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Assessment of reclaimed asphalt pavement (RAP) as recycled aggregate for concrete

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ASSESSMENT OF RECLAIMED ASPHALT PAVEMENT (RAP) AS RECYCLED AGGREGATE FOR CONCRETE

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ABSTRACT

A study about the performances of different reclaimed asphalt pavement (RAP) sourced from 5 different Italian collection sites is presented to evaluate RAP as aggregate for concrete. Several RAP properties were investigated: physical properties (particles size distribution, water absorption, open porosity, wettability), microstructure (optical and scanning electron microscopy), dimensional stability (drying shrinkage of mortar and concrete with 100% of RAP as aggregates) and durability assessment by freeze-thaw cycles. Several differences between RAP and natural aggregates used for concrete were highlighted. The use of RAP as recycled aggregate for concrete is a promising route, but a complete characterization is needed to ensure concrete performance and durability.

KEYWORDS

Reclaimed asphalt pavement; RAP; recycled aggregate; concrete aggregate; microstructure; durability.

HIGHLIGHTS

- Reclaimed asphalt pavement (RAP) was tested as aggregate replacement for concrete.
- Five types of RAP sourced by different Italian collection sites were characterized.
- RAP shows irregular porous surface due to bitumen covering the natural aggregate.
- RAP shows hydrophobic behavior.
- RAP exhibits dimensional stability and frost resistance.

1. Introduction

Every activity related to the built environment has significant environmental, economic, social and even cultural impacts. In particular, the consumption of energy and non-renewable natural resources are the most relevant environmental aspects. Many studies have highlighted the negative impact of the production of cementitious materials in the construction industry, even if they are among the most used and competitive construction materials. Concrete production may contribute to 4-8% of the global carbon dioxide (CO_2) emissions and to the consumption of a huge quantity of natural resources [1].

The total or partial replacement of natural aggregates with recycled ones in concrete mixes is a possible route towards the production of more environmentally sustainable materials [2,3]. A viable solution involves the use of reclaimed asphalt pavement (RAP) to be applied as recycled aggregate for concrete. RAP is a solid waste generated by the demolition and milling of existing asphalt pavements during the maintenance of degraded roads [4], thus falling into the category of construction and demolition waste (CDW). RAP is a material constituted by natural aggregates covered by a bituminous layer and a dust film due to the method applied for crushing pavements and their storage [5]. In 2020, RAP amount produced in Europe and USA has been estimated 40 and 87 million tons, respectively. Most of the available RAP is reused in the asphalt paving industry, while the remaining is directly sent to landfill or used in other sectors [6]. In Italy, asphalt road pavements are widespread thanks to several factors such as a well-established tradition, technical expertise, quick execution, relatively low cost, easy maintenance and renovation operations. So, with 9.5 million tons, Italy is the second country in Europe for RAP production, only behind Germany with 11.6 million tons [6].

The use of RAP as recycled aggregate for concrete can contribute to minimize the economic and environmental impact of the most popular and largely used construction material. The main advantages can be the limited exploitation of natural resources due to the reduction of aggregates mining, energy saving related to the extraction and transport of natural raw materials, and lower CO_2 emissions especially linked to transportation. In addition, RAP recycling can mitigate the issues related to waste transport and disposal, reducing the amount of landfilled material [7,8].

In the past, RAP was mainly reused in asphalt mixes after demolition or as coarse aggregate after extraction of bituminous layer; however, a limited amount of RAP was applied in this practice [9]. High percentages of RAP in asphalt mixes may cause cracking and durability problems, due to RAP high stiffness and brittleness [10,11]. Currently, RAP can be successfully added in asphalt preparation up to 30 wt% of total aggregates [12]. Scientific research has also focused on improving the properties of asphalt mix containing up to 60 wt% of RAP as natural aggregate replacement, considering the addition of a soft binder or a rejuvenator which restores the properties of RAP aged binder [13–16]. In addition, RAP concentration can be successfully increased by considering RAP from lower layers, being less involved in the natural ageing of bituminous materials [17,18].

Only more recently, RAP has been applied as natural aggregate replacement in cementitious mortar and concrete. In several research studies [19–25], it was observed that the incorporation of RAP in concrete significantly reduces the mechanical performances as function of RAP amount added in the mixture. Such behavior was further confirmed by other recent studies that were aimed at the use of high percentages of RAP (up to 100 wt%) in concrete mixes [26–31]. So far, the use of RAP as recycled aggregate in concrete is usually recommended for non-structural application [8,22,24] and some authors recommended 50 wt% as the maximum content of RAP over total aggregates in concrete [32,33]. Moreover, it was found that RAP addition as natural aggregate replacement negatively affects some concrete properties at the fresh state such as workability measured by slump test [20,27].

Similarly, studies on cementitious mortars containing RAP also pointed out the decrease of mechanical properties with the increase of RAP amount [33,34]. Adhesion problems between cement matrix and RAP, due to the presence of bituminous layer, were highlighted as the main reason of strength reduction [35,36]. Moreover, since RAP is constituted by a high concentration of agglomerated particle, its typical particle size distribution exhibits fewer fine fractions and higher amount of coarse fractions compared to the natural aggregates usually applied for concrete production [8,20,32,37]. Even if RAP agglomerated particles can easily break down when subjected to an external stress [19], some recent studies were focused on improving the bond between cement matrix and RAP by applying surface treatments to RAP, thus obtaining improvements in terms of mechanical properties and durability [5,28,36]. At the same time, it was demonstrated that the use of RAP in concrete enhances some properties, such as toughness due to the presence of bituminous layer which arrests crack propagation [19,20] and frost resistance due to larger open pores in the hardened samples compared to traditional concrete [34,38].

Although the scientific literature already provides several studies on the performance of cementitious mortars and concrete containing RAP, specific studies on RAP characterization to investigate its ability to act as concrete aggregate are still lacking. Indeed, as natural aggregates are the main constituent of concrete (about 80 wt%), it is fundamental that RAP, when used as recycled aggregate, can satisfy some essential requirements such as frost resistance and dimensional stability. For this reason, the aim of this work was to characterize RAP coming from five different Italian sites, in order to assess their ability to act as natural aggregate replacement in concrete production. Physical properties of RAP were investigated in terms of particle size distribution, water absorption, total open porosity and wettability properties. Their microstructure was assessed by microscopic techniques. Some of the measured RAP physical properties were also compared to those available in literature for natural aggregates (NA) and recycled concrete aggregates (RCA).

Moreover, RAP dimensional stability was considered by measuring the drying shrinkage of mortar and concrete samples with 100% of RAP as aggregates following the accelerated curing reported in EN 1367-4 [39]. Finally, a durability assessment was carried out in terms of frost resistance by subjecting RAP to freeze-thaw cycles according to EN 1367 (part 1 [40] and 6 [41]) as prescribed for natural aggregates. The results of dimensional stability test and freeze-thaw cycles were assessed according to EN 12620 [42] requirements.

2. Materials and methods

The investigated RAP was provided by Pavimental S.p.A. and collected from five different operative units located in Anagni (Frosinone, Italy), Arezzo (Italy), Zola Predosa (Bologna, Italy), Magliano Sabina (Rieti, Italy) and Piacenza (Italy). The five samples were named with the following designation: AN (Anagni), AR (Arezzo), BO (Zola Predosa), MA (Magliano Sabina), PI (Piacenza).

Petrographic analysis, reported in Table 1, shows that all the investigated RAP is constituted by a mix of sedimentary and igneous rocks, covered by bitumen. AN, BO and PI samples are richer of sedimentary rocks (70-74%) compared to AR and MA (56 and 42%, respectively). In the case of PI, acidic igneous rocks were also detected. Bitumen content of the investigated RAP is comparable and it is around 5.0 – 5.6 %, a usual concentration for road surface course [43]. All the provided RAP presents coarse particles and some agglomerated particles (Figure 1) in accordance with the literature [5,8,19,20,37].

Table 1: Petrographic analysis (in terms of lithotypes) of the investigated RAP.

Samples	Sedimentary rocks (limestone) (%)	Basic igneous rocks (basalt) (%)	Acidic igneous rocks (%)
AN	74	26	-
AR	56	44	-
BO	72	28	-
MA	42	58	-
PI	70	18	12

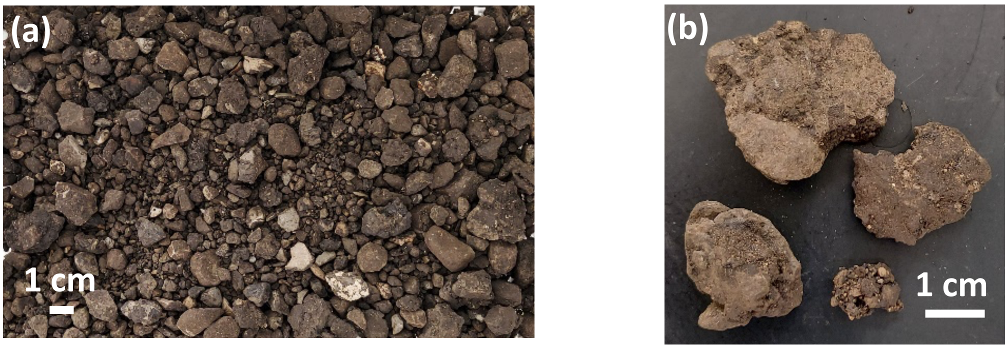

Figure 1: (a) AN RAP and (b) an enlargement of some RAP agglomerated particles.

Microstructure and physical properties of the investigated RAP were analyzed on samples preliminary washed and oven-dried at 85°C for 24 hours. Each sample of the five different RAP was obtained by quartering method from the original delivered batch (about 20 kg for each RAP).

Particle size distribution of each RAP was determined by sieving using at least 2.5 kg of material. Geometric density and water absorption were determined with different test methods as function of RAP size range. The pycnometer method was used on about 1 kg of RAP with particle size distribution between 0.063 and 4 mm in accordance with EN 1097-6 [44], returning geometric density (ρ_{Gp}) and water absorption (WA_p) values of the fine fraction. Water absorption on coarse RAP was carried out on samples, each of them constituted by 20 RAP particles with a diameter of about 10 mm. After drying at 85 °C to reach constant mass, RAP sample was immersed in water until saturation (WA_i), according to ASTM C127 [45]. When water saturation was reached, geometric density (ρ_{Gh}) was also calculated by hydrostatic weighing.

In addition, water absorption was determined by under-vacuum test method (WA_{uv}). After drying at 85 °C to reach constant mass, RAP samples were placed in a vacuum chamber that was evacuated to a pressure of (10 ± 5) kPa for 30 min. Then, samples were submerged by allowing water entering the vacuum chamber and vacuum level was maintained for additional 30 min. Samples were then weighed in saturated surface-dry (SSD) condition. To confirm the complete saturation, the test was repeated on the same RAP samples for longer times until a mass variation of less than 0.1% was reached.

Total open porosity and pore size distribution of the investigated RAP were determined by mercury intrusion porosimeter (MIP, Thermo Scientific Pascal 140 and 240 Mercury Porosimeters instruments). The operative conditions were as follows: Hg contact angle $\theta = 141.3°$, Hg surface tension $\gamma = 0.48$ N/m, applied pressure: from 0.1 kPa to 200 MPa. MIP measurements were carried out on samples of three RAP particles with a diameter of about 10 mm and each measurement was repeated at least two times. All the reported MIP results were treated by the S.O.L.I.D. software (SOLver of Intrusion Data, Thermo Scientific) that allows the correction of the sample compressibility due to the presence of bitumen layer. The use of MIP for porosity and pore size distribution is frequently debated [46-48] due to limitations related to the technique [38]; however, its use for construction materials is generally accepted [34, 38, 49-51] for comparison purpose, as applied in the present study.

Contact angle measurements were performed in accordance with EN 15802 [52]. RAP for testing was selected with flat surfaces: the analysis was performed at least on two different positions of the same RAP or on two different samples of the same RAP type, for a reproducibility purpose.

Morphological observation of samples was carried out using optical and scanning electron (SEM) microscopy on RAP with particle size between 8 and 16 mm. Optical observations were obtained by an optical microscope Olympus SZX10, applying a zoom ratio 10:1. SEM observations were carried out by using a field emission gun scanning electron microscope (FEG-SEM, Tescan Mira3) under high vacuum conditions, applying an accelerated voltage of 10 KeV and a working distance of 10 mm. RAP was observed on free surface and in cross-section. RAP cross-section was prepared by embedding the samples in epoxy resin at room temperature and polishing them up to 1000 grit silicon carbide abrasive paper. Lastly, mounted samples were made conductive by coating them with gold using a Quorum Q150R ES + sputter coater.

The dimensional stability of RAP was assessed according to EN 1367-4 [39] which involves the measurement of drying shrinkage of concrete prisms of 50×50×200 mm prepared with 100% content of RAP. This test was also performed on mortar prisms of 25×25×285 mm to test RAP with different particle size distribution. The accelerated curing conditions reported in EN 1367-4 [39], consisting of samples immersed in water for 120 hours followed by drying at 85°C for 72 hours, were applied for both concrete and mortar prisms.

Three concrete prisms were prepared using CEM II/A-L 42.5R, distilled water, 100% of dried fine (0.125-4 mm) and coarse (4-20 mm) RAP, with the following proportion (wt/wt): cement/aggregates = 1/6 and W/C = 0.55.

Two mortar prisms were prepared using CEM II/A-L 42.5R, distilled water and fine RAP (0.125-4 mm) in dry condition, with the following proportions (wt/wt): cement/aggregates = 1/2.25 and W/C = 0.47. Fine RAP with the size distribution reported in UNI 11504 was used as only aggregate [53].

As reference samples, mortar and concrete prisms were prepared using normalized silica sand [54] and granitic coarse aggregates. Drying shrinkage (S) of mortar and concrete containing RAP or natural aggregates was calculated by means of the change in length from the wet to the dry state.

The assessment of RAP durability was carried out considering the resistance to freeze-thaw cycles. The test was performed according to EN 1367-1 [40] and EN 1367-6 [41], the latter method including the presence of sodium chloride (NaCl) solution. Dried RAP was soaked in demineralized water or in 1 wt% NaCl solution for 24 hours. Then, RAP was subjected to 10 freeze-thaw cycles lasting 24 hours each. Each cycle involved freezing at -17.5 ± 2.5 °C for 4 hours and then thawing to +20 ± 3 °C for 10 hours. For each type of the investigated RAP, freeze-thaw cycles were carried out on 3 samples formed by 2 kg of RAP having particle size between 8 and 16 mm. RAP resistance to freeze-thaw cycles was evaluated in terms of mass loss (F) of the samples.

3. Results and discussion

3.1. Microstructure and physical characterization

As shown in Figure 2, the five investigated RAP have a similar particle size distribution, characterized by a larger amount of coarse fraction (> 4 mm) than fine one (≤ 4mm). PI sample has the lowest content of fine fraction (cumulative passing % = 9). The determined particle size distributions are very similar to those reported in literature [20,32,37,43], thus indicating that grinding procedures generate comparable RAP.

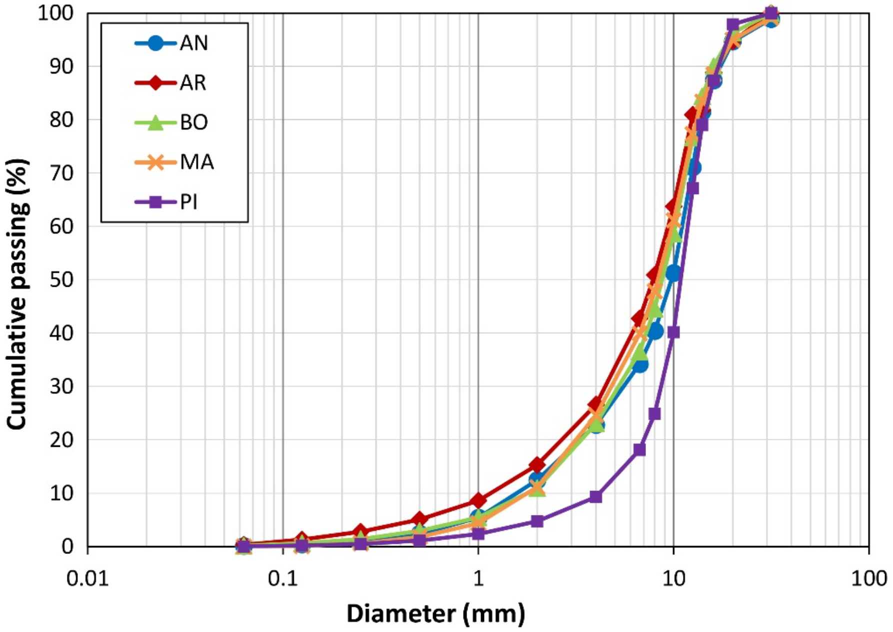

Figure 2: Particle size distribution of the five types of RAP in as-provided condition.

For the investigated RAP, geometric density and water absorption of fine (≤ 4 mm) and coarse (10 mm) particles are reported in Table 2, whereas total open porosity and static contact angle (θ) of 10 mm RAP are reported in Table 3. RAP with size of 10 mm has been selected as representative of coarse fraction.

Table 2: Geometric density and water absorption results of fine and coarse RAP (ρ_{Gp} and ρ_{Gh} are geometric densities determined by pycnometer and hydrostatic weighting test methods, respectively; WA_p, WA_i and WA_{uv} are the values obtained by pycnometer, immersion and under-vacuum test, respectively).

Sample	**ρ_{Gp} (g/cm^3) for 0.063-4 mm**	**ρ_{Gh} (g/cm^3) for 10 mm**	**WA_p (%) for 0.063-4 mm**	**WA_i (%) for 10 mm**	**WA_{uv} (%) for 10 mm**

AN	2.24	2.46	0.81	0.81	0.82
AR	2.30	2.45	1.32	1.22	1.34
BO	2.23	2.37	2.01	1.32	1.59
MA	2.21	2.35	1.32	1.02	1.08
PI	2.16	2.36	1.70	1.25	1.39

Table 3: Static contact angle (θ) and total open porosity measured by mercury intrusion porosimetry of 10 mm-RAP.

Sample	Total open porosity (%)	θ (°)
AN	5.4 ± 1.7	135
AR	3.3 ± 0.0	135
BO	6.5 ± 2.0	135
MA	5.3 ± 0.3	130
PI	6.1 ± 1.4	130

Comparing results obtained in terms of geometric density, coarse RAP presents higher values than fine one. The latter has higher specific surface and consequently they are largely covered by bituminous layer [27], thus exhibiting lower density.

Among the five RAP types, BO and PI samples show the highest water absorption values considering both fine and coarse particles and the highest total open porosity. Water absorption values of 10 mm-RAP are generally lower than the ones obtained for fine RAP, due to their lower specific surface [43]. During the determination of water absorption by immersion test, saturated surface dried condition on 10 mm-RAP was difficult to obtain and three consecutive measurements, respectively after 24, 48 and 72 hours, were needed until the difference between the mass measurements was lower than 0.1%. This behavior highlights difficulties in reaching pore saturation probably due to the presence of the bituminous layer. Moreover, water absorption results by under-vacuum test return higher values than those obtained by immersion, thus indicating that the conventional immersion method normally adopted for water absorption determination of natural aggregates may not be the most suitable method for RAP.

A comparison between water absorption values measured by immersion test on coarse fraction of RAP, natural aggregates (NA) and recycled concrete aggregate (RCA) is reported in Table 4. Most of the literature studies are focused on the use of coarse recycled aggregates as replacement of natural ones in concrete mixture, as both RCA and RAP fine fractions are not recommended for structural applications [43,55,56]. The five investigated RAP exhibit water absorption values comparable to the data obtained in [57], while other studies reported slightly higher values. In any case, water absorption of coarse RAP is in the same range of that one of natural aggregates, whereas recycled concrete aggregates exhibit much higher values and presents a large variability, mainly due to the remaining old cement paste [57-61].

Table 4: Comparison of water absorption values determined by immersion test of coarse natural aggregates (NA), recycled concrete aggregate (RAC) and reclaimed asphalt pavement (RAP).

Aggregate fraction	**References**	**WA (%)**		
		NA	**RCA**	**RAP**

Coarse	[57]	1.95	3.5	1.35
	[58]	1.4	7.7	-
	[59]	1.48	7.91	1.9
	[60]	1.5	4.6	2.1
	[61]	1.1	6.4	2.1

To better elucidate the effect of the bituminous layer in RAP, contact angle measurements were carried out to obtain indications of the hydrophobicity or hydrophilicity of RAP surface. In general, contact angle values significantly higher than 90° indicate that water drop does not significantly expand on the surface and a hydrophobic behavior is assessed. The determined average values of contact angle (θ) for all the RAP samples are between 130° and 135°, thus indicating that RAP surfaces are mainly hydrophobic (Table 3). This result agrees with the difficulties experienced on water penetration by immersion. Natural aggregates commonly used for concrete production present good affinity to water, having contact angle values within the hydrophilic range (e.g., contact angle measured on granite-type aggregates is in the range 39-48°) [62,63]. Contact angles comparison highlights a different behavior when RAP or natural aggregates are added to a cement paste; in the former case, a worse adhesion between RAP and cement binder shall be expected [64]. Total open porosity values, determined by MIP, are not influenced by the presence of bituminous layer. RAP generally exhibits higher porosity than natural aggregates, which have an average open porosity of 2.7% (Figure 3a). RAP also presents pore size distributions where a noteworty contribute of macroporosity is evident.

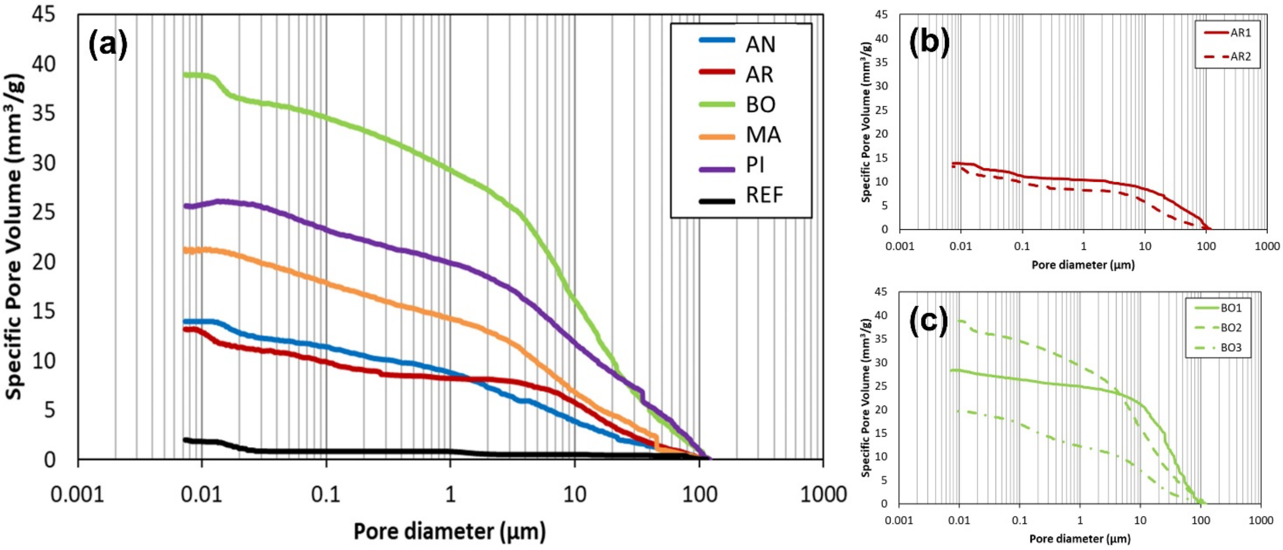

Figure 3: Pore size distribution analyzed by MIP of (a) all the investigated RAP and natural aggregate; (b) two samples of AR RAP, (c) three samples of BO RAP.

BO and PI RAP are the most porous samples, with an open porosity equal to 6.5% and 6.1%, respectively. This trend is in accordance with water absorption values. The standard deviation associated to the open porosity values is a significant marker. MIP tests carried out on AR and MA RAP give comparable results already after two measurements (Figure 3b), while AN, BO and PI samples have a noteworthy variability of results (Figure 3c). This may be linked to the origin of the

RAP: the petrographic analysis of AR and MA samples highlights a higher concentration of igneous rocks compared to the others.

RAP surface was further investigated by optical and SEM microscopy. Coarse RAP samples show similar morphologies and, for this reason, Figure 4 reports selected optical microscopy images of AN samples as representative example. It is observed a rough surface and an almost continuous layer of bitumen, as already reported in other studies [19,20,28].

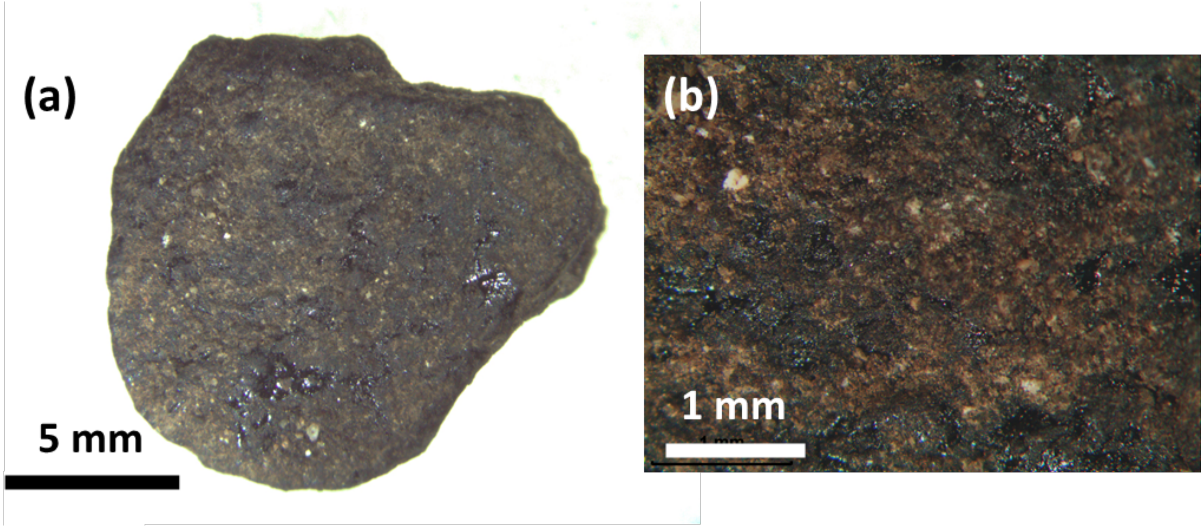

Figure 4: Optical microscopy observation of a representative RAP (AN sample): (a) image of a RAP particle, (b) enlargement of the sample surface.

Figure 5 a and b highlight the presence of fine aggregates embedded in the bituminous layer and the presence of well adherent dust film on the bituminous layer, as already observed in literature [5,26]. RAP cross-section observations, acquired by BSE (Figure 5 c and d), clearly evidence natural aggregates (light color areas) surrounded by bituminous layer (dark color areas). Bituminous layer is variable in the range of 300 - 800 µm for all the samples The interface between natural aggregate and bituminous layer appears continuous and smooth, as observed elsewhere [63].

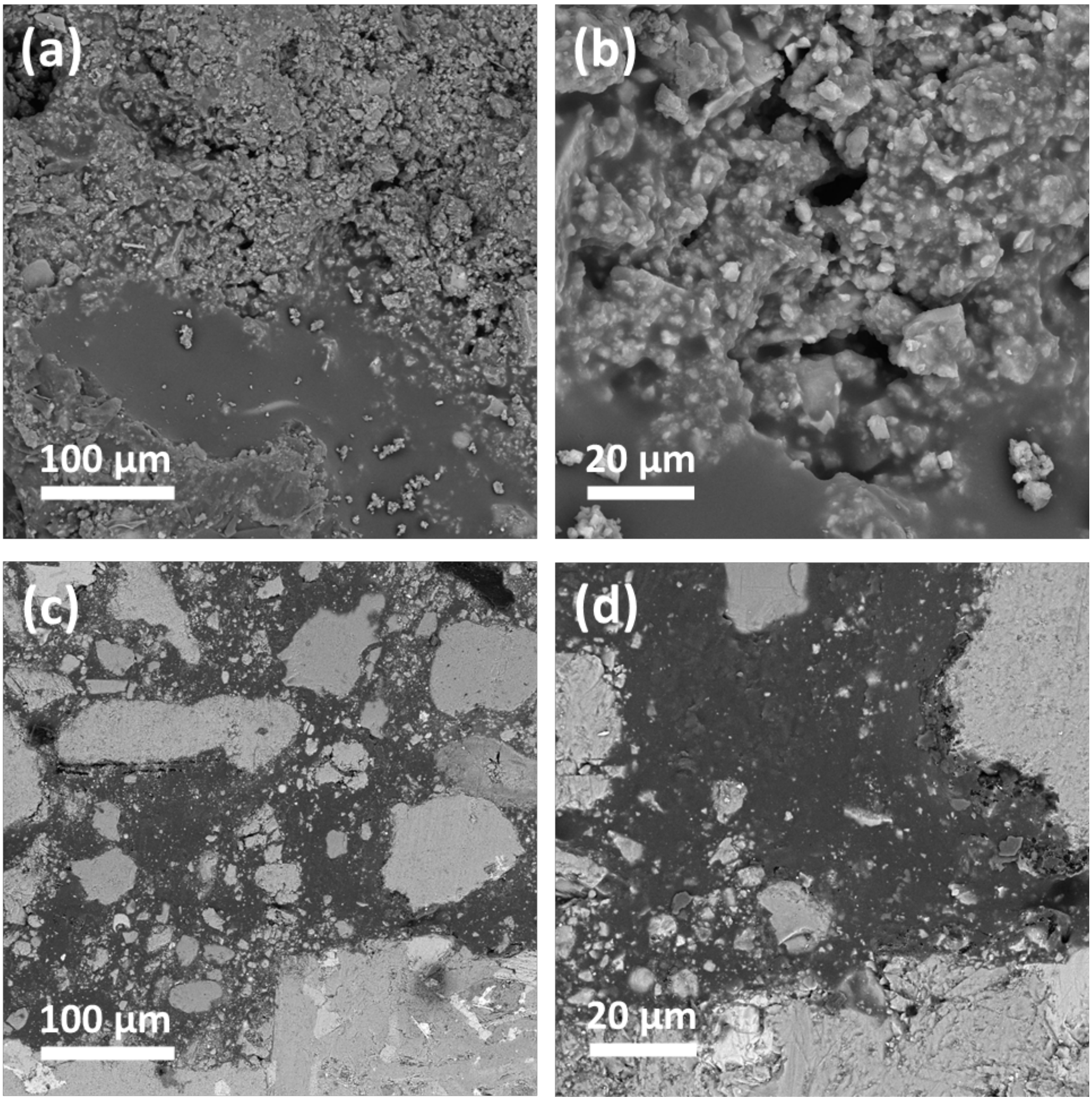

Figure 5: SEM micrographs of AN RAP acquired by backscattered electrons (BSE): (a,b) RAP free surface covered by dust film; (c,d) the interface between natural aggregate and bituminous layer.

3.2. Dimensional stability

Results of RAP dimensional stability are reported in Table 5 and they are expressed in terms of drying shrinkage (S) of mortar and concrete prisms prepared with 100 % RAP as fine and coarse aggregate, respectively. Mortar prisms made with AN and MA show the lowest drying shrinkage values (S=0.151 % and S=0.153 % respectively), whereas prisms containing AR exhibit the highest drying shrinkage (S=0.186 %).

Table 5: Drying shrinkage S (%) of mortars and concrete prisms obtained in accordance with EN 1367-4 [39] *(in italics the discarded value).*

Samples	**S (%)**	
	Mortar	**Concrete**
AN	0.151 ± 0.006	0.064 ± 0.003
AR	0.186 ± 0.003	*0.096 ± 0.020*
BO	0.167 ± 0.002	0.114 ± 0.002
MA	0.153 ± 0.001	0.043 ± 0.004
PI	0.178 ± 0.005	0.054 ± 0.001
REF	0.115 ± 0.001	0.039 ± 0.004

Drying shrinkage measured for concrete samples is lower than the ones reported for mortars with the relevant RAP, the latter being affected by the high specific surface of fine RAP. However, the same trend for the lowest values of shrinkage has been observed for mortar and concrete prisms. In particular, concrete and mortar prisms made with AN and MA exhibit S equal to 0.064 and 0.151 % and 0.043 and 0.153%, respectively. In concrete samples, the highest drying shrinkage (S=0.114%) was determined when BO RAP was used as aggregates. For AR RAP a too high standard deviation was obtained, thus, in agreement with EN 1367-4 [39] procedure, the relevant S% value was discarded. Mortar and concrete samples made of RAP as aggregate present higher values of drying shrinkage, compared to mortar and concrete samples containing only natural aggregates. Such behavior is probably due to the organic polymeric part in the bitumen which is more sensitive to the accelerated curing conditions used for this test. Although EN 12620 [42] reports a limit of S=0.075% when aggregates are used for concrete for structural applications, it shall be noted that RAP in concrete prisms do not overcome that limit except in the case of BO.

3.3. Durability

Results about resistance to freeze-thaw cycles of RAP after water and NaCl solution saturation, expressed as mass loss and respectively named F and F_{EC} (where EC means in extreme condition) are reported in Table 6, in accordance with the relevant category specified in EN 12620 [42]. Freeze-thaw cycles in presence of NaCl solution induce a more evident degradation of RAP compared to what occurs in water, so F_{EC} values are generally higher than F. In both conditions, BO and PI RAP present the highest mass loss, exhibiting the worst behavior in terms of frost resistance and falling in the second class of resistance (F_2 and $F_{EC}4$) according to the ranking reported in EN 12620 [42]. This result is mainly linked to the fact that BO and PI RAP are the most porous samples, as reported in Table 3, so they are more sensitive to freeze-thaw cycles. On the other hand, AN, AR and MA samples show lower and comparable values between the two tests, and they are classified within the first class of resistance (F_1 and $F_{EC}2$).

Table 6: Results and classification of RAP as aggregate subjected to freeze-thaw test in distilled water (F) and in presence of salt (F_{EC}). EN 12620 [42] *classification states: F_1 when $F \leq 1$; F_2 when $1 < F \leq 2$; $F_{EC}2$ when $F_{EC} \leq 2$; $F_{EC}4$ when $2 < F_{EC} \leq 4$).*

Sample	F (%)	Category	F_{EC} (%)	Category in EC
AN	0.89 ± 0.24	F_1	0.88 ± 0.03	$F_{EC}2$
AR	0.93 ± 0.10	F_1	0.97 ± 0.17	$F_{EC}2$
BO	1.63 ± 0.13	F_2	2.25 ± 0.25	$F_{EC}4$
MA	0.86 ± 0.09	F_1	1.20 ± 0.32	$F_{EC}2$
PI	1.95 ± 0.10	F_2	3.27 ± 0.72	$F_{EC}4$

RAP was observed by optical microscope after freeze-thaw cycles. In Figure 6, some images of AN RAP after freeze-thaw cycles in NaCl solution are showed as a typical example. Freeze-thaw cycles induce the damage of some RAP, partially removing the bituminous layer. This damage mechanism is better highlighted in Figure 7, where AN RAP after freeze-thaw cycles in water and in NaCl solution is reported. Especially in presence of NaCl solution, a sharp detachment of bituminous layer is clearly observable.

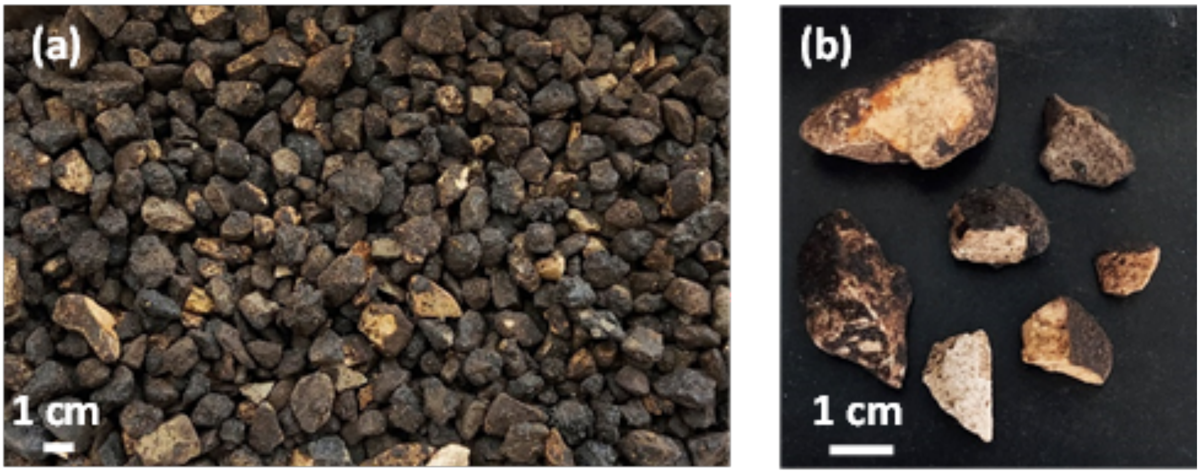

Figure 6: Images of (a) AN RAP and (b) a detail of RAP after freeze-thaw cycles in presence of NaCl solution.

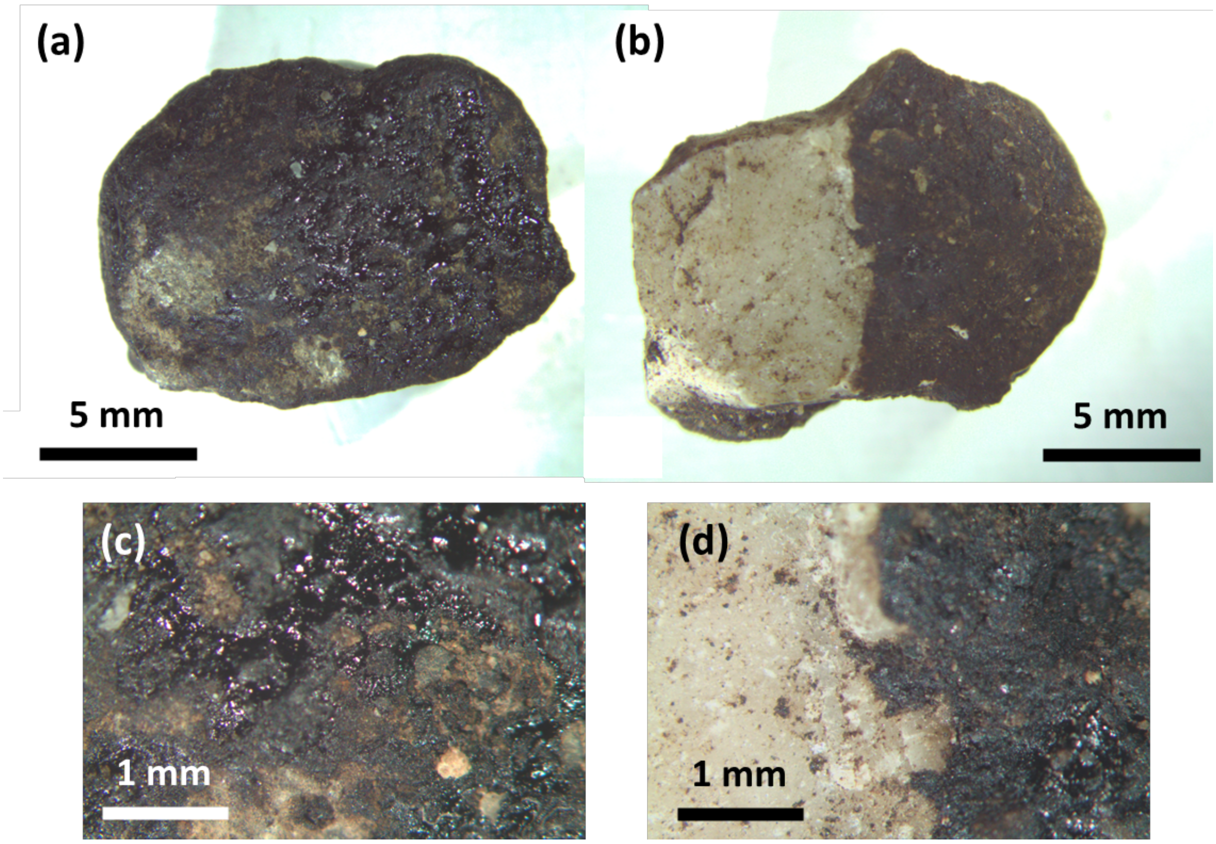

Figure 7: Morphological observations at different magnification by optical microscopy of representative AN RAP after freeze-thaw cycles (a, c) in water and (b, d) in presence of NaCl solution.

In addition, the same RAP subjected to freeze-thaw cycles was then analyzed in terms of water absorption by immersion and under-vacuum test methods. Results reported in Figure 8 are compared with those obtained on RAP before the tests. Standard surface condition during water absorption by immersion was reached after 48 hours for all the RAP subjected to freeze-thaw cycles. In general, for each RAP type there is a progressive increase in water absorption values proportional to the damages induced by freeze-thaw cycles. Indeed, this result is linked to the partial removal of bituminous layer thus promoting higher water absorption. As previously observed, under-vacuum test generally leads to higher values of water absorption compared to immersion test method.

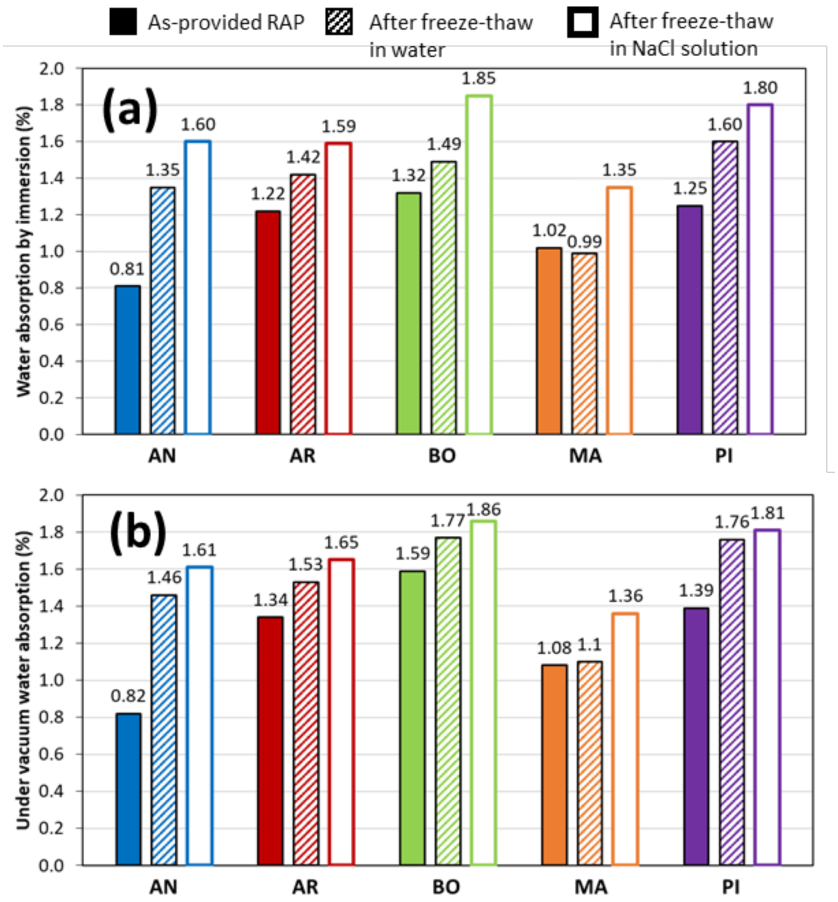

Figure 8: Water absorption values of RAP in as-provided condition, after freeze-thaw cycles in water and in presence of NaCl solution obtained (a) by immersion and (b) in under-vacuum conditions. Each sample is constituted by 20 RAP particles with a diameter of about 10 mm.

4. Conclusions

With the aim to assess the actual possibility of using RAP as recycled aggregate in concrete, a complete characterization of five different types of RAP sourced by Italian collection sites has been carried out. From the results of this study, the following conclusions can be drawn:

- the presence of bituminous layer is responsible of the hydrophobic behavior of RAP. While natural aggregates usually show contact angle values around 40°, values between 130 and 135° have been measured for all the investigated RAP. Moreover, it was determined that RAP has higher open porosity and shows larger pore size compared to natural aggregate. Both hydrophobic behavior and total open porosity shall be carefully assessed when RAP is used in concrete mixes as these parameters can promote workability problems;
- from the microstructural point of view, nevertheless bitumen layer well covers the natural aggregates, a porous interface between the bitumen and aggregate and a dust film on the bituminous surface was observed;
- most of the tested RAP show promising performances in terms of dimensional stability and frost resistance, confirming that RAP is potentially suitable to be used as recycled aggregate in concrete mixes. Even if dimensional stability of RAP is lower than that one determined by natural aggregates, most of the selected RAP exhibit shrinkage values below the requirements of EN 12620 for structural applications. In addition, RAP

generally presents good resistance to freeze-thaw cycles, both after water saturation and in presence of NaCl solution. Lower frost resistance behavior has been observed on the most porous RAP samples (Bologna and Piacenza sites).

Furthermore, the importance of a complete RAP characterization in view of its use in concrete mixes is a mandatory step if durable concrete is requested and the goal to improve the diffusion of circular economy approach in building construction sector is desired. Moreover, conventional test methods shall be validated to understand if they are also applicable when waste-based materials are used. Finally, further studies are running in the framework of RAPCON ("Sustainable concrete made with recycled asphalt pavement") project (2020–2023), funded by Cariplo Foundation under the "Circular Economy for a sustainable future" call (2019). Topics such as concrete mix design optimization for durability, adhesion properties between RAP and cement matrix, Life Cycle Assessment (LCA) of optimized concrete containing RAP, are some of the researches currently under investigations.

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