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# Recycling of RAP (Reclaimed Asphalt Pavement) as aggregate for structural concrete: experimental study on physical and mechanical properties

**Nicoletta Russo[1] · Andrea Filippi[1] · Maddalena Carsana[1] · Federica Lollini[1] · Elena Redaelli[1]**

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**Abstract**
The replacement of natural aggregate in concrete with artificial and/or recycled one has recently gained attention as meaningful strategy to reduce the environmental impact of structural concrete and promote circular economy principles. This study investigated the possibility to use Reclaimed Asphalt Pavement (RAP), in the "as received conditions", as a partial or complete substitution of natural aggregate for structural concrete. RAP aggregate was firstly characterized in terms of grain size distribution, density, assessment of fines, chloride content, moisture content and water absorption. Subsequently, a total of twenty-four concrete mixes were designed, considering two cement types, two w/c ratios and several aggregate substitution percentages. For each mix, properties at the fresh and hardened state were investigated, such as workability, density and total open porosity, compressive strength, dynamic modulus of elasticity, and electrical resistivity. Results showed that RAP has a good potential to be used in reinforced concrete, provided that different water absorption and moisture content are considered in the mix design. RAP concrete was characterized by a lower density and increased total open porosity; however, an accurate tailoring of the concrete recipe could compensate the strength loss for several applications. Other properties, such as electrical resistivity and the relationship between dynamic modulus of elasticity and compressive strength did not result significantly altered by the presence of RAP.

**Keywords** C&D waste recycling · Reclaimed Asphalt Pavement (RAP) · Recycled aggregate · Structural concrete · Physical–mechanical properties

## 1 Introduction

Reinforced concrete is one of the most widely used construction materials worldwide, and the procurement of its raw constituents are responsible for a significant environmental impact, in terms of high energy consumption, $CO_2$ emissions and depletion of natural resources [1]. This latter aspect is particularly related to the supply of aggregate, which is the main constituent of concrete in terms of occupied volume (about 70% of the total) [2], and consists of stones and sand, excavated from quarries, or dredged from riverbeds. Just considering Italy, 160 million tonnes of natural aggregate were produced in 2019, sourced from 2800 extraction sites, i.e. quarries and pits, located over the national territory [3]. Therefore, to promote a higher environmental sustainability in the construction industry, one of the possible strategies is to substitute the natural aggregate partially or totally with recycled and/or artificial ones

✉ Nicoletta Russo, nicoletta.russo@polimi.it; Andrea Filippi, andrea.filippi@polimi.it; Maddalena Carsana, maddalena.carsana@polimi.it; Federica Lollini, federica.lollini@polimi.it; Elena Redaelli, elena.redaelli@polimi.it | [1]Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy.

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[1, 4]. This strategy would allow to re-use and value industrial by-products or waste materials, such as recycled glass, automotive shredder residue, construction and demolition waste and industrial solid waste, in a view of promoting circular economy principles [5]. Within this framework, RAPCON project was initially conceived with the aim of responding to a specific need, *i.e.* to investigate the possibility of recycling RAP (Reclaimed Asphalt Pavement) for structural concrete purposes. RAP is a granular bituminous material, generated in huge quantities every year from the maintenance operations of road pavements. Considering the situation in Italy, according to some esteems [6], 9–10 million tons per year were on average produced in the period 2017–2019, constituting about 18% of the total amount of construction and demolition waste, and about 8% of all non-hazardous waste. Only about 30% of the total amount of RAP produced is recycled to produce new asphalt pavement, far less than in other European countries [7], and this has led to congestion at RAP reception and reuse plants [6]. At the same time, the use of RAP for other applications, such as aggregate for cementitious composites, is still quite limited, due to restrictions imposed by current laws, deriving from insufficient knowledge on the mechanical- and durability-related performances of RAP concrete [8].

RAP aggregate consists of siliceous natural aggregate covered by a bituminous layer [9], and for its nature and characteristics it is potentially compatible with the use in cementitious composites [10]. From the available literature, several RAP applications were analysed, such as structural concrete [11–20], concrete pavements [21–25], cement mortar [9, 26, 27], precast paver blocks [28] and fibre-reinforced cementitious composites [29]. In general, it was found that the use of RAP did not affect the cement hydration reactions [22], but the different physical characteristics (e.g. grain size distribution and water absorption) must be carefully considered to tailor the mix design [20]. Moreover, other properties, such as the lower mechanical strength with respect to the virgin aggregate, should be carefully considered since they would inevitably affect the properties of the cementitious composite at hardened state. RAP properties were reported to be strictly related to the parent materials used, and to the procedures adopted for extraction, post-processing, and storage of RAP. For example, the extraction procedure affects the grain size distribution of RAP, as shown in ref. [30]. Milling is usually applied to the most superficial layer of the road pavement, and produces coarse RAP aggregates with good mechanical properties, but with a lack of particles in the finer fractions. On the other hand, the demolition procedure of the whole road section produces well-graded RAP fines. The maximum aggregate diameter is usually reported between 20 and 25 mm [16, 22], compatible with the use of RAP as aggregate in concrete. The possible strategies to partially replace natural aggregate are, therefore, to replace either only the coarsest fractions, as in refs. [13, 15–17, 25], or to replace the fine fractions only, as in refs. [9, 26, 27, 29]. More rarely, the substitution of RAP was performed considering both the fine and the coarsest fractions, e.g. in ref. [12, 18, 24]. Moisture content of RAP is usually very variable and depends on the storage conditions of RAP. Water absorption is typically higher than that of the natural aggregate, *e.g.* it was reported to be around 2.5% in ref. [16]. This parameter, however, may be affected by the presence of fines and impurities on the external bituminous surface of RAP particles [31]. To decrease the absorption parameter, several methods have been proposed to remove, or at least reduce, such fines and impurities [31]. Anyway, these procedures would lead to additional consumption of natural resources and energy, cancelling, at least in part, the environmental benefits of having used a waste material.

Considering the properties of RAP concrete at fresh and hardened state, most of the authors agree that a significant decrease in concrete compressive strength occurs by increasing the RAP content, due to the weak bituminous interface between the RAP aggregate and the new cement paste. However, there is no consensus on the RAP content threshold above which the decrease in mechanical performances becomes significant, e.g. above 15% of aggregate substitution in ref. [16], while over 40% in ref. [22]. Other properties, such as workability at fresh state and toughness at hardened state, were reported to be improved by the inclusion of RAP aggregate with respect to ordinary concrete [14, 16]. It was however also reported that, in some cases, higher workability in RAP concretes at fresh state may have been caused by the incorporation of a significant amount of air, which would then be detrimental from a mechanical point of view at hardened state [32]. Furthermore, considering a possible compatibility of RAP to be used for reinforced structural concrete applications, the possible presence of contaminants that may pose a threat to reinforcement causing premature corrosion should be carefully considered. This is the case, for instance, of chlorides, which are often included in RAP aggregate since de-icing salts are typically employed on road pavements. Finally, scarce information is available on the long-term durability performances of RAP concrete, either concerning its resistance to the penetration of aggressive species such as chlorides and carbonation, nor on the corrosion behaviour of steel rebar in RAP concretes.

Aim of this work is to evaluate the use locally available RAP as a partial or total replacement of natural aggregate for structural concrete applications, through a systematic study of several variables related to the concrete mix design. RAP was supplied by an industrial partner, consisting in one of the main RAP producers in Italy, that in a previous collaboration supplied RAP for the realization of a culvert prototype in concrete containing recycled aggregate. Although in that case the RAP content was low, in that preliminary examination encouraging results were obtained, also regarding the corrosion of steel reinforcement [33]. In view of improving environmental sustainability of the process, and contrary to what is usually found in the literature, the project was aimed at the utilisation of RAP in the "as received" condition, to substitute both the fine and coarse fractions, up to the complete substitution of natural aggregate. In a first phase, therefore, a better knowledge on the available RAP was performed, in terms of RAP grain size distribution, density, amount of fines through blue methylene test, moisture content and water absorption through ponderal and pycnometer methods. Particular attention was devoted to the experimental methodology, since some modifications in the standard procedures for aggregate characterization were necessary to account for the bituminous nature of RAP aggregate. Moreover, as novel results with respect to literature, a systematic study was performed to evaluate the combined effects of RAP content and other mix design variables (cement type and water/cement ratio), on the fresh and hardened properties of concrete, specifically aimed at structural purposes. In total, twenty-four different concrete mixes were designed, considering the combinations of several aggregate substitution percentages (from reference concrete with only natural aggregate, to 100% RAP content), two different cement types (Portland-Limestone and Pozzolanic), and two different w/c ratios (0.45 and 0.65), chosen to be representative of structural concrete under specific exposure conditions (either carbonation- or chloride-induced corrosion of steel rebar). Physical and mechanical characterizations of RAP concretes at fresh and hardened state, at different curing times, were performed by evaluating workability through slump test, compressive strength, density, total open porosity through mercury intrusion porosimeter, dynamic modulus of elasticity through ultra-sonic pulse velocity measurements, and electrical resistivity through the uniaxial method.

## 2 Materials and methods

Particular attention was devoted to the definition of a methodological approach, for the characterization of the two types of aggregate, which appropriately considered the different origin and nature of the natural and RAP aggregate, and in the definition of concrete mixtures. Test procedure from European regulations were in general followed, except in some cases where slight modifications were necessarily introduced, to adapt to the bituminous nature of RAP aggregate.

### 2.1 Aggregates

Natural aggregate (NAT) and Reclaimed Asphalt Pavement aggregate (RAP) were employed in this study (Fig. 1).

The natural aggregates were crushed limestone aggregates, subdivided into six different fractions, as shown in Fig. 2a, named powder (P) and L1–L5 (maximum aggregate diameter of 15 mm). The various fractions were combined to approach the Fuller curve, considered as optimal distribution (in Fig. 2a the combination curve is shown in red, while the Fuller curve in green). RAP aggregate was supplied by Amplia Infrastructures S.p.A., and sourced from Anagni, one of their plants in Italy. Sieving test on three different batches was firstly performed, to retrieve grain size distribution. Figure 2b shows the curves for the three batches and the average curve (maximum aggregate diameter 22 mm). RAP aggregate was used in the "as received" condition, therefore for mix design purposes, for the RAP fraction the average grain size distribution was considered (red curve in Fig. 2b). For comparative purposes, the Fuller curve is also reported


(a) (b)

**Fig. 1** **a** Calcareous natural aggregates and **b** RAP aggregates

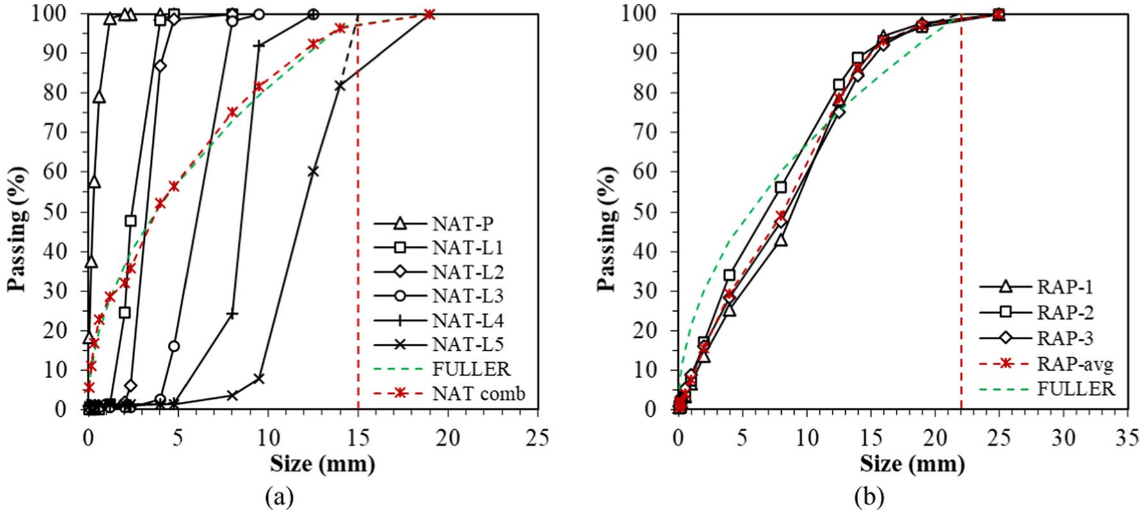


**Fig. 2** Size distribution curves of **a** natural (NAT) and **b** RAP aggregate; green dotted line indicates the Fuller distribution while the red dotted line the combination curve (for natural aggregate) or the average curve (for RAP aggregate)

in Fig. 2b (green line). It is worth noticing that the distribution curve of RAP aggregate in the "as received" condition was quite close to the Fuller ideal one, which made the RAP aggregate suitable also for the 100% substitution percentage.

## 2.2 Aggregates testing

### 2.2.1 Moisture content, water absorption and density

Due to the difficulty in separating the finer RAP particles and dust impurities from the coarsest aggregate particles, the characterization of RAP aggregate in terms of moisture content, water absorption and density was performed on particles with size higher than 4 mm. Concurrently with the analyses performed on the RAP aggregate, the same procedures were applied to the natural aggregate, except in those cases where the bituminous nature of RAP required slightly different procedures.

Moisture content was assessed on both natural and RAP aggregate, by ponderal method. For natural aggregate, two samples of about 40 g were tested (mass at testing time, $M_h$). The samples were then oven dried at a temperature of 110 °C until reaching constant mass (dry mass, $M_d$). Analogous procedure was followed for RAP aggregate, considering six different samples of approximatively 40 g, which were collected from the RAP supply in the "as received" conditions. For RAP aggregate it was necessary to lower the drying temperature to a value around 45 °C, not to melt the bituminous layer, until it reached constant mass (dry mass, $M_d$). Moisture content (*MC, %*) was then assessed as follows:

$$MC = \frac{M_h - M_d}{M_d} \cdot 100 \tag{1}$$

Water absorption and density were assessed on both natural and RAP aggregates, considering two different methods, *i.e.* ponderal and by pycnometer. With ponderal method, three samples of approximatively 40 g each for both RAP and natural aggregate were immersed in demineralized water for 24 h. Aggregates were then taken out and wiped from excess water, so that each sample could be weighted in the saturated surface dry conditions ($M_{ssd}$). Finally, aggregate samples were placed in an oven at 45 °C for RAP, 110 °C for natural, until they reached a constant dry mass ($M_d$). Water absorption ($WA_{pond}$, %) was then calculated as:

$$WA_{pond} = \frac{M_{ssd} - M_d}{M_d} \cdot 100 \tag{2}$$

To quantify the effect of impurities on the water absorption parameter, the pycnometer method was also performed, which is usually performed on aggregates cleaned from impurities. Three samples, about 40 g each, of both natural and RAP aggregate, were firstly subjected to a washing operation under running water, and then immersed in demineralized water for 24 ± 0.5 h, at a constant temperature of 22 ± 3 °C. The mass of the pycnometer plus the aggregates was then measured by filling the pycnometer with demineralized water to a predefined level ($M_2$). The aggregates were then removed from the pycnometer, and the pycnometer was weighted after being filled again with demineralized water to the same level used to measure $M_2$ (mass $M_3$). The removed aggregates, on the other hand, were wiped from excess water with a wet cloth and weighted in saturated surface dry condition ($M_1$). Finally, the aggregate samples were placed in oven at 45 °C for RAP and 110 °C for natural, until a constant mass was achieved ($M_4$). The equation to calculate the water absorption ($WA_{pycn}$, %) value is [34]:

$$WA_{pycn} = \frac{M_1 - M_4}{M_4} \cdot 100 \tag{3}$$

The density of the aggregates at saturated surface dry conditions ($\rho_{SSD}$, in g/cm$^3$) was calculated according to the equation [34]:

$$\rho_{SSD} = \frac{M_1}{M_1 - (M_2 - M_3)} \cdot \rho_W \tag{4}$$

where $\rho_W$ is the density of water at the test temperature (g/cm$^3$).

### 2.2.2 Assessment of fines

Blue methylene test was conducted on RAP aggregates for the assessment of fines. This technique is used for the characterization of geomaterials and is based on a semi-quantitative analysis that allows to detect the presence of clay minerals. The test was performed by quantifying of the ionic adsorption capacity of the media by measuring the amount of methylene blue required to cover the total surface area of the sample. The test was carried out on three samples, about 30 g each, collected from the 0/0.125 mm fine fraction of RAP aggregates. Samples were oven-dried at 45 °C and their weight was monitored every 24 h, until constant mass was reached (dry mass, $M_1$). The dried samples were then mixed with demineralized water. The solution was stirred at 600 rpm for 5 min, and 5 mL of dye solution were injected at steps of one minute. After each injection, the stain test was performed, *i.e.* a small amount of solution was collected, and a drop was deposited on filter paper. If the halo of the drop disappeared during the first 4 min, further 5 mL of dye solution were added. If the halo disappeared during the fifth minute, only 2 mL of dye solution were added. In either case, the stirring continued and the stain test procedure was repeated until the halo persisted for 5 min. The total volume of dye solution used ($V_1$) was then used to calculate the methylene blue factor ($MB_F$), through the equation [35]:

$$MB_F = \frac{V_1}{M_1} \cdot 10 \tag{5}$$

### 2.2.3 Chloride content

To investigate the compatibility of RAP with reinforced concrete, chloride content was measured, through two different tests.

The concentration of chlorides included in the RAP was measured on a sample of RAP (dry mass around 3 g), ground to powder and digested in boiling nitric acid. Potentiometric titration was then performed on the obtained solution to evaluate the concentration of acid-soluble chlorides.

The chloride amount that could be possibly released from the RAP aggregate to the cement paste was estimated on leachate. A sample of RAP (around 150 g) was immersed in demineralized water (RAP:water = 10:1 in mass), for several immersion times (24, 48, 72 h, 1 week and 2 months). At each immersion time, chloride concentration in water was measured through potentiometric titration.

### 2.3 Concrete mixes

Table 1 summarizes the mixing proportion of the twenty-four mixes that were designed, considering several RAP replacement levels, as well as other compositional parameters such as cement type and water/cement ratio (w/c). Two different cement types were selected, a Portland-limestone cement, type CEM II/A-LL 42.5R according to EN 197, and a pozzolanic cement, type CEM IV/A (P–V) 42.5N-SR, with additions of natural pozzolan and fly ash. The two cement types are identified with letters "L" and "P", respectively, in the mix label. Two w/c ratios were considered, equal to 0.45 and 0.65, named "a" and "b" in the mix label, respectively. These values were selected as representative of concrete mixtures typically designed for structures exposed to moderately aggressive environments with risk of carbonation (e.g. exposure class XC1 according to EN 206, for the 0.65 value), and more aggressive environments due to the presence of chlorides (e.g. exposure class XS3 or XD3, for the 0.45 value). The mixing proportions were calculated by keeping constant the volume fraction occupied by cement paste, and, consequently, the volume fraction occupied by aggregates. The reference mixes were designed with only natural aggregates, named "N" in the mix labels. Five replacement levels of RAP aggregate were then considered, calculated as percentage replacement with respect to the total mass of aggregate, up to the full replacement (100% RAP aggregates, named "R" in the mix labels). The dosage of RAP was obtained considering that the two types of aggregates are characterized by different density (more details can be found in ref. [36]). Intermediate replacement levels were named as the letter "R" followed by the mass percentage substitution (*e.g.* "R40" for the concrete mix with 40% substitution of natural aggregates with RAP aggregates, Table 1).

A sulphonated naphthalene superplasticizer (SP) admixture was also considered in the mix design, with the aim of achieving a target consistence class of S4, compatible with reinforced concrete structures. In some cases, a higher amount with respect to the designed value was necessary, to improve workability. Concretes constituents were mixed with the following procedure: first only aggregates were blended in the mixer (90 s), then cement was added and blended (90 s), finally water

**Table 1** Mixing proportions of the concrete mixes; contents of natural (NAT) and RAP aggregate refer to saturated surface dry conditions

| Mix label | w/c | RAP content (%) | Mixing proportions (kg/m$^3$) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Cement | Water | NAT | RAP | SP |
| L-a-N | 0.45 | 0 | 357 | 161 | 1980 | – | 6.5 |
| L-a-R20 | 0.45 | 20 | 357 | 161 | 1565 | 391 | 6.1 |
| L-a-R40 | 0.45 | 40 | 357 | 161 | 1153 | 769 | 7.7 |
| L-a-R60 | 0.45 | 60 | 357 | 161 | 756 | 1134 | 8.7 |
| L-a-R80 | 0.45 | 80 | 357 | 161 | 371 | 1485 | 9.7 |
| L-a-R | 0.45 | 100 | 357 | 161 | – | 1826 | 10.6 |
| L-b-N | 0.65 | 0 | 283 | 184 | 1981 | – | 4.5 |
| L-b-R20 | 0.65 | 20 | 283 | 184 | 1566 | 391 | 3.1 |
| L-b-R40 | 0.65 | 40 | 283 | 184 | 1154 | 769 | 3.6 |
| L-b-R60 | 0.65 | 60 | 283 | 184 | 755 | 1134 | 2.8 |
| L-b-R80 | 0.65 | 80 | 283 | 184 | 372 | 1486 | 4.7 |
| L-b-R | 0.65 | 100 | 283 | 184 | – | 1827 | 4.7 |
| P-a-N | 0.45 | 0 | 357 | 161 | 1980 | – | 9.8 |
| P-a-R20 | 0.45 | 20 | 357 | 161 | 1565 | 391 | 9.2 |
| P-a-R40 | 0.45 | 40 | 357 | 161 | 1153 | 769 | 9.5 |
| P-a-R60 | 0.45 | 60 | 357 | 161 | 756 | 1134 | 9.9 |
| P-a-R80 | 0.45 | 80 | 357 | 161 | 371 | 1485 | 12.3 |
| P-a-R | 0.45 | 100 | 357 | 161 | – | 1826 | 7.1 |
| P-b-N | 0.65 | 0 | 283 | 184 | 1981 | – | 3.8 |
| P-b-R20 | 0.65 | 20 | 283 | 184 | 1566 | 391 | 2.8 |
| P-b-R40 | 0.65 | 40 | 283 | 184 | 1154 | 769 | 3.7 |
| P-b-R60 | 0.65 | 60 | 283 | 184 | 755 | 1134 | 4.1 |
| P-b-R80 | 0.65 | 80 | 283 | 184 | 372 | 1486 | 5.0 |
| P-b-R | 0.65 | 100 | 283 | 184 | – | 1827 | 4.0 |

SP: superplasticizer admixture

admixed with initial amount of SP was added and mixed (90 s). In case a further addition of SP was necessary, further 90 s of mixing were applied.

Cubic specimens were cast in metallic moulds, side dimension of 100 mm, compacted on a vibrating table, and covered with a plastic film. The day after casting, specimens were demoulded and placed in a moist curing chamber (RH > 95% and T = 20 °C), until being tested at different curing times.

## 2.4 Concrete testing

### 2.4.1 Workability

To characterize concrete at a fresh state, consistency class was assessed during casting, through slump test. The target consistence class of S4 could not be achieved in some cases, even after the further addition of superplasticizer. However, the total amount of superplasticizer added to the mix was always kept under 3% vs. cement mass (Table 1) to avoid the risk of segregation. When workability was not satisfactory, particular attention was dedicated to performing a good compaction of fresh concrete on the vibrating table.

### 2.4.2 Compressive strength, density, and total open porosity

To characterize concrete mechanical performances, compressive strength was measured on two replicate specimens soon after demoulding (1 day) and after 7, 28 and 90 days of moist curing. Prior to the compressive strength test, specimens were weighted so that density could be assessed. Two tests with mercury intrusion porosimeter (MIP) were performed for each concrete mix, on fragments of concrete (dimension about 1 $cm^3$) from one of the two replicate specimens tested after 7 days of moist curing (more details on the procedure are reported elsewhere [37]).

### 2.4.3 Dynamic modulus of elasticity

The dynamic modulus of elasticity was estimated through ultra-sonic pulse velocity measurements on the same replicate cubic specimens, prior to the compressive strength test. The dynamic modulus of elasticity ($E_d$, in GPa) was then calculated as [38]:

$$E_d = 10^{-9} \cdot D \cdot v^2 \cdot \frac{(1+\delta)\cdot(1-2\delta)}{(1-\delta)} \tag{6}$$

where $D$ is concrete density (in $kg/m^3$), $v$ is the ultra-sonic rate (in m/s) and δ is the dynamic Poisson’s ratio assumed equal to 0.27 [38]. The measurements were conducted considering the two couples of parallel surfaces that did not include the casting surface.

### 2.4.4 Electrical resistivity

Bulk electrical resistivity was estimated through the uniaxial method, by placing concrete specimens between two external metallic electrodes. Electrical conductivity measurements were performed prior the compressive strength, on four other replicate cubic specimens at several moist curing times (1, 7, 28 and 90 days of curing). The electrical resistivity ($\rho$, in Ω m) was then calculated from the conductivity measurement, according to the equation:

$$\rho = \frac{10^5}{C} \tag{7}$$

where C is the conductance (in μS). Measurements were carried out in all the three different directions: on the two couples of parallel faces of the cube avoiding the casting surface, and in the direction including the casting surface.

## 3 Results and discussion

### 3.1 RAP aggregate characterization

Figure 3 summarizes the results in terms of moisture content and water absorption of the natural and RAP aggregate. The moisture content, evaluated through ponderal method, resulted significantly higher for RAP aggregate, around 4.3%, and with a higher variability, with respect to natural aggregate (around 0.9%). Regarding water absorption, the two different procedures, ponderal and pycnometer, gave comparable results in the case of natural aggregate, around 1% with very low variability (Fig. 3). Therefore, at the time these analyses were performed, natural aggregates were in slightly unsaturated conditions, being the moisture content slightly lower than the water absorption.

As it concerns RAP aggregate, water absorption resulted around 2.5% with both the techniques (Fig. 3), in accordance with other results available in literature [16]. In this case the moisture content value was higher than the water absorption value, meaning that RAP aggregates were in wet conditions. It is reasonable to assume that this difference was due to the storage environment, which mainly affects the moisture content parameter. However, in the case of RAP aggregate, the presence of a layer of dust and impurities on the bituminous layer may also have influenced the values of water absorption and moisture content by absorbing a higher amount of water and moisture from the environment. This effect was evaluated by comparing the water absorption results obtained through ponderal and pycnometer test, being the last one preceded by a washing procedure under running water. For the RAP aggregate employed in this study, the average value of water absorption measured through the two procedures resulted comparable (Fig. 3). This was one of the reasons why RAP from Anagni plant was selected as the most suitable to investigate its use in structural concrete. In fact, in a first phase of the project, RAP sourced from five different asphalt plants was characterized, and the difference between the results through the two water absorption tests were much more evident for RAP supplies coming from other asphalt plants [39]. It is worth noting, however, that results with pycnometer method presented significantly higher variability (Fig. 3), which could be related to the effectiveness of the washing procedure performed prior to each pycnometer test. On the other hand, the modification of the drying temperature for RAP aggregate, during both ponderal and pycnometer tests, proved to be effective in avoiding the melting of the bituminous layer, as observed in the existing literature for standard drying temperature [9]. For concrete mix design purposes, the average values of water absorption evaluated through pycnometer test were taken into consideration, while moisture content was evaluated prior to each casting, to adjust water content in each concrete mix.

Finally, through the pycnometer test, the density of the two types of aggregate was assessed, in saturated surface dry conditions. Natural aggregate resulted characterized by a density equal to 2803 kg/m$^3$, while RAP aggregate showed a density of 2524 kg/m$^3$.

The nature of the dust film was investigated through the methylene blue test, and the average $MB_F$ value obtained on three RAP samples was around 3.4 g/kg. While being the $MB_F$ beyond the limit value indicated by the standard for natural aggregates for concrete [35], through the methylene blue test a higher amount of impurities and fines was found in the RAP coming from other sites, which presented $MB_F$ values around 5–6 g/kg [39]. This feature was another reason behind the choice of the RAP coming from Anagni plant for the production and characterization of RAP concrete. It

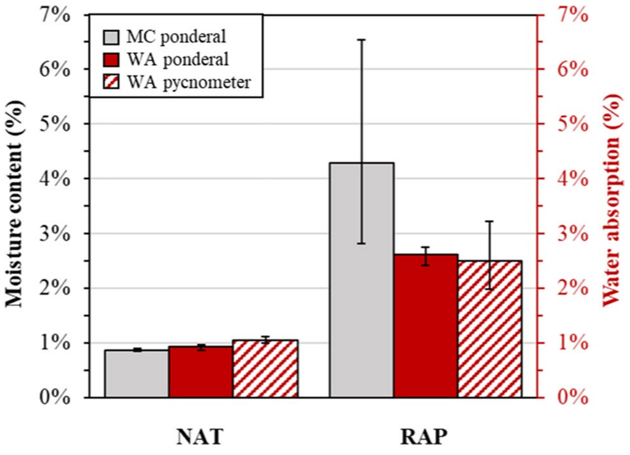


**Fig. 3** Moisture content (MC) and water absorption (WA), evaluated through the two different procedures, ponderal and pycnometer, on natural and RAP aggregate

should however be taken into consideration that the presence of a significant amount of clayey minerals is of particular relevance when considering the use of RAP as aggregate for concrete, since it may adversely affect the physical and mechanical properties of concrete at both fresh and hardened state. In fact, a high amount of silty-clayey particles in aggregates is usually associated with a higher demand of water in concrete at fresh state (influencing workability), and a reduction in compressive strength at hardened state. Other analyses for the microstructural and elemental characterization of the external layer of RAP aggregate were previously performed and can be found in [39], in terms of optical and SEM microscopy analyses, elemental microanalyses (EDS) and XRD analyses. These analyses, however, did not give any evidence of significant difference among the several RAP supplies, and did not influence the choice of RAP to be employed for RAP concrete characterization.

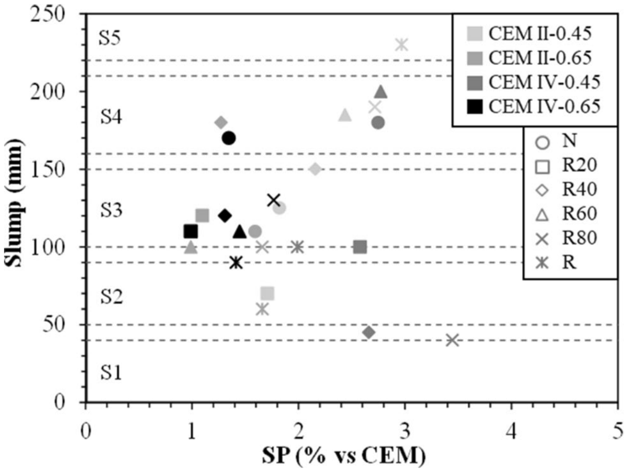
Finally, the last analyses performed on RAP aggregate investigated the presence of chlorides. According to the RAP supplier, the concentration of chlorides is usually not negligible in RAP soon after the demolition of a road pavement. However, the concentration of acid-soluble chlorides in RAP powders resulted lower than 0.01% vs sample mass [39]. Comparable results were obtained also on the leachate solution after several times of immersion, up to two months. In this case, results from other sites gave similar results [39]. At this regard it is worth to notice that after road demolition, RAP aggregates are usually stored for a certain period in external outdoor conditions, therefore rain and other atmospheric agents may contribute to wash away chlorides to a significant extent. The fact that chlorides were not found in the analysed samples does not exclude that, in other supplies from the same site, these may still be present in a non-negligible amount.

### 3.2 Concrete properties at fresh state

Figure 4 summarizes the results obtained in terms of workability at fresh state as a function of the amount of superplasticizer added to the mix, for all the twenty-four concrete mixes. In the Figure, the consistency class is also reported with the respective intervals of slump, as prescribed in EN 12350. It can be noticed that a variable amount of superplasticizer was added to several mixes, always included between 1 and 3%. In most of the cases, above all considering concrete mixes with the higher w/c ratio (and, hence, higher dosage of water), a consistency class of S3 was reached with a superplasticizer content close to 1–2% vs cement mass, and in these cases the workability was considered satisfactory. For the mixes with the lower w/c ratio, on the other hand, it was more difficult to reach a satisfactory consistency. In some cases, the successive addition of superplasticizer, until reaching a total content around 2–3% vs cement mass allowed to reach S3, S4 or even S5 class. In other cases, this was not possible and the workability of five mixes out of twenty-four resulted in a S2 or even S1 consistency class.

Considering the effect of RAP content on workability, most of the cases in which slump was equal or below 100 mm were mixes with a RAP content equal to 80% and 100%. These results confirm that the use of RAP in place of natural aggregates may significantly affect workability, above all for high substitution percentages, as reported also in other studies [32]. Anyway, despite a workability not always satisfactory, all the mixes showed good cohesion and could be compacted, so that after demoulding no segregation was observed in the specimens. Finally, the air content may also have played a significant role on the workability of concrete mixes at fresh state [32]. The air content, anyway, was not

**Fig. 4** Slump test results for all the concrete mixes, as a function of the superplasticizer (SP) content (consistency classes also reported)



measured at fresh state but was estimated through mercury intrusion porosimeter at hardened state, which gives an estimation of the total open porosity.

## 3.3 Concrete properties at hardened state

### 3.3.1 Effect of RAP content on density and total open porosity

The content of RAP had a clear effect in decreasing the density of hardened concrete, as can be seen in Fig. 5, which shows, in grey, the trend of concrete density after 7 days of moist curing for all the mixes, as a function of RAP content. Reference concrete showed a density around 2450–2500 kg/m$^3$, while values around 2200–2300 kg/m$^3$ were recorded for concretes containing only RAP aggregates. This result was expected, since the density of RAP aggregate is lower than that of natural aggregate, as previously shown. However, lower density of RAP concrete could also be related to a higher porosity in the cement paste. To investigate this aspect, data of total open porosity obtained through mercury intrusion porosimeter are also reported, in red, in Fig. 5. Total open porosity shows a mirrored trend with respect to concrete density: it progressively increases for increasing values of RAP content. This is particularly evident for RAP content of 60% (R60): concretes with w/c of 0.45 showed particularly low values of density, and, at the same time, particularly high values of total open porosity (Fig. 5). It can be concluded that the increase of RAP content in a concrete mix will affect the density as a combined effect of lower aggregate density and a higher amount of total open porosity, likely due to entrained air at a fresh state.

### 3.3.2 Effect of RAP content on compressive strength

Figure 6 reports all the results obtained in terms of compressive strength (average values and variability) for all the concrete mixes at different times of moist curing. Considering reference mixes (N), after 1 day of curing limestone concretes (CEM II) reached a compressive strength of 33 MPa and 22 MPa, for w/c of 0.45 and 0.65, respectively, while pozzolanic concretes (CEM IV) showed 1-day strength of 28 MPa and 12 MPa, for w/c of 0.45 and 0.65, respectively. As expected, compressive strength increased at higher curing times. For example, after 28 days of curing, a compressive strength of 65 MPa and 45 MPa was achieved for limestone concretes with w/c of 0.45 and 0.65, respectively, while values of 60 MPa and 35 MPa were achieved for pozzolanic concretes with w/c of 0.45 and 0.65, respectively. At all the curing times a quite good reproducibility of data was obtained. By substituting natural aggregate with RAP aggregate a progressive decrease in compressive strength was observed with the increase in the RAP content, independently from the cement type and w/c ratio considered. The decrease in compressive strength seemed to be significant for RAP contents up to 60%, and less marked for 80% and 100% RAP contents. Furthermore, the loss in mechanical performances resulted more limited when considering a pozzolanic cement type rather than a limestone cement. In fact, considering for example the 40% RAP content, pozzolanic concretes showed a decrease in compressive strength of about 28% and 21% for 0.45 and 0.55 of w/c ratio, respectively, with respect to reference concretes, compared to a reduction of 36% and 45%, respectively, for the limestone concretes. Other factors, such as the development in time of compressive strength seems to remain unaltered for increasing RAP contents, only slightly more limited for pozzolanic concretes and high RAP contents.

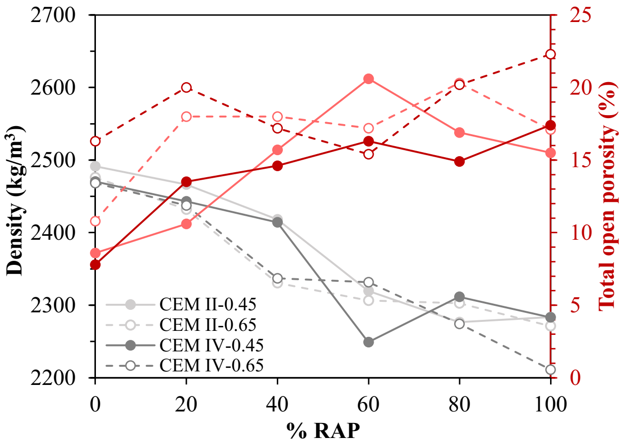


**Fig. 5** Density (grey) and total open porosity (red) as a function of RAP content, for all the concrete mixes after 7 days of curing (lighter and darker colours for CEM II and CEM IV concretes, while plain and dotted lines for w/c of 0.45 and 0.65, respectively)

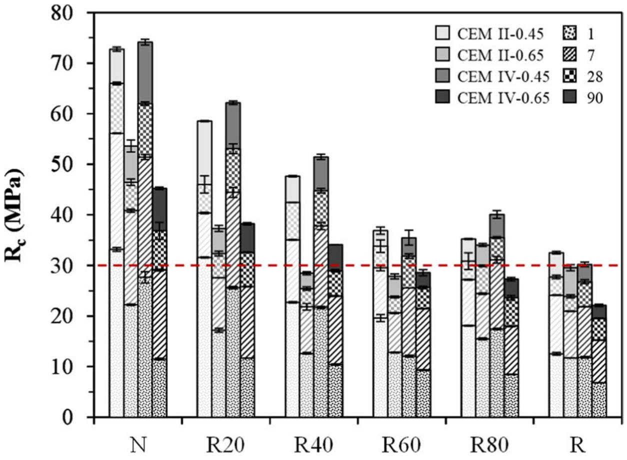


**Fig. 6** Average values (histograms) and variability (error bars) of compressive strength results, for all the concrete mixes and RAP contents, at different moist curing times (in days)

The decrease in mechanical performances of concrete for increasing RAP contents is usually associated to the bituminous layer in RAP particles, which constitutes a weak interfacial transition zone and reduces adhesion of the inner aggregate core with the cement paste matrix. On top of this, the high amount of silty-clayey fine particles found through the methylene blue test is also likely responsible for the decrease in bond and load transfer between the bitumen layer of RAP aggregate and the cement paste. The increase in porosity as a function of RAP content (Fig. 5) is also expected to have a clear effect on concrete compressive strength. Figure 7 shows the correlation between the compressive strength ($R_c$) and the total open porosity measurements. It can be noticed that compressive strength decreases linearly with increasing the total open porosity, with a quite good correlation, especially for high RAP contents. This effect could have significant consequences from a durability point of view, since more porous concretes will be more permeable to detrimental species that can penetrate from the environment (this aspect will be further investigated through durability tests on the same concrete mixes). However, the amount of entrained air at the fresh state could also be controlled with the addition of an anti-air admixture, which will have effects on both properties at fresh and hardened state [32].

Despite the negative effect of RAP on mechanical performances of hardened concrete, it is however worth noting that the tailoring of the concrete mix with cement type and w/c ratio could anyway guarantee comparable mechanical performances with respect to conventional concrete for several applications. For example, a mechanical strength of 30 MPa at 28 days of curing can be achieved with a RAP content up to 60% in the case of concrete mixes with w/c of 0.45 independently from the cement type considered in this study, and with a RAP content up to 20% for concrete mixes with w/c of 0.65 independently from the cement type (Fig. 6, red dashed line). From the study of several variables related to concrete mix design carried out in the present work, it possible to derive the empirical correlations known as Abrams' law curves. These curves give, for each specific application, the w/c ratio that can be employed to guarantee a certain compressive strength after a certain curing time. For conventional concrete, the correlations depend only on the cement type considered, but for a concrete that incorporates RAP as recycled aggregate, they resulted highly affected also by the RAP replacement level [36].

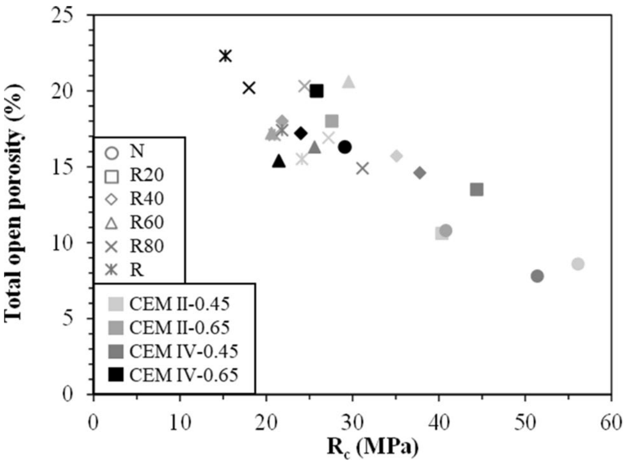


**Fig. 7** Total open porosity as a function of the compressive strength ($R_c$) results, for all the concrete mixes after 7 days of curing

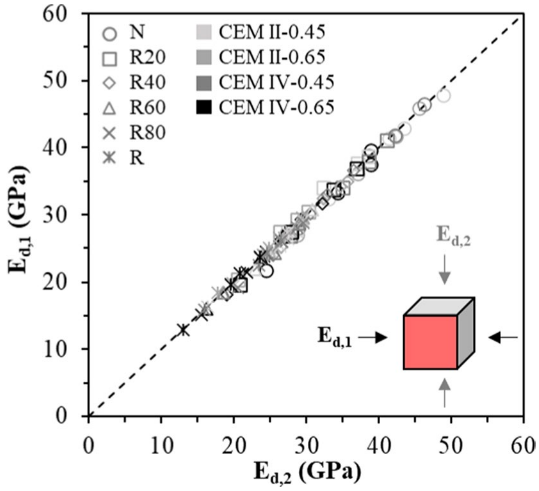


**Fig. 8** Dynamic modulus of elasticity through parallel mould surfaces (in grey) for all the concrete mixes and curing times (cast surface in red)

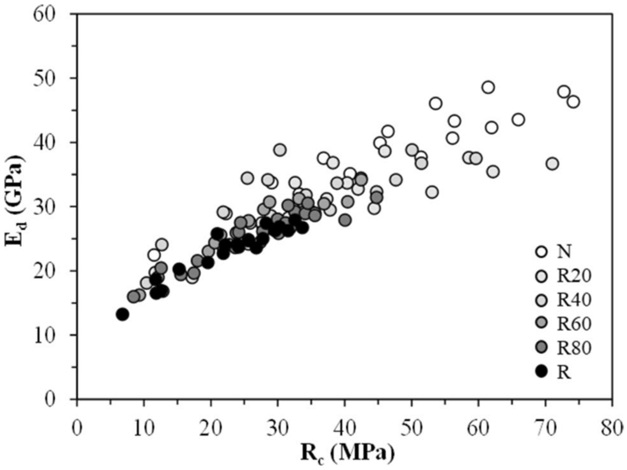


**Fig. 9** Dynamic modulus of elasticity as a function of compressive strength at different moist curing times and for all the concrete mixes, with various RAP contents

### 3.3.3 Effect of RAP content on dynamic modulus of elasticity

The other concrete mechanical property that was analysed was the dynamic modulus of elasticity. This property was evaluated considering the two parallel mould surfaces, and the comparison between the results obtained in the two directions is reported in Fig. 8, which presents results at all curing times, for all the concrete mixes. In general, values included between 10 and 50 GPa were obtained, with a quite good reproducibility in the two directions, meaning that the material was quite homogeneous.

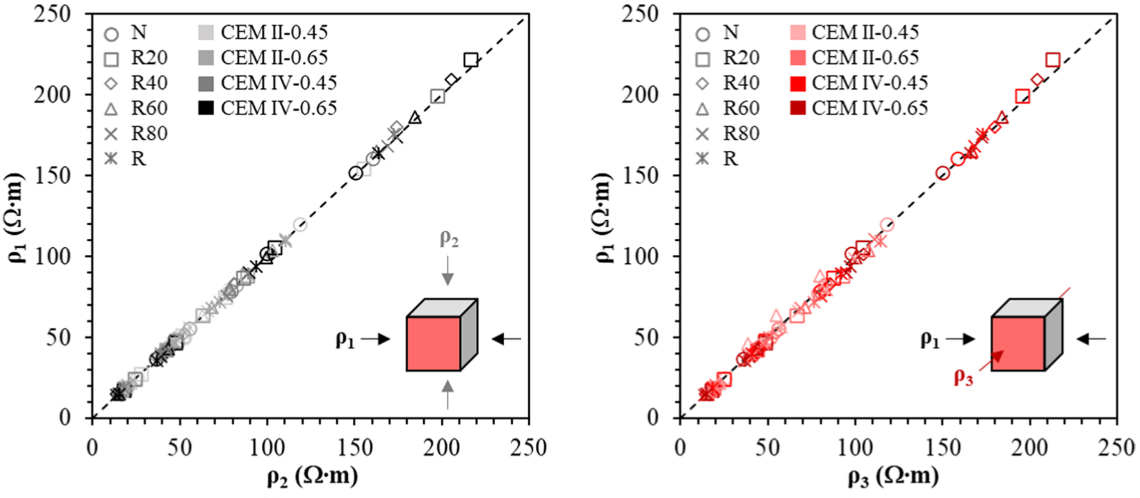
Figure 9 presents the relationship between the two mechanical parameters considered in this study, *i.e.* compressive strength and dynamic modulus of elasticity, for all the mixes and curing times considered. In the Figure, symbols with different colours highlight different substitution percentages of natural aggregate with RAP aggregate. As expected, results concerning reference concretes, independently from cement type and w/c ratio considered, presented higher values of both compressive strength and dynamic modulus of elasticity, mainly included between 30 and 50 GPa (Fig. 9). At the same time, the lowest values of both compressive strength and dynamic modulus of elasticity, mainly included between 15 and 30 GPa, were recorded for the mixes with RAP aggregate only (Fig. 9). The concrete mixes with intermediate RAP contents presented intermediate values of both the mechanical parameters. However, the RAP content did not seem to affect the relationship between compressive strength and dynamic modulus of elasticity, even for higher substitution percentages (Fig. 9), which may imply that the mechanical behaviour of concrete is not altered by the presence of RAP.

### 3.3.4 Effect of RAP content on concrete electrical resistivity

Finally, the microstructure of RAP concretes was evaluated through another non-destructive technique, *i.e.* concrete electrical resistivity. This is usually considered as one of the main parameters that regulates the corrosion rate of steel reinforcement in a concrete structure but can give also important hints on the microstructure of concrete and its evolution in time. In fact, through non-destructive electrical resistivity measurements, it is possible to follow the evolution of pore refining that occurs during moist curing, as a consequence of further hydration of cement. Moreover, it can give some information on concrete microstructure in correspondence of the cast surface, which, usually, presents a higher porosity with respect to the mould surfaces. Due to the dependence of resistivity measurements on the microstructure and pore refinement of the cement paste, electrical resistivity is also used as a measure to estimate some durability-related parameters, such as the resistance of concrete to chloride penetration [2].

Figure 10 shows all the values of electrical resistivity measured at the different curing times for the concrete mixes. In the Figure, the effect of different surfaces is also shown, i.e. resistivity measured across parallel mould surfaces is shown in Fig. 10a, while the resistivity measured along the direction of the cast surface is shown in Fig. 10b. In general, values included between 10 Ω m and 230 Ω m were obtained, with a quite good reproducibility across parallel mould surfaces (Fig. 10a) and considering the direction of the cast surface (Fig. 10b). This implies that the cast surface did not present a higher porosity and therefore that it had not experienced some processes that may cause it, such as segregation and bleeding.

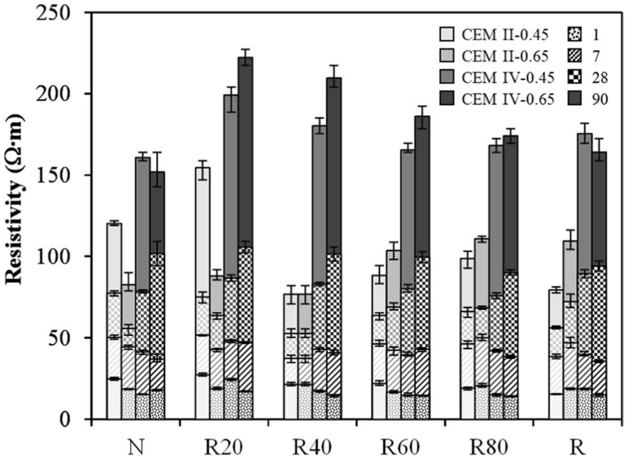
Figure 11 summarizes the results obtained in terms of electrical resistivity (average values and variability) for all the concrete mixes and at different curing times. Electrical resistivity mainly depends on capillary porosity, and as expected, values obtained in this study showed an increasing trend in time independently from the w/c or the cement type considered, due to the evolution of pore refinement. This effect, however, resulted emphasised for CEM IV concretes, which at 90 days of curing showed a significant increase of electrical resistivity with respect to the values after 28 days. This was expected, since pozzolanic activity in CEM IV concretes leads to a more refined pore microstructure in time. As it concerns the effect of RAP substitution, it is not possible to identify a clear trend of the electrical resistivity as a function of RAP content. For example, considering results after 28 days of curing, electrical resistivity slightly decreases with increasing RAP content for CEM II concretes with w/c ratio of 0.45 and CEM IV concretes with w/c of 0.65. At the same time, it seems to slightly increase with increasing RAP content for CEM II concretes with w/c of 0.65 and CEM IV concretes with w/c of 0.45. Again, the superimposition of several factors seems to influence the effect that RAP replacement has on the properties of concrete. In the case of electrical resistivity, two contrasting effects may play a significant role. On one hand, total open porosity increases with increasing RAP content (Fig. 6), which is expected to result in a decrease of concrete electrical resistivity. On the other hand, RAP aggregates contain insulating portions of bitumen, which is expected to result in an increase of concrete electrical resistivity. Two further factors, in general, may affect the values



(a) (b)

**Fig. 10** Electrical resistivity through parallel mould surfaces (dark and light grey arrows in the drawing) and in the direction of cast surface (red arrows in the drawing) for all the concrete mixes and moist curing times

**Fig. 11** Average values (histograms) and variability (error bars) of electrical resistivity, for all the concrete mixes and RAP contents, at different curing times (in days)



of concrete electrical resistivity but can be neglected in this study. The different ratios between aggregate and cement paste, which can be neglected since all concrete mixes were designed to have the same volume of cement paste, and different moisture contents in concrete, which can be neglected since all specimens were in the same conditions (kept in the same moist curing chamber). It is worth noting, however, that the difference in the values of electrical resistivity as a function of the RAP content were not significantly high. In fact, this parameter may change of several orders of magnitude depending on the moisture content of concrete, therefore considering the variability range of this parameter, the effect of RAP content could be considered negligible. In literature, electrical resistivity measured in analogous way was also used to estimate the resistance to chloride penetration of concrete containing several RAP contents, up to 50% [17]. Similar results were reported, i.e. resistivity values included between 250 Ω m and 360 Ω m, and no clear trend as a function of RAP content [17]. Those values were associated to a low concrete permeability to the penetration of chlorides [17], however, in view of all the above-mentioned aspects that could affect concrete electrical resistivity in a combined way, more specific tests will be employed for the assessment of chloride penetration resistance for the concrete mixes presented in this study, together with other durability-related performances.

## 4 Conclusions

In this study the possibility to use Recycled Asphalt Pavement (RAP) as partial or total replacement of natural aggregate in concrete was investigated, in combination with other mix design variables. RAP was analysed in terms of grain size distribution, density, assessment of fines, chloride content, moisture content and water absorption. Subsequently, twenty-four concrete mixes were cast considering two cement types, Portland-limestone and pozzolanic, two w/c ratios, 0.45 and 0.65, and different replacement percentages of natural aggregate with RAP, to compare RAP concrete performances with reference concretes containing only natural calcareous aggregate. The following conclusions can be drawn:

- The granulometric analysis on RAP showed a size distribution curve close to the Fuller ideal distribution, potentially adequate for a complete replacement of natural aggregate. The chlorides content was negligible, in compliance with requirements for reinforced concrete applications. However, a significant amount of silty-clayey particles was found on RAP surface, that likely led to a higher variability and average values of water absorption and moisture content.
- RAP concretes required higher dosages of superplasticizer admixture compared to reference concretes to improve workability. It was not always possible to achieve S3-S4 consistency classes, above all with substitution percentages higher than 80%.
- For the same cement type and w/c ratio, compressive strength of RAP concretes showed a decreasing trend for increasing RAP contents, more marked for contents up to 60%, and less marked from 60 to 100% of RAP content. The development of compressive strength in time and the effect of the cement type and w/c ratio did not seem to be affected by the presence of RAP.
- RAP concretes showed progressively lower densities for increasing values of RAP contents, down to 2200–2300 kg/m$^3$, as a combined effect of lower density of the RAP aggregate itself, and a higher total open porosity of concrete.

- Dynamic modulus of elasticity was progressively lower for increasing contents of RAP, however the correlation between compressive strength and dynamic modulus of elasticity did not seem to be altered by the presence of RAP.
- Electrical resistivity measurements showed microstructural properties of concrete were homogeneous in all directions, however, this parameter did not seem to be significantly influenced by the content of RAP.

RAP seemed to be a promising recycled material that could be employed in place of natural aggregate in concrete, as far as the different aggregate characteristics are carefully taken into consideration in the mix design. Among the implications of the current work is that the experimental procedures usually employed for natural aggregate characterization need to be adjusted for the presence of the bituminous layer in RAP aggregate. From a mechanical point of view and for most applications, adjustments to the concrete recipe, considering a different type of cement and/or a different w/c ratio, could compensate for the loss of compressive strength caused by the replacement of natural aggregate with RAP. Further studies are needed to investigate the durability performances for structural concrete applications. Next experimental steps of the Project include a detailed investigation of durability-related parameters and corrosion behaviour of steel rebar in RAP concrete for durability design. Finally, an investigation will be implemented on whether the same concrete properties obtained under controlled laboratory environment are reproducible in concrete made in ready mix plants.

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**Data availability** Data sets generated during the current study are available from the corresponding author on reasonable request.

**Code availability** Not applicable.

## Declarations

**Competing interests** The authors declare no competing interests.

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