



Mechanical and durability performance of concrete produced with recycled aggregates from Greek construction and demolition waste plants

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ABSTRACT

Greece has to recycle 70% of Construction and Demolition Waste (CDW) by 2020, in the context of the enforcement of Waste Framework Directive (WFD) 2008/98/EC. CDW recycling has started only recently to a small extent and is restricted to road works. The reuse of CDW in new concrete production could contribute to the construction sector sustainability through minimizing landfill and the need for new raw materials. Literature data are found regarding the performance of recycled concrete, but limited knowledge is available regarding the chemical and mineralogical properties of recycled aggregates (RA) and how these affect concrete. Moreover, Greek aggregates are not siliceous aggregates as are most of the aggregates investigated in literature. Against this background, this study aims to evaluate for the first time mechanical and durability performance of concrete made with RA from different Greek recycling plants. All recycled materials used were characterized in terms of chemical and mineralogical composition and certain chemical and physical properties have been determined. It was found that all RA are enriched in Si, Al, and alkali oxides, which was mineralogically verified by the identification of quartz and minor quantities of mica and feldspars. They proved though innocuous to alkali aggregate reaction. Higher water absorption of coarse RA is their most negative physical characteristic. Fine fractions of RA have low Sand Equivalent and significantly high water absorption values, which make them unsuitable to replace natural sand. Water soluble ions are at the same level to that of natural aggregates.

Furthermore, concrete mixtures were prepared using an RA percentage ranging from 0% to 75%. Results indicate that the compressive strength of recycled concrete ranges from significantly lower (37% reduction) to equal, compared to conventional concrete, depending on the composition of RA. The majority of literature data relate the inferior quality of RA to their high water absorption, the findings of the present research though indicate that the presence of clay minerals has a more pronounced adverse effect to concrete's strength. As for the durability properties examined, i.e. water absorption, sorptivity, frost and carbonation resistance, the recycled concrete mixtures exhibited somewhat lower performance than reference concrete.

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1. Introduction

The recycling of Construction and Demolition Waste (CDW) has been recognized by the EC as an important step towards the sustainability of the construction sector. This is stated in the Waste Framework Directive (WFD) 2008/98/EC, according to which the target of 70% recycling has to be achieved by 2020. As it is reported in

RILEM TC 217-PRE Report (2013) as well as by Poon (2007), Li (2008, 2009) and Hadjieva-Zaharieva et al. (2003) the need for recycling CDW's has been identified in most developed countries and generally the interest for using recycled materials is increasing worldwide, especially where the availability of landfill places is low. Although the construction sector is the largest waste stream in EU, as it was also the case in Greece before 2010 when the economic crisis started, recycling percentages vary significantly among the member states from 90% (Germany, Netherlands) down to 5% (Greece, Cyprus).

Recycled Aggregates (RA) are mainly used in road sub base and earth works. Their restricted use in structural concrete is mainly

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attributed by the lack of confidence in the performance of these materials as it is presented in various cases in [RILEM TC 217-PRE Report \(2013\)](#).

Important research has been published concerning the effect of using RA on the mechanical performance of concrete. [Etxeberria et al. \(2007\)](#) used recycled coarse aggregates in wet condition from a waste recycling area in Spain and studied the influence on compressive strength, tensile strength and modulus of elasticity by preparing concrete mixtures of medium strength (25–35 MPa). According to their results, use of 100% recycled coarse aggregates results in 20–25% less compression strength, 2–10% less tensile strength and 16–17% lower modulus of elasticity than conventional concrete at all ages with the same effective w/c ratio.

[Tabsh and Abdelfatahl \(2009\)](#) used laboratory crushed aggregates from old 30 and 50 MPa concrete as well as commercially available RA from a dump site and made 30 and 50 MPa concrete mixtures with 100% coarse RA. Their results showed that the strength of the old concrete favors the strength of the new recycled concrete since the use of coarse aggregates made from 50 MPa old concrete produced a concrete with compressive and tensile strength comparable to that of conventional concrete. On the other hand the percentage loss of compressive strength of concrete made with commercial RA was 35% for 30 MPa concrete class and 15% for 50 Pa concrete class. In addition, the percentage loss of tensile strength was 30% and 20% respectively.

On the other hand, [Rahal \(2007\)](#) prepared in the laboratory coarse aggregates by crushing waste concrete beams of two old buildings in Kuwait and found that concrete mixtures with target cube strength between 20 and 50 MPa, prepared with 100% coarse RA in saturated surface dry (SSD) condition exhibited only a 10% decrease in strength.

Moreover, according to the test results of [Sagoe-Crentsil et al., 2001](#), there is no significant difference in compressive and tensile strength between recycled and conventional concrete. The authors evaluated the performance of 25 MPa grade concrete containing 100% crushed and graded coarse RA from a recycling plant in Australia. The recycled aggregates were used in presaturated condition.

To the contrary, the use of fine RA from crushed concrete has been found detrimental by [Khatib \(2005\)](#). The reduction of 28d compressive strength at 25–75% replacement was found to be 25% but at a 100% replacement with RA it reached 36%. On the other hand no significant reduction was observed when fine aggregates from crushed brick replaced natural sand. With up to 50% replacement, the long-term strength is similar to that of the control, whereas at 100% replacement, only less than 10% reduction is observed.

Durability performance is reported to be inferior by [Bravo et al. \(2015a\)](#) but acceptable by [Abbas et al. \(2009, 2009\)](#) studied freezing and thawing resistance, chloride penetration and carbonation of mixtures made with two types of coarse RA from old concrete, specifically limestone and granitic aggregates. The relative dynamic modulus was found to range from 90% to 100% demonstrating that all mixtures had a good performance against freezing and thawing. Carbonation depths up to 7 mm were measured at all specimens throughout the 140 days of exposure in an accelerated carbonation chamber with 3% CO₂. Carbonation coefficients ranged from 0.51 mm/day for reference concrete to 0.63 mm/√day for recycled concrete with recycled limestone aggregates. Respective values for specimens containing granitic RA were 0.54 mm/√day to 0.51 mm/√day. The increased carbonation coefficients observed in the case of mixtures with recycled limestone aggregates were attributed by the authors to the lower cement content of the new concrete. On the other hand despite the fact that the mixtures with recycled granitic aggregates also contained lower content of

cement, they exhibited carbonation coefficients similar to the reference concrete. The authors attributed this difference to the presence of fly ash in the old aggregates that compensates for the lower alkalinity of the new mixtures.

[Bravo et al. \(2015b\)](#) evaluated the durability performance of recycled concrete made with RA from different waste recycling plants in Portugal. For that purpose, absorption by immersion and capillarity, carbonation resistance and chloride ion penetration resistance were measured. The replacement percentages examined were 10%, 25%, 50% and 100% of coarse as well as fine aggregates. The composition of these RA was visually analyzed and found to consist of 68–86% concrete, mortar and natural sand and 1%–29% masonry-clay materials. Water absorption by immersion was found not to be affected up to 25% replacement of coarse aggregates and up to 10% replacement of fine ones. Beyond these percentages the increase of water absorption of the mixtures with coarse aggregates ranges from 0.9% to 20.6% for 50% replacement and from 16.5% to 52.9% for 100% replacement. The authors justified these significant variations by the additional water needed to keep the slump constant, the greater water absorption of the recycled aggregates and the higher content of ceramic materials in the recycled aggregates from certain recycling plants. Water absorption by capillarity (g/mm²) generally increased with the aggregates replacement ratio. Beyond 10% the results of the mixtures with coarse aggregates showed wide scatter ranging from –6.3% to +22.2% at 25% replacement, –3.9%–28.2% at 50% replacement and 11.8%–44.6% at full replacement. These differences were attributed to the differences in the composition of these recycled aggregates, mainly to the ceramic materials content that varied between 4.2% and 28.6%. Carbonation resistance measurements showed lower carbonation resistance of the recycled concrete depending on the type of RA used. Carbonation depths up to 12 mm were measured in all specimens with coarse RA throughout the 91 days of exposure in an accelerated carbonation chamber with 5% CO₂. Higher carbonation depths were measured in mixtures with coarse RA with high ceramic content. The phenomenon is more intense in mixtures with replacement ratio greater or equal to 25%. At 25% replacement the percentage difference ranged from –8% to 85.6% at 56d and from –15.8% to 55.2% at 91d. The respective ranges for 50% replacement are, 25.6%–93.3% and 26.8%–93.7%. The lowest carbonation resistance was measured in mixtures with RA with ceramics content around 30%.

These controversies in the available results regarding the suitability of RA, the specificities of various properties affecting their behavior and the performance of the recycled concrete indicate that research has to be conducted on a country or even on a regional basis.

Moreover, although old concrete and RA composition seem to play an important role on the recycled concrete's performance, limited chemical and mineralogical characterization of RA is available. Relative experimental studies tried to identify possible uses of various sizes of RA in the production of different building materials ([Bianchini et al., 2005](#); [Angulo et al., 2009](#); [Rodrigues et al., 2013](#)). [Limbachiya \(2007\)](#) studied the influence of RA's chemical composition on the chemical composition of the resulting concrete.

In Greece organized production of RA has started only recently. There is very little to almost no data available regarding their characteristics and their influence in concrete. [Savva \(2010\)](#) produced CDW in the laboratory from concrete test cubes to study the effect of the old concrete homogeneity on the splitting and compressive strength and the durability of recycled concretes. Moreover, [Mavridou \(2009\)](#) investigated the effect of the RA percentage on the mechanical and physical characteristics as well the behavior of RA concretes when exposed to high temperatures. In

both cases no chemical or mineralogical evaluation was performed. However, evaluation of laboratory produced RA compared to RA from only one Greek recycling plant, presented by Alexandridou et al. (2014), has revealed differences in their chemical and mineralogical composition. Dolomitic minerals are identified in laboratory produced RA, whereas commercial RA is enriched in aluminosilicate minerals. The latter contains also higher percentages of water and acid soluble chlorides. This indicates that laboratory produced recycled materials cannot be used to “simulate” the performance of concrete made with RA. Moreover Greek aggregates are not siliceous aggregates as most of the aggregates investigated in the literature.

Therefore, the purpose of this study is to provide for the first time with detailed knowledge on the composition and properties of RA commercially produced in Greece and at the same time to investigate the effect of replacing coarse aggregates on the properties of the concrete. The RA used in the present study are commercially produced from three plants. These materials have undergone chemical, physical and mineralogical characterization. Mechanical performance was evaluated through compressive strength at 28 days of RA concrete mixes with 0%, 25%, 50% and 75% replacement percentage. Additionally, in order to evaluate the durability of these concrete mixes the material from the plant in Southern Greece was used based on its better strength performance. The following properties were measured: absorption by immersion and capillarity, carbonation as well as freezing and thawing resistance.

2. Materials and methods

2.1. Materials

The commercially produced recycled materials investigated in this study were supplied by three different recycling plants: two of them located in Northern Greece (thereafter called N(1) and N(2)) and one in Southern Greece (thereafter called S(1)). According to the Greek recycling system, the demolition waste is delivered to the recycling plants by the waste producers. The production process includes sorting (hand picking), fragmentation, magnetic separation and sieving. Crushing is performed with a rotor crusher in S(1) plant while N(1) and N(2) plants use a jaw crusher. The S(1) plant is ISO 9001 certified and produces a recycled material that is characterized as an all in aggregate with 31.5 mm maximum grain size. The N(1) and N(2) plants designate their products as 0/40 mm and supply them in the market as landfill material. The natural aggregates used in comparison were collected from the ‘Araxos’ quarry through a ready mix company operating in Patras. Table 1 presents the code given to each sample. Further on S(1), N(1) and N(2) were sieved in order to separate the fine 0/4 mm from the coarse 4/31.5 mm fraction. Natural aggregates were used as received.

Table 1
Sample codes.

Code	Description
S(1):	Recycled Aggregate from Plant in Southern Greece
N(1)	Recycled Aggregate from Plant (1) in Northern Greece
N(2)	Recycled Aggregate from Plant (2) in Northern Greece
G -N	Coarse natural aggregate 11.2/22.4 (Gravel)
FG-N	Coarse natural aggregate 2/11.2 (Fine Gravel)
S -N	Fine natural aggregate 0/4 (Sand)

2.2. Testing methods

2.2.1. Classification

Coarse fractions of S(1), N(1) and N(2) RA were examined in accordance with the procedure of EN 933-11 (2009d) to determine the relative proportions of constituent materials.

2.2.2. Chemical, mineralogical composition

X-Ray Fluorescence was used for chemical analysis and X-Ray Diffraction for mineralogical composition. Linear regression analysis using least squares was used to quantify the mineralogical composition. For this purpose, chemical data for the identified minerals were found in www.webmineral.com/data (2009).

2.2.3. Chemical properties

The chemical properties were evaluated according to the requirements of EN 12620 standard (2002). The water soluble chloride and sulfate ions were determined in accordance with EN 1744-1 standard (2009b), the acid-soluble chloride ion as per EN 1744-5 standard (2009c). Following the procedure of EN 1746 (2006) coarse fraction of RA were soaked in water for 3 h. The extract was then used to prepare cement pastes according to EN 196.3 (2011) to study the changes in the initial setting time.

2.2.4. Physical properties

EN 933-1 (2012a) was implemented to perform granulometric analysis. Particle density and water absorption were measured following EN 1097-6 (2013a) standard. Other researchers have questioned the suitability and the accuracy of the standard method for measuring the water absorption of recycled aggregates (RA) mainly because prolonged drying of RA to 110 °C might lead to evaporation of chemically bound water which would lead to lower oven dry density and overestimation of water absorption (Tam Vivian et al., 2008). This may be valid when the RA contain significant amounts of gypsum, which is known to lose its crystalline water at 100 °C. Cement hydrated phases, namely CH and CSH are known to dehydrate at higher temperatures (Zhang and Ye, 2012). On the other hand, mineralogical analysis of the RA used in this study did not indicate the presence of gypsum. Therefore, the standard method EN 1097-6 was preferred in order also for the results to be directly compared with literature data. EN 933-8 (2012b) was used to measure Sand Equivalent. Resistance to fragmentation was measured as per EN 1097-2 standard (2010). Preliminary evaluation of the potential reactivity of siliceous components in the RA with alkalis in cement concrete was performed in accordance with the procedure from ASTM C289 (2007). Although the results of this test should not be used as the sole basis for acceptance or rejection they still can provide useful data.

2.2.5. Compressive strength

For the evaluation of concrete strength, eight concrete mixtures were prepared under laboratory conditions: one reference concrete with 280 kg/m³ cement and three recycled concretes with N(1) replacing the natural coarse aggregates (G-N) by 25%, 50% and 75% by weight as well as one reference concrete made with 330 kg/m³ cement and three with the S(1) and N(2) using the same replacement percentages. The concrete mixtures were proportioned targeting at a C20/25 concrete with S3 slump, based on the mix design typically used by the ready mix company for C20/25 concrete using the same natural aggregates. Portland cement CEM IV32.5 R was used. Mixture data are given in Table 2. Six 150 × 150 mm cubes were moulded for each mixture to measure compressive strength at 28 days. After 24 h they were demoulded and stored at 20 °C in water. Compressive strength was measured according to EN 12390-3 (2009a).

Table 2
Mixture data.

	Control Mix 1	N(1)25	N(1)50	N(1)75
% Replacement	0%	25%	50%	75%
Cement (kg/m ³)	280	280	280	280
Water (kg/m ³)	180	180	180	180
Sand (kg/m ³)	1045	1045	1045	1045
Fine Gravel (kg/m ³)	105	78	52	26
Gravel (kg/m ³)	727	545	363	182
N(1) (kg/m ³)	–	208	416	623
	Control Mix 2	S(1)25	S(1)50	S(1)75
% Replacement	0%	25%	50%	75%
Cement (kg/m ³)	330	330	330	330
Water (kg/m ³)	191	191	191	191
Sand (kg/m ³)	998	998	996	996
Fine Gravel (kg/m ³)	99	99	99	99
Gravel (kg/m ³)	689	499	320	154
S(1) (kg)	–	166	320	462
	Control Mix 2	N(2)25	N(250)	N(275)
% Replacement	0%	25%	50%	75%
Cement (kg/m ³)	330	330	330	330
Water (kg/m ³)	191	191	191	191
Sand (kg/m ³)	998	1005	1005	1005
Fine Gravel (kg/m ³)	99	100	100	100
Gravel (kg/m ³)	689	501	324	157
S(1) (kg)	–	167	324	472

2.2.6. Concrete absorption

For the evaluation of recycled concrete absorption, the procedure of ASTM C642 (2013) was implemented as follows: two 150 × 150 mm cubes were cast for each mixture with 0%, 25%, 50% and 75% replacement and cured following the same procedure as with the specimens for strength tests. At the end of 28 days period, they were stored in the laboratory. After that, four rectangular pieces were cut from each cube and kept in an oven at 100 °C. After attaining a constant weight, they were immersed in water (21 °C) until constant weight, then boiled for 5 h and left to cool naturally for at least 14h, and finally weighed in water.

2.2.7. Sorptivity

For the evaluation of recycled concrete sorptivity the procedure of ASTM C1585 (2013) was implemented as follows: one 100 × 100 × 400 mm prism was cast for each mixture with 0%, 25%, 50% and 75% replacement. The prisms were then cured as described above for the water absorption tests. After that, four rectangular pieces were cut from each prism and kept in an oven at 50 °C until attaining a constant weight. Lower drying temperature was used in order to minimize damage to the microstructure from excessive drying.

2.2.8. Freezing and thawing resistance

The freeze-and-thaw tests were carried out using beam test as specified in PD CEN/TR 15177 (2006). Four test beams 400 mm × 100 mm × 100 mm from each mixture were subjected to freeze-thaw attack in presence of de-ionised water for 1, 8, 14, 28, 42 and 58 cycles. The freeze-and-thaw damage was monitored by measuring the relative dynamic modulus of elasticity using the equation $RDM_{UPPT,n} = \left(\frac{t_{s,0}}{t_{s,n}}\right)^2 \times 100$ [%] where $t_{s,0}$ is the initial ultrasonic pulse transit time through the specimen in μ s and $t_{s,n}$ is the ultrasonic pulse transit time through the specimen after n freeze-thaw cycles in μ s. The change of mass was also calculated by using the equation $\Delta m_n = \frac{m_n - m_0}{m_0} \times 100$ [%], where m_n is the mass of the specimen after n freeze-thaw cycles and m_0 is the mass at the beginning of the test.

2.2.9. Carbonation resistance

The carbonation resistance was measured by an accelerated laboratory test, where samples were exposed to an atmosphere containing 1% CO₂ at a temperature of (21 ± 2 °C) and relative humidity (RH) of (60 ± 10 %) as specified in EN 13295 (2004). Two beams 200 mm × 100 mm × 100 mm were cast for each mixture. They were demoulded one day after casting and wrapped in film and left in standard laboratory conditions until placed in the carbonation chamber. After removing each specimen from the chamber at each measuring age, ca 50 mm thick slices were sawed off from its ends, and the remaining piece was returned to the chamber for further exposure to carbonation. The freshly cut surface of each slice was sprayed with 1 g phenolphthalein indicator solution in 70% ethanol. The surface that was not carbonated turned pink while the carbonated concrete retained its original color. Measurement of the depth of carbonation was made 60 min after spraying, normal to the four sides of each slice at 56, 90, 182 and 272 days.

3. Results and discussion

3.1. Classification

S(1) material had a greyish white and dry appearance, similar to natural aggregates, while N(1) and N(2) were reddish with soil adhered to the particles.

The results obtained are presented in Table 3.

Significant differences are observed between these samples, as far as the Rc and Ru contents are concerned. S(1) is rich in concrete and mortar while in N(1) and N(2) unbound and bound aggregates prevail. In N(2) their contents are equal. Additionally the percentage of soil and clays is higher in N(1) and N(2) samples. All three of them contain the same percentage of bituminous materials and waste from bricks and tiles. The variations observed may be attributed to the different origin and/or the different production process. It seems that 70% of the S(1) material originates from old concrete structures.

3.2. Chemical, mineralogical composition

Table 4 includes the chemical composition results of both natural aggregates and RA. It is verified that CaO is the only oxide actually present in natural aggregates since the aggregates in Greece are basically calcareous. All RA have higher SiO₂, Al₂O₃, Fe₂O₃ and alkali oxides content. The SO₃ determined is increased when compared to natural aggregates but generally low (<0.5%) for all samples. The CaO content of S(1) is much higher than that of N(1) and N(2), thus indicating different originally processed material and/or different sorting process, as concluded from the classification test results. Analogous with CaO are the differences of LOI, showing thus that LOI's main origin is calcite.

Table 3
RA classification.

Constituent	Description	S(1)	N(1)	N(2)
	Proportions % Test sample (4/31.5 mm)			
Rc	Concrete, mortar masonry	Rc ₅₀	Rc ₁₀	Rc ₄₅
Ru	Unbound aggregate, natural stone	Ru ₂₀	Ru ₇₀	Ru ₄₅
	Hydraulically bound aggregate.			
Rb	Bricks and tiles	Rb ₁₀₋	Rb ₁₀₋	Rb ₁₀₋
Ra	Bituminous Materials	Ra ₁₀₋	Ra ₁₀₋	Ra ₁₀₋
Rg	Glass	Rg ₂₋	Rg ₂₋	Rg ₂₋
X	Other (soil and clays)	X ₁₋	X ₃	X ₃
FL	Floating Material cm ³ /kg	FL _{0.2-}	FL ₅₋	FL ₂₋

Table 4
Chemical composition (%).

	G-N	FG-N	S-N	S(1) 0/4	S(1) 4/31.5	N(1) 0/4	N(1) 4/31	N(2) 0/4	N(2) 4/31.5
SiO ₂	0.18	0.24	0.46	10.85	8.33	28.71	16.92	39.97	19.81
Al ₂ O ₃	0.05	0.08	0.13	2.03	1.65	5.78	3.4	7.05	3.84
Fe ₂ O ₃	0.04	0.06	0.08	1.13	0.98	2.29	1.33	3.05	1.48
CaO	55.09	54.93	54.59	45.17	47.61	30.95	40.43	24.09	38.59
MgO	0.34	0.37	0.38	0.83	0.73	2.39	2.18	1.66	1.60
K ₂ O	0.02	0.02	0.02	0.24	0.17	0.83	0.48	1.15	0.61
Na ₂ O	0	0	0	0.13	0.08	0.7	0.5	1.19	0.59
SO ₃	0.02	0.02	0.02	0.37	0.33	0.18	0.13	0.23	0.33
TiO ₂	0.01	0.01	0.01	0.11	0.09	0.26	0.16	0.33	0.15
P ₂ O ₅	0.03	0.04	0.05	0.02	0.02	0.06	0.03	0.09	0.05
Cr ₂ O ₃	0	0	0	0.02	0.02	0.02	0.02	0.02	0.02
MnO	0.01	0.01	0.01	0.02	0.02	0.05	0.05	0.07	0.05
ZnO	0	0	0	0	0	0	0	0.04	0.01
SrO	0.03	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02
LOI	43.72	43.89	43.85	38.76	39.66	27.48	34.11	20.88	32.44
TOTAL	99.54	99.71	99.63	99.70	99.71	99.72	99.76	99.85	99.59

Additionally, difference in composition is observed between coarse and fine fractions. SiO₂, Al₂O₃, Fe₂O₃ and alkali oxides are higher in the below 4 mm fraction of N(1) and N(2) and the CaO is lower.

Mineralogical composition of natural aggregates is pure limestone (Fig. 1). In RA calcite is still the main mineral, but also quartz, alkali feldspars, mica (muscovite), and dolomite are identified (Figs. 2–4).

The characteristic halo of amorphous phases from cement hydration was not observed. The two main sources of calcite in the RA is the calcite of the old aggregate and that which is produced after the carbonation of cement hydration products. Feldspars, and mica may be connected to the presence bricks/tiles which contain such minerals. The fact that samples from N(1) and N(2) recycling plants contain higher amounts of those minerals is related to higher percentage Ru material (bound and unbound aggregates and natural stone) determined in classification tests. Feldspars and micas in fine fraction of N(1) and N(2) are calculated to be almost twice of those in coarse fractions whereas in S(1) they are almost the same. Only the mineralogical composition of coarse fraction of S(1) is

similar to that of natural aggregates. Detailed mineralogical semi quantitative analysis data are given in Table 5.

In contrast to these findings, results from analogous investigations of RA in other countries have shown that they are enriched in Ca and Al oxides compared to their natural aggregates that have a siliceous composition. Very low amounts of similar aluminosilicate minerals and calcite were reported to be present in RA from Great Britain investigated by Limbachiya (2007). Similarly Italian RA proved to be constituted mainly by quartz while phyllosilicates such as illite, muscovite and chlorite tend to increase in fine grain size fractions (Bianchini et al., 2005). Quartz and alkaline feldspars are the main minerals of Brazilian RA. Micas, illite and kaolinite, related to clay and ceramic are also present. Only fractions below 0.15 mm seem to be enriched in calcite from the binder (Angulo et al., 2009).

3.3. Chemical properties

Table 6 presents the results of the chemical tests performed. Water soluble chloride ions are generally low in the RA examined

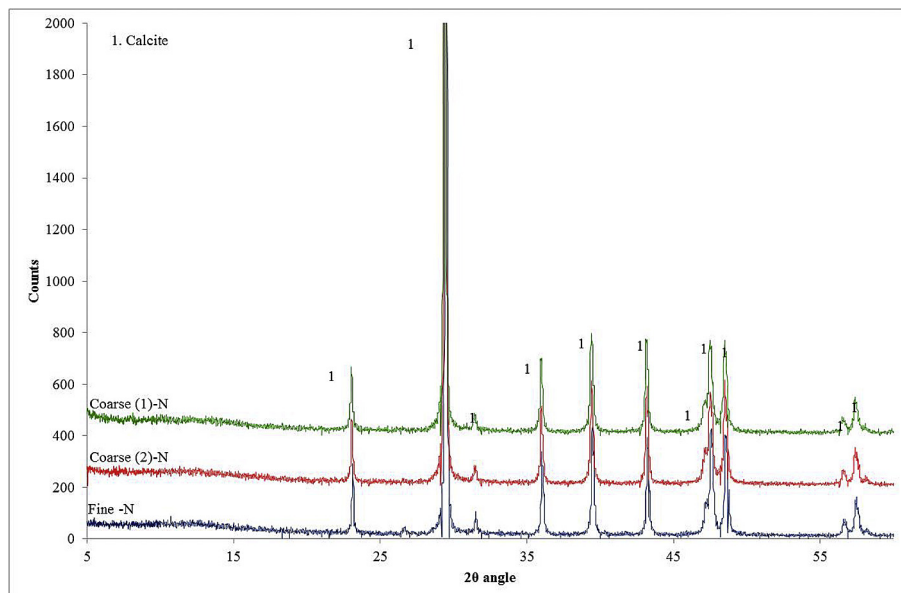


Fig. 1. XRD patterns of natural aggregates.

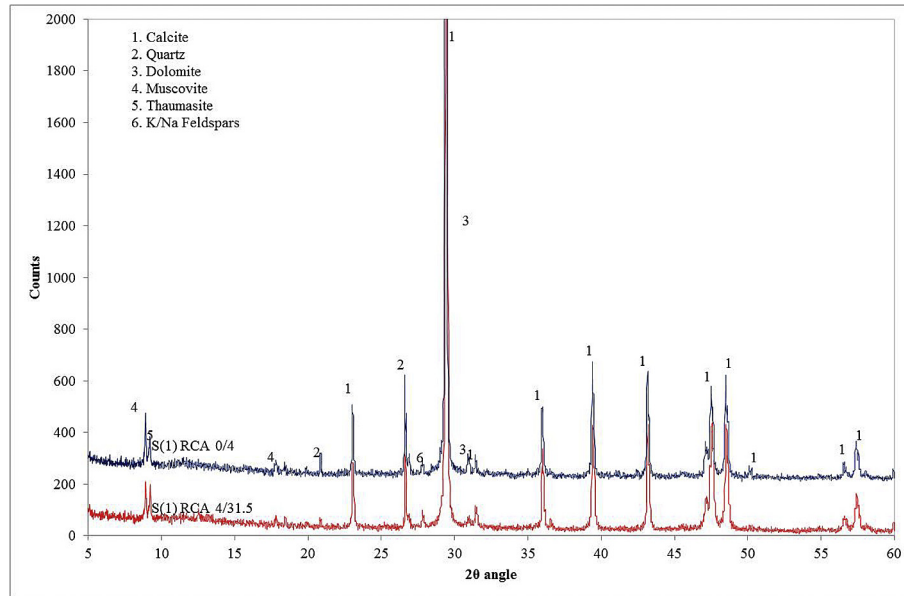


Fig. 2. XRD patterns of S(1) 0/4, S(1) 4/31.5.

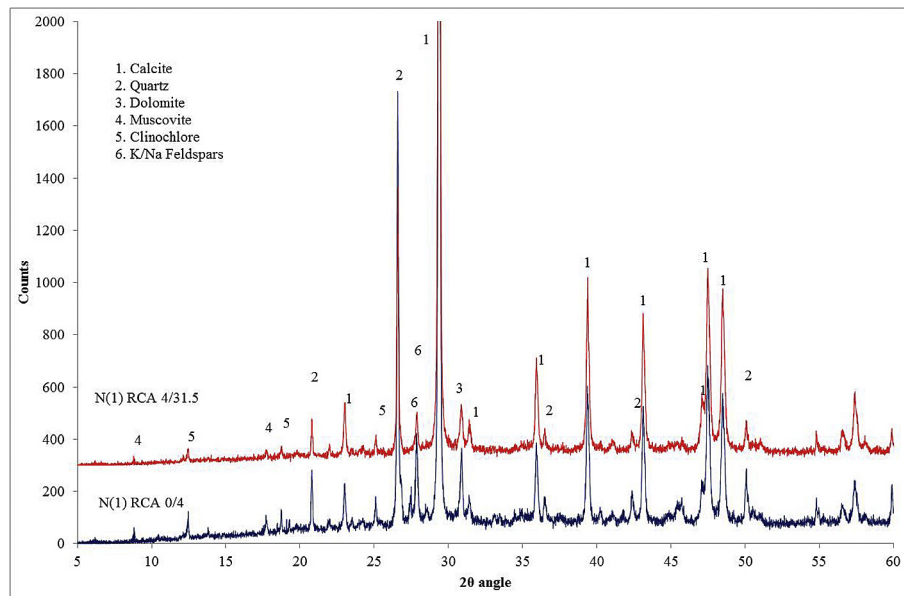


Fig. 3. XRD patterns of N(1) 0/4, N(1) 4/31.5.

but differences of one order of magnitude among them are observed. Acid soluble chlorides on the other hand are increased in S(1) and N(2) but not in N(1). Acid soluble chloride of N(1) is not higher because the chloride ions must originate from chlorides combined in the structure of clay minerals and not in calcium and other phases of old concrete and mortar, out of which it is difficult to be extracted in water although the samples are finely ground, EN 12620 (2002). The opposite proves to be the case with S(1) that contain higher amounts concrete and mortar (Table 3). In order to be on the safe side, EN 12620 (2002) advises to use the value of acid soluble chloride content to calculate the chloride ion of concrete by mass of cement. For this determination EN 206 (2013b) proposes to calculate the sum of the

contributions of each raw material based either on the maximum chloride content (declared or permitted) or on the average of test results plus 1.4 times their standard deviation. The maximum value determined (0.03) would result to a contribution of 0.08% while the average (0.04) to 0.11%. These calculations are the “worst case” scenario for a typical C20/25 concrete mixture that contains 300 kg cement and 800 kg coarse RA per m^3 , which stands for 100% replacement of the amount of natural coarse aggregates typically used.

Very low percentages of water soluble sulfates were determined that range from 0.0001 to 0.0005%. These values satisfy the maximum limits of 0.7 and 0.2 set in EN 206-1 standard (2013b) and in EN 12620 (2002) respectively. Corresponding values

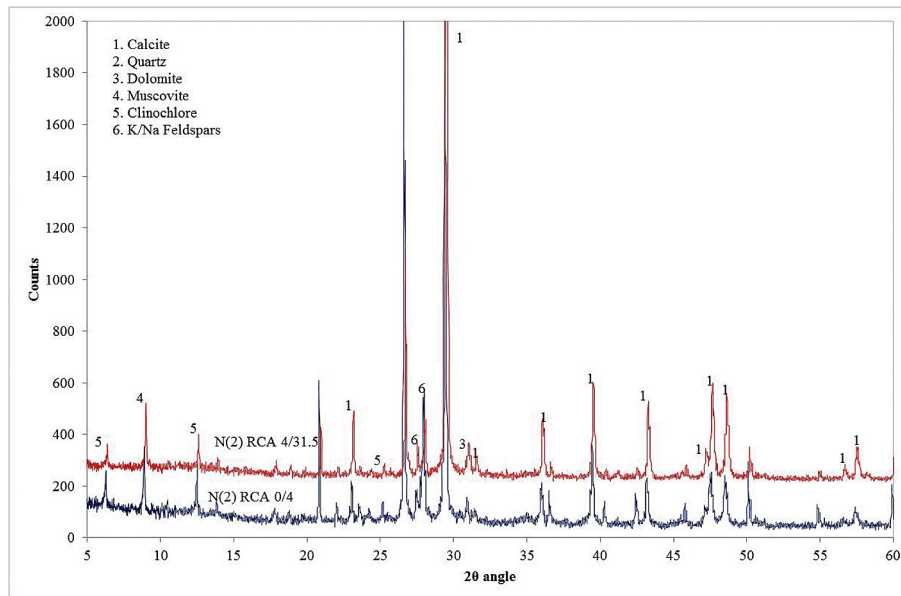


Fig. 4. XRD patterns of N(2) 0/4, N(2) 4/31.5.

Table 5
Mineralogical semi-quantitative composition.

Description	G-N	FG-N	S-N	S(1) 0/4	S(1) 4/31.5	N(1) 0/4	N(1) 4/31	N(2) 0/4	N(2) 4/31.5
Mineralogical phases									
Calcite	97%	97%	96%	75%	81%	56%	71%	43%	69%
Dolomite			3%	5%	4%	2%	3%	1%	1%
Quartz			1%	7%	5%	17%	10%	24%	11%
K/Na Feldspars				3%	3%	8%	6%	14%	7%
Mica				4%	3%	7%	3%	7%	4%
Chlorite						10%	7%	11%	8%
Thaumasite				6%	4%	—	—	—	—

Table 6
Results of the chemical tests.

Property	G-N	FG-N	S-N	S(1) 0/4	S(1) 4/31.5	N(1) 0/4	N(1) 4/31	N(2) 0/4	N(2) 4/31.5
Water soluble chlorides(%)	<0.001	<0.001	0.002	0.001	0.009	0.010	0.010	0.020	0.010
Acid soluble chlorides (%)	<0.01	<0.01	<0.01	0.003	0.02	<0.01	<0.01	0.02	0.02
Water soluble sulphates (%)	n.d	n.d	n.d	0.0004	0.0005	0.0001	0.0002	0.0001	0.0005
Change in initial setting time (min)	—	—	—	n.d	5min	n.d	–10min	n.d	–25min

reported by Rodrigues et al., 2013 for RA from recycling plants in Portugal are much higher. Changes in initial setting time results indicate that all samples have a retarding effect. As per EN 12620 (2002) S(1) and N(1) can be classified as A10 since the change in initial setting time is below or equal to 10 min, while N(2) as A40 because the change is below 40 min.

3.4. Physical properties

The size of the particles of the aggregates as well as their distribution play an important role to concrete's compacity and strength (Neville, 1996). Table 7 displays the results of the sieving analysis performed in all samples. Results indicate that coarse fractions of N(1), N(2) and S(1), as they were prepared in the lab have a particle size distribution which is between those of FG-N and

G-N. Fine fractions of N(1) and N(2) have a similar to S-N size distribution but a very high fines content, which exceeds the specified national limit of 16%. Fines contents of S(1) on the other hand is far below this limit.

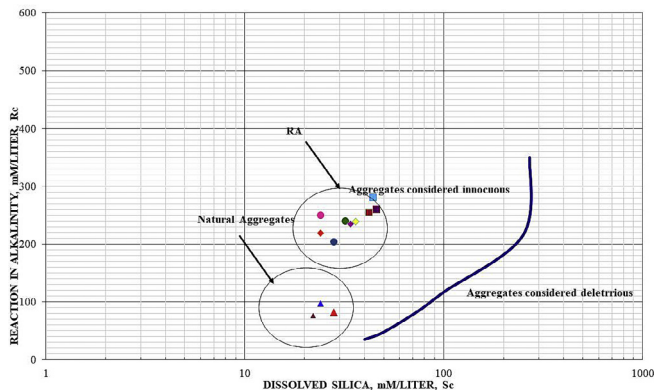
The results of the other physical tests performed are shown in Table 8. Coarse fractions have higher water absorption and lower particle densities than the natural aggregates as reported by other researchers (Rodrigues et al., 2013; Savva, 2010; Katz, 2003) due to the porosity of the old mortar that is attached to the RA particles. For the same reason the resistance to fragmentation of S(1) is lower (Rao, 2011) as it is proved by the higher value of Los Angeles coefficient, but still compliant to the Greek specification which is $LA \leq 40$. Low Sand Equivalent and significantly high water absorption values of fine fractions of N(1) are prohibitive for use in concrete. According to the performance-based aggregate

Table 7
Sieving analysis.

Description	G-N	FG-N	S -N	S(1) 0/4	S(1) 4/31.5	N(1) 0/4	N(1) 4/31	N(21) 0/4	N(2) 4/31
Sieve size (mm)	Passing (%)								
31.5	100	100	100	100	100	100	100	100	100
16	59	100	100	100	95	100	74	100	73
8	3	80	100	100	57	100	31	100	38
4	1	16	100	100	5	99	5	100	11
2	1	2	84	60	1	82	1	72	6
1	1	1	59	33	1	63	1	56	6
0.50	1	1	40	19	1	48	1	44	6
0.25	1	1	23	11	0	37	0	32	5
0.125	1	1	18	7	0	30	0	23	4
0.063	1.1	1.2	14.5	4.8	0.4	24.9	0.5	16.4	2.9

Table 8
Results of physical tests.

Description	G-N	FG-N	S -N	S(1) 0/4	S(1) 4/31.5	N(1) 0/4	N(1) 4/31	N(2) 0/4	N(2) 4/31.5
ρ_x (mg/m ³)	2.74	2.73	2.74	2.57	2.66	2.72	2.67	2.61	2.55
ρ_{rd} (mg/m ³)	2.70	2.69	2.69	1.93	2.30	2.00	2.50	2.09	2.37
ρ_{ssd} (mg/m ³)	2.71	2.71	2.71	2.18	2.43	2.27	2.56	2.29	2.44
WA (24h)%	0.54	0.52	0.67	12.8	5.8	13.1	2.4	9.4	3.1
SE			75	74		32		34	
Los Angeles	25	25	n/a		35		n.d		n.d
Classification (R.V. Silva et al. (2014))	AI	AI	AI	CII	BI	CII	AII	CI	BI

**Fig. 5.** Results for Potential Alkali-Silica Reactivity of Aggregates (chemical method).**Table 9**
Compressive strength results (Mpa).

% Replacement	N(1)	% Δ	S(1)	% Δ	N(2)	% Δ
0%	24.7(±1.19)		30.1(±1.20)		30.1(±1.20)	
25%	23.8(±0.35)	-4%	30.1(±1.71)	0%	29.0(±2.25)	-4%
50%	21.4(±0.49)	-14%	28.1(±1.32)	-7%	26.3(±2.33)	-13%
75%	15.5(±2.10)	-37%	27.6(±0.69)	-8%	24.0(±1.65)	-20%

classification system proposed by R.V. Silva et al. (2014) normal aggregates are characterized as AI while fine RA as CI and CII. Coarse RA on the other hand can be classified closer to normal, namely as AII and BI.

The outcome of the evaluation of the potential reactivity of siliceous components in the RA with alkalis in cement is presented in Fig. 5. All samples are characterized as innocuous.

3.5. Compressive strength

The compressive strength results obtained are shown in Table 9 as mean values and standard deviations (data in parenthesis). Compressive strength values reduce as the content of the recycled increases. Maximum reduction is observed at 75% replacement. The compressive strength of S(1) is up to 8% inferior to that of reference concrete at 75% replacement. On the other hand the strength reduction of N(1) and N(2) recycled concretes varies from 20% up to 37% at the same replacement percentage. This reduction was not observed by Savva (2010), where admixtures have been added in the mix design. High water absorption of RA may be the reason for this reduction because it creates a porous interfacial transition zone that reduces concrete strength (Poon et al., 2004). It must be noted though that although N(1) and N(2) have lower water absorption than S(1), this effect is more intense in N(1) and N(2) mixtures. Probable reason for this increased reduction is the higher content of clay minerals (16% and 19% compared to 6% of S(1)). As it was reported by M. Bravo et al. (2015a), these fine particles coat the RA grains and absorb the mixing water, causing an inadequate bond between the RA and the cement paste, which results to an increase of the porosity of these mixes and consequently to a decrease in compressive strength. The lower cement content of N(1) recycled concrete enhances the observed reduction.

3.6. Concrete absorption

The water absorption by immersion test is used to evaluate the open porosity of concrete that is due to the pores of aggregate, the air remaining after mixing and the excess water to the one necessary for cement hydration. The results are represented graphically in Figs. 6 and 7.

The results of Fig. 6 show that the water absorption increases linearly ($R^2 = 0.96$) with the replacement percentage of aggregates. This trend is reflected also in the volume of open pores as

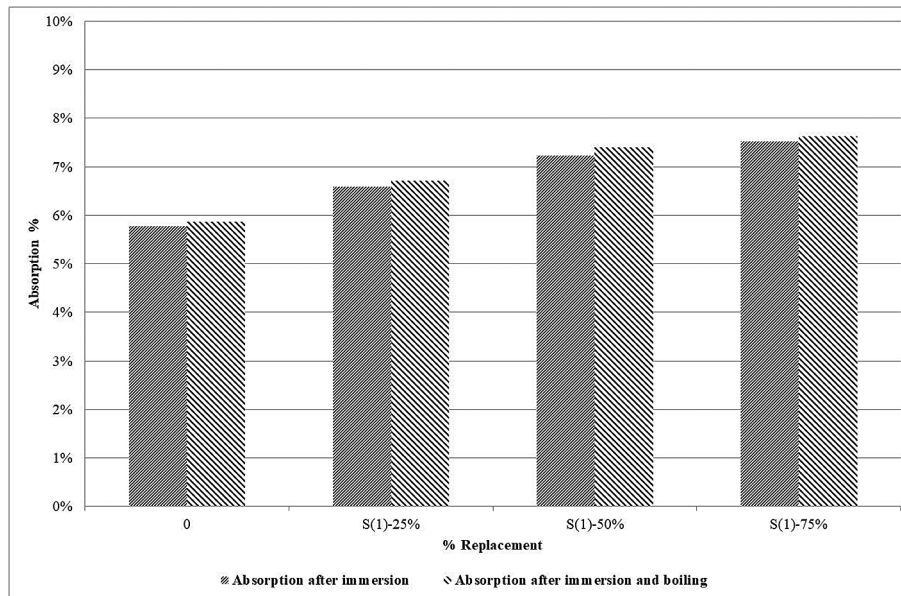


Fig. 6. Concrete water absorption.

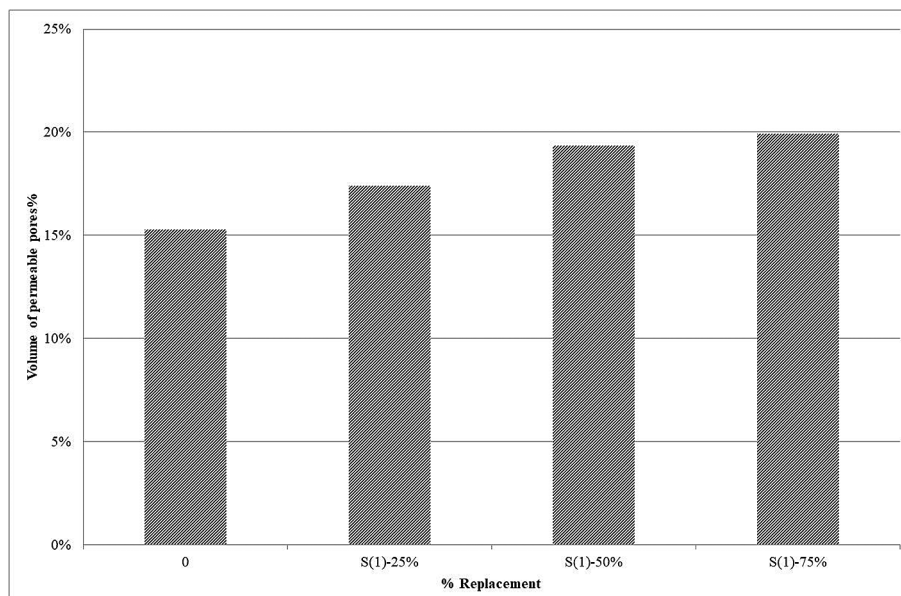


Fig. 7. Volume of open pores.

it is shown in Fig. 7. Up to 30% higher values were measured for the mixture with 75% replacement with the actual values of water absorption to range between ca 6–8%. Concrete water absorption of max 10% is regarded as quality concrete and could be used for a wide range of applications including structural concrete (Bravo et al., 2015b). These results are much lower to those measured by Bravo et al. (2015a), who used RA with water absorption ca 12%, but similar to those measured by Sagoe-Crentsil et al., 2001 and Chakradhara et al. (2011). As Sagoe-Crentsil et al., 2001 have indicated, the RA' water absorption was 5.6%, i.e. similar to the one measured in this study. For full replacement, these authors found that the water absorption by immersion increased by 25%. These results indicate that the higher water absorption of the RA may contribute to increased concrete water absorption.

3.7. Sorptivity

Durability of concrete depends largely on the penetrability of its pore system. The rate of ingress of water or other fluids into concrete (sorptivity) is largely controlled by absorption due to capillary rise.

Water sorptivity test results are shown in Figs. 8 and 9. Each value presented is the average of four measurements. Initial and Secondary rate of absorption were calculated as per ASTM C1585 (2013). For the regression analysis of initial rate of absorption all the points from 1 min to 6 h were used, whereas of the secondary all the points from 1 to 7 days. Replacement by 25% and 50% leads to a similar increase of the initial rate of absorption by 12% and 14% respectively while replacement by 75% to a 52% increase. Actual values range from 2.0×10^{-3} to 3×10^{-3} mm/ \sqrt{s}

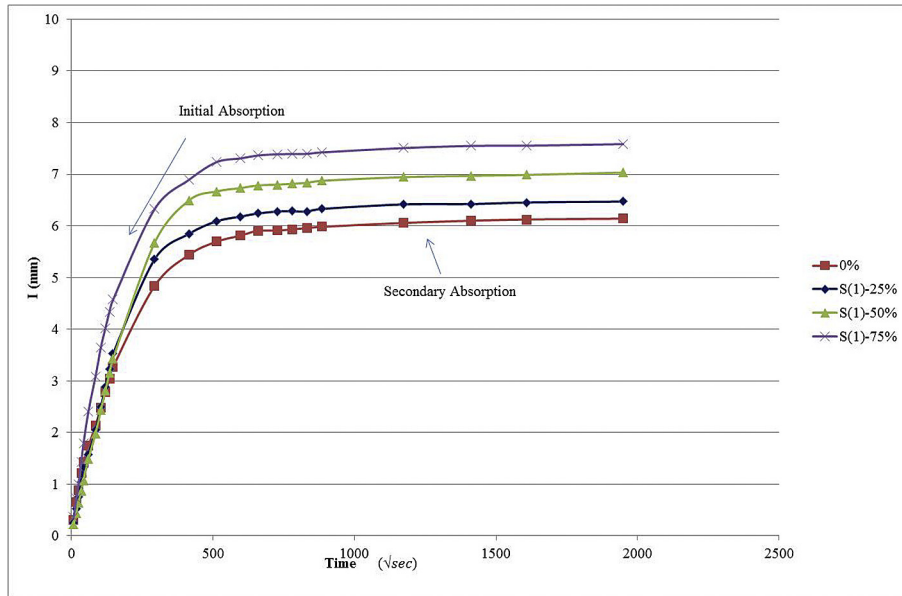


Fig. 8. Absorption I (mm) by capillarity versus square root of time (\sqrt{s}).

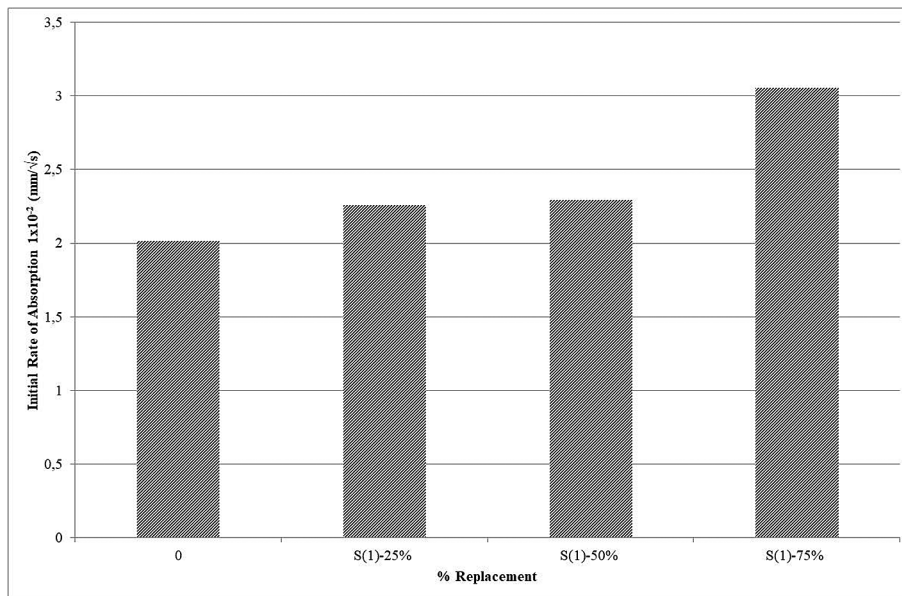


Fig. 9. Initial rate of absorption (mm/\sqrt{s}) versus aggregates' replacement ratio.

(correlation coefficient 0.99). Aghabaglou et al. (2014) reported the same trend as they found that water sorptivity of recycled concrete increased with increasing replacement level of aggregates up to 60%.

On the other hand, no significant difference is observed at the secondary rate of absorption. The calculated values were in the order of $2.0 \times 10^{-3} \text{ mm}/\sqrt{s}$ although it must be noted that secondary rate of absorption could not be established with high confidence (correlation coefficient of 0.92 was calculated).

3.8. Freeze and thaw resistance

The Ultrasonic Relative Dynamic Modulus of Elasticity (RDUPPT) gives an estimation of the freeze-thaw resistance of concrete with regard to internal structural damage. Fig. 10

illustrates the variation of the relative dynamic modulus of elasticity with the number of freeze–thaw cycles for all concrete mixtures. Each value presented is the average of the measurements in the four specimens per concrete mix evaluated. The RDMU_{PPT} values of all recycled concrete mixes are in the range of 97% up to the 14th freezing and thawing cycle, very close to those of the reference concrete mixture indicating no damage in their microstructure. After the 14th cycle a rapid decrease is observed, evidence of greater damage. Fig. 11.

Mass change data indicate minor changes in the mass of all samples, with a maximum $\pm 0.2\%$. It is noted that a decrease is observed in the mass of all S(1) samples up to the 8th FT cycle. As the number of FT cycles increased the weights of all S(1) specimens increased, probably because the water penetrated the inner cracks of these samples.

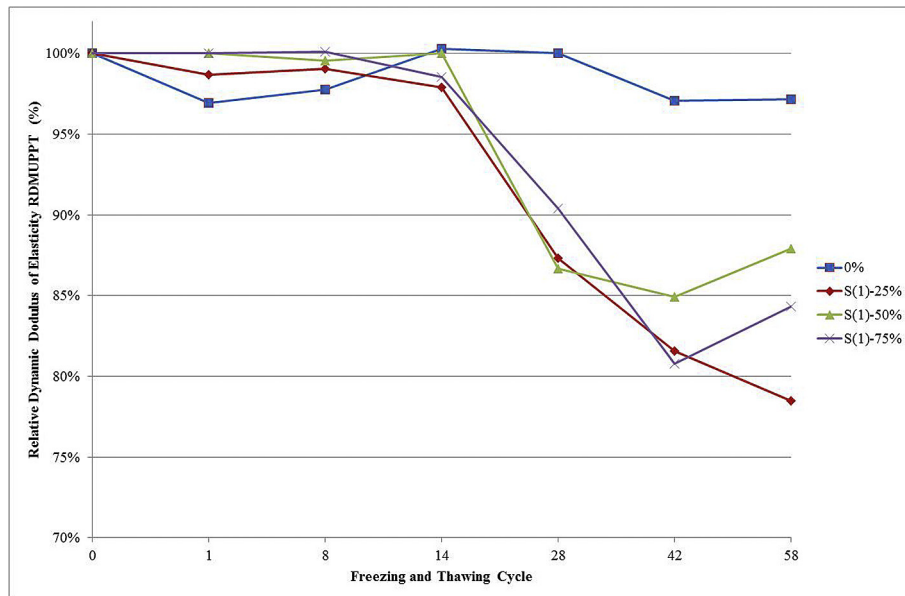


Fig. 10. Relative dynamic modulus vs number of FT cycles.

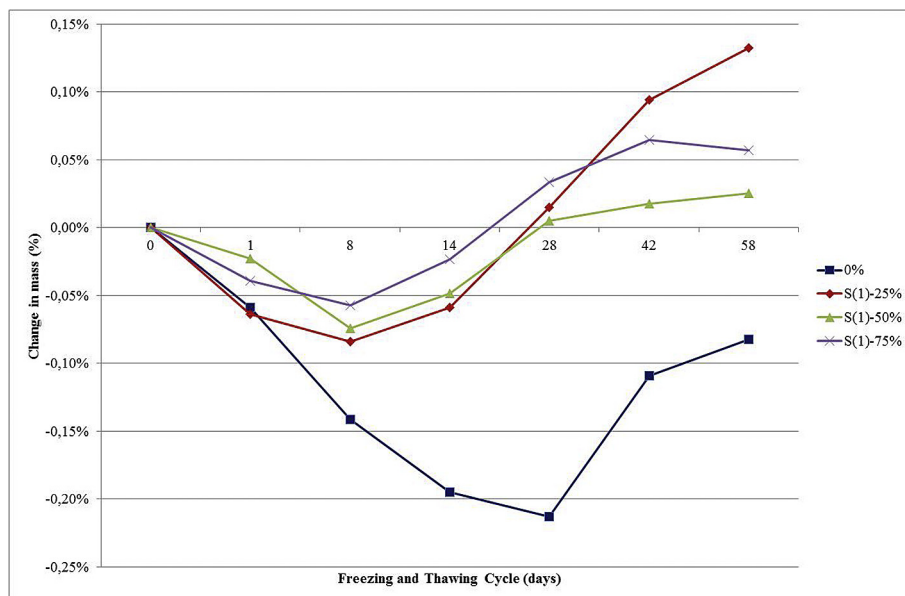


Fig. 11. Mass Change vs number of FT cycles.

These results are similar to those reported by Gokce et al. (2004), who investigated the freezing and thawing resistance of air-entrained concrete incorporating recycled coarse aggregate. Their results showed that recycled coarse aggregate caused poor freezing and thawing resistance in concrete because the adhered mortar caused disintegration of the recycled coarse aggregate in itself and disrupted the surrounding new mortar after a limited number of freezing and thawing cycles.

3.9. Carbonation

Concrete protects steel bars in reinforced concrete through the alkaline environment it creates around them. Carbonation takes

place in the pores of concrete and may limit the service life of reinforced concrete. Atmospheric carbon dioxide diffuses into concrete and reacts with calcium hydroxide to produce calcium carbonate. This leads to reduction of pH below 9, which may depassivate the layer that protects the reinforcing steel against corrosion. Carbonation depends on the cement's composition, aggregate type and porosity.

The carbonation depth measured after 56, 90, 182, and 272 days inside the carbonation chamber are represented graphically in Fig. 12. Dk_1 is the average of the measurements of the four sides of the exposed face of each duplicate sample per concrete mix examined. An increase in carbonation depth is observed at all replacement percentages and at all time of exposure.

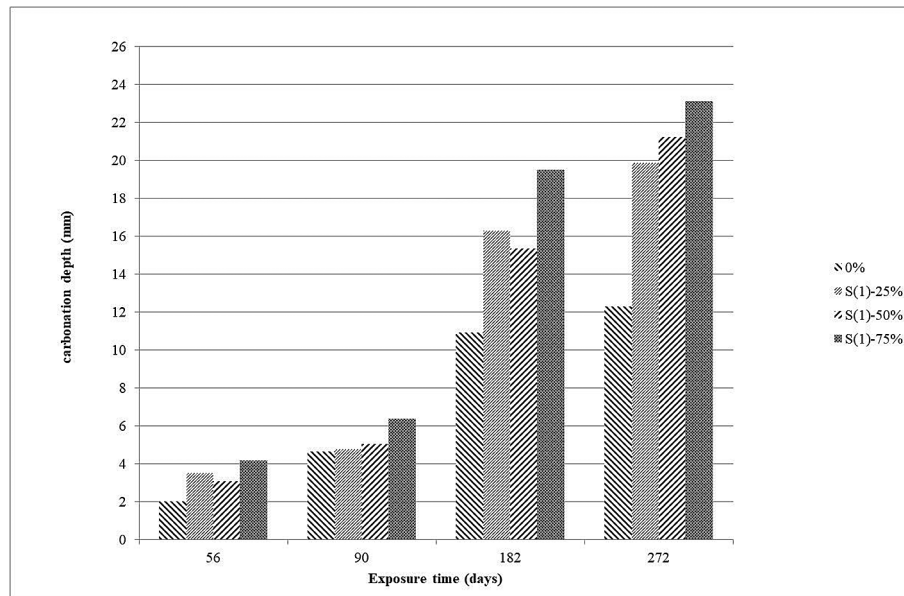


Fig. 12. Carbonation depth over exposure time.

Measurements of mixtures with 25% and 50% replacement show no significant difference. The difference is more intense at 56 and 272 days, reaching its maximum 112% at 272 days for the concrete mix with 75% replacement. This trend was also observed in the sorptivity data and not in the water absorption data, which was expected since both properties depend upon the pore structure of cement. De Schutter and Audenaert, 2004 reported that although water absorption by immersion gives an estimate of the volume of a concrete's open pores, it is not a reliable way of determining the concrete's chloride and carbonation resistance, since this depends more on capillary absorption.

The same trend has been established by Bravo et al. (2015b) and Bodin and Hadjieva-Zaharieva, 2002, who evaluated the carbonation resistance of concrete with commercially produced coarse and fine RA. Lower increase in the carbonation depth has been determined when laboratory crushed RA were used (Sagoe-Crentsil et al., 2001; Gomes and de Brito, 2009). The actual carbonation depths measured in this study cannot be compared with analogous studies in literature because of the lower CO₂ concentration in the environmental chamber (1% instead of 3–5%) and variable cement contents used for the recycled concrete production.

4. Conclusions

Greece has started recently to recycle CDW. Their use is restricted to road works. There is very little to almost no data available regarding the characteristics of these CDW and their influence in concrete. Some literature data are found regarding the performance of recycled concrete but limited knowledge is available regarding the chemical and mineralogical properties of RA and how these affect concrete. Moreover Greek aggregates are not siliceous aggregates as most of the aggregates investigated in the literature. Therefore, this research addressed this lack by performing a comprehensive chemical, physical, mineralogical investigation of commercially produced RA and analyzed the influence of these characteristics on the mechanical performance and the durability of the concrete produced with them.

Chemical tests proved that the RA's contain higher contents of SiO₂, Al₂O₃, Fe₂O₃ and alkali oxides. The SO₃ determined is increased when compared to natural aggregates but is generally

low (<0.5%). Mineralogical analysis showed that RA have similar mineralogical compositions, that differ quantitatively. Calcite is the main mineral. Low amounts of quartz, alkali feldspars, mica (muscovite), and dolomite were found.

No water-soluble ions that may adversely affect the initial setting time of cement paste were determined. Higher water absorption and lower particle densities were measured and were attributed to porous cement paste adhered to the aggregates. Finally, these results indicate that concrete mixtures containing recycled concrete aggregates present compression strengths that range from significantly lower to equal compared to conventional concrete, depending on the RA composition. Most literature data relate the inferior quality of recycled concrete to high water absorption of RA due to the old mortar adhered to their particles. The findings of the present research though indicate that the presence of clay minerals has a more pronounced adverse effect to concrete's strength. Mixtures with RA containing increased percentages of clay minerals gave the lower strength results.

It is also concluded that the use of coarse RA reduces the durability of hardened concrete. Water absorption increases linearly with the replacement percentage. An increase in carbonation depth is observed at all replacement percentages and all times of exposure. Results from mixtures with 25% and 50% replacement show no significant difference. The difference is more intense for the concrete mix with 75% replacement after 56 and 272 days in the carbonation chamber. This trend was also observed in the sorptivity data. Recycled concrete mixtures showed the same to reference concrete frost resistance up to the 14th freezing and thawing cycle. After that the Ultrasonic Relative Dynamic Modulus of Elasticity was reduced to values between 80 and 85% indicating greater internal damage. In conclusion the results of the present investigation are encouraging in what concerns the use of coarse recycled aggregates as partial replacements of natural coarse aggregates in the production of new concrete of accepted quality.

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