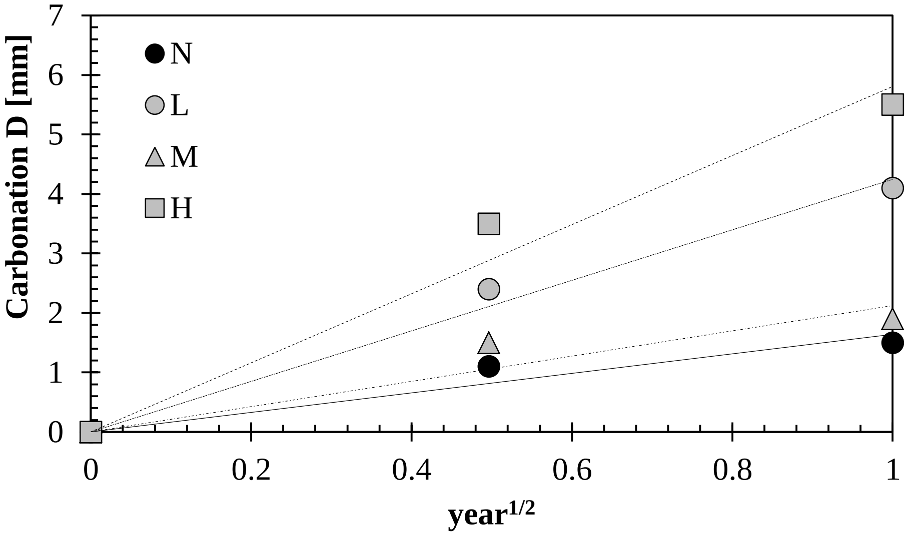


Figure 20: Calibration of the carbonation coefficient for the concrete mixtures.

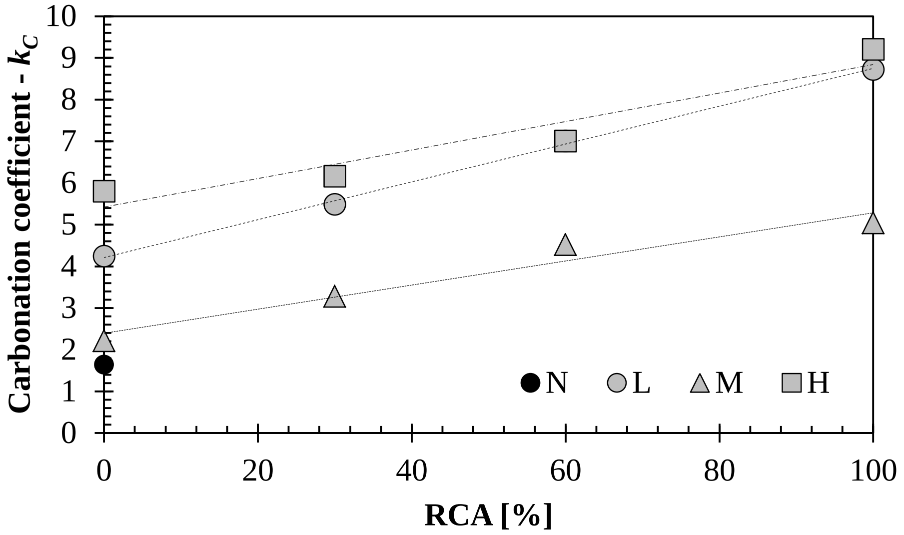


Figure 21: Influence of RCAs and FAs on the carbonation coefficient for concrete.

Table 1: Chemical composition and physical properties of cement and fly ash.

Chemical compound	**CEM I 42.5 R**	**Fly ash**
CaO (%)	64,06	2,30
SiO_2 (%)	18,90	46,90
Al_2O_3 (%)	4,90	28,50
Fe_2O_3 (%)	3,66	6,22
SO_3 (%)	2,92	0,04
MgO (%)	0,82	1,23
Loss of Ignition (%)	3,18	6,20
Specific gravity (kg/m^3)	3110	2100

Table 2: Sieved aggregates used in concrete mixtures.

Index		RCA	NA
Shape Index	EN 933-4	SI 20	SI 15
Flakiness Index	EN 933-3	FI 20	FI 15
Particle density	EN 1097-6	2369 kg/m^3	2690 kg/m^3
Water absorption	EN 1097-6	1.8 – 12.2 %	0.3 – 1.2 %

Table 3: Size fractions, mass densities and water absorption capacity of NAs and RCAs.

Fraction range [mm]		Mass density [kg/m^3]		Water absorption [%]	
		Natural Aggregates	Recycled Aggregates	Natural Aggregates	Recycled Aggregates
N3:	20 - 31.5	2690	2370	0.3	1.8
N2:	10 – 20			0.5	3.0
N1:	2 – 10			0.7	6.0
Sand:	0-2			1.2	12.2

Table 4: Concrete mixtures.

Mixture	**CEM I 42.5R** [kg/m^3]	**FA** [kg/m^3]	**RCA** [%]	w_{free} [l/m^3]	w_{add} [l/m^3]	w_{free}/b	$(w/b)_{eff}$
N	280	0	0	150	14.02	0.54	0.56
LN	250	80	0	150	14.02	0.53	0.56
LR30	250	80	30	150	21.86	0.53	0.57
LR60	250	80	60	150	38.16	0.53	0.60
LR100	250	80	100	150	109.65	0.53	0.73
MN	250	220	0	150	11.28	0.53	0.46
MR30	250	220	30	150	17.85	0.53	0.47
MR60	250	220	60	150	28.68	0.53	0.49
MR100	250	220	100	150	98.84	0.53	0.59
HN	200	255	0	150	11.28	0.64	0.52
HR30	200	255	30	150	17.85	0.64	0.53
HR60	200	255	60	150	28.68	0.64	0.54
HR100	200	255	100	150	98.84	0.64	0.66

Table 5: Chloride ions penetrability vs charge passed.

Charge Passed (coulombs)	**Chloride ions Penetrability**
> 4 000	High
2000 – 4 000	Moderate
1000 – 2 000	Low
100 – 1 000	Very Low
< 100	Negligible