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Sustainability in Concrete Production: Reclaimed Asphalt Pavement as Recycled Aggregate

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Abstract

In recent years, scientific research on concrete has focused on the development of sustainable mixes containing recycled materials to avoid the exploitation of non-renewable resources and to reduce the amounts of landfilled materials. In this regard, considering that aggregates are the most used material for concrete production, a virtuous solution may involve the use of recycled ones, such as reclaimed asphalt pavement (RAP). Few studies on RAP as concrete recycled aggregates and their use in concrete production have been already published. Aiming to fill this gap, a systematic study on the use of RAP to produce more sustainable concrete is proposed. Firstly, RAP sourced from two Italian collection sites was characterized as concrete aggregate. Then, microstructure of concrete containing RAP was studied by mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM). Finally, the environmental assessment of concrete containing RAP and natural aggregate was carried out using a life cycle assessment (LCA) tool in terms of the global warming potential (GWP) impact category reduction. Results showed that the well adherent bituminous layer on the aggregate surface in RAP induces hydrophobic behavior, not evident in natural concrete aggregates. In hardened concrete containing RAP, an increase in total open porosity and discontinuity in the interface between RAP and cement paste were observed. Finally, the use of RAP as natural aggregate replacement is a promising route in terms of sustainability issues, as demonstrated by LCA analysis.

Keywords

Recycled aggregate, Recycled asphalt pavement, Microstructure, Sustainability, Life cycle assessment, Concrete, Microstructure, Porosity

Introduction

Concrete is one of the most widely used building materials in roads, buildings, bridges, and other infrastructure; its production contributes to about 8% of the global carbon dioxide (CO_2) emissions and to the consumption of a huge quantity of natural resources [1]. The construction industry has long been oriented to the development and the use of sustainable products and materials in order to prevent the exploitation of non-renewable resources, reduce pollution and the amount of material disposed to landfill [2]. Several routes have been pursued in recent years, such as the use of alternative binders (i.e., alkali-activated materials and geopolymers), more sustainable cements with the addition of supplementary cementitious materials (i.e., LC^3 technology) and/or recycled aggregates [3-5]. Related to this latter aspect, the total or partial replacement of natural aggregates with construction and demolition waste (CDW) is a viable solution to achieve more sustainable concrete mixtures, considering that aggregates comprise about 80% of concrete mixes and are the most consumed material after water [1]. In the last decade, the feasibility of using RAP as recycled aggregate for concrete has been assessed [6, 7]. RAP is a CDW generated by milling operations involved in road pavement maintenance [8]. It is a solid waste constituted by natural aggregates covered by a bituminous layer and a dust film due to maintenance operations [9]. In view of its nature, RAP has long been successfully recycled in the paving industry, while in the concrete industry its use is mainly hindered by the lack of codified guidelines [7]. For this purpose, a recent study was aimed at developing a test protocol on RAP as recycled aggregates for concrete [10]. The preliminary characterization of RAP and the formulation of an optimized concrete mix design provides encouraging results [10, 11].

The present study is set in the framework of the research project "Sustainable concrete made with recycled asphalt pavement" (RAP-CON, 2020-2023) granted by Fondazione Cariplo ("Circular Economy for a sustainable future" call, 2019). Preliminarily, physical, and microstructural properties (i.e., geometric density, water absorption, total open porosity, static contact angle, and surface morphology) of two types of RAP from different Italian collection sites were evaluated. These RAP samples were provided by Amplia Infrastructures S.p.A., one of the industrial partners of the RAPCON project, and were selected as were both derived from Italian highway maintenance process. Then, the assessment of the microstructure and the sustainability of the most promising concrete mixes formulated and characterized by Redaelli et al. [12], as part of the same research project, was carried out. Since the environmental impact of concrete containing RAP was recently evaluated in specific pavement applications [8, 11, 13], this analysis was set up and the first results were reported in terms of GWP impact category considering the production of 1 m^3 of concrete.

Materials and Method

Materials

RAP was kindly sourced by Amplia Infrastructures S.p.A. from two different highway collection sites located in Anagni (Frosinone, Italy) and Zola Predosa (Bologna, Italy). These two RAP samples were named AN and BO, respectively. Besides the bituminous layer, both the RAP has a similar composition: 72 - 74% sedimentary rocks (limestone) and 26 - 28% basic igneous rock (basalt), from the petrographic analysis reported in the technical data sheet supplied by Amplia Infrastructures S.p.A. Materials used were of nanoscale.

RAP microstructure and physical properties were assessed. Geometric density and water absorption were evaluated on fine (FRAP, 0.063-4 mm) and coarse (CRAP, > 4 mm) fractions. All the RAP was preliminarily rinsed with water and oven-dried at 85 °C in order to avoid partial melting of the bituminous layer. Measurements on FRAP were carried out on samples of 1 kg of RAP applying the pycnometer method in accordance with EN 1097-6 [15], as depicted in figure 1.

As a significant sample of CRAP, 20 RAP particles with a diameter of about 10 mm were tested. The water absorption test was carried out by immersing the dried 20 particles in water until saturation, in accordance with ASTM C127 [16]. Geometric density was determined by hydrostatic weighing of the samples after water saturation. Contact angle measurement was performed on RAP particles with flat surfaces according to EN 15802 [17]. MIP was used to determine the total open porosity of RAP. The analysis was carried out using Thermo Scientific Pascal 140 and 240 instruments, with the following operative conditions: Hg contact angle θ = 141.3°, Hg surface tension $\gamma = 0.48$ N/m, applied pressure: from 0.1 kPa to 200 MPa. Samples of three RAP particles with a diameter of about 1 mm were used for MIP analysis. RAP morphological observation was performed by SEM (Philips XL 20) using secondary electrons. Samples were observed in cross-section after embedding a RAP particle in epoxy resin and polishing with abrasive paper up to 1000 grit. Before SEM observation, samples were made conductive by coating them with gold using a Quorum Q150R ES+ sputter coater.

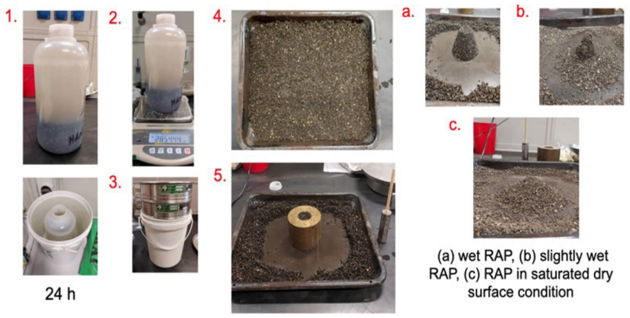

Figure 1: Schematic reporting the different phases (1-5) of testing FRAP with the pycnometer method.

Mix design

Concretes were prepared by Politecnico di Milano (as a partner in the RAPCON project) with commercially available cement CEM II/A-LL 42.5 R and CEM IV/A (P-V) 42.5 N-SR (named *L* and *P*, respectively) in accordance with EN 197-1 [18], a water to cement (W/C) ratio of 0.45 and different percentages of Anagni RAP (from 0 to 100%). Formulations of the tested concrete are shown in table 1. Information about the concrete mix preparation and sample casting are reported elsewhere [12]

Determination of porosity

The MIP instrument (with the same specifications described above) was used to determine the total open porosity and the pore size distribution of concrete samples and morphological observations were performed by SEM on fracture surfaces as indicated for RAP in the previous paragraph. Concrete fragments of about 1 cm^3 from specimens tested at 7 days of curing were used for both analyses.

LCA analysis

LCA analysis was performed according to ISO 14040 standard series [19-23] using SimaPro 9.2 software. To obtain results in terms of CO_2 emissions of L-concrete production with an increasing amount of RAP in the mix, a "cradle-to-gate" approach (i.e., from the extraction and production of materials to the production of concrete in the batching plant) was performed. The functional unit used for this analysis was 1 m^3 of concrete. Input data related to the extraction and production of materials commonly used in concrete

Table 1: Mix designs of the analyzed concretes in terms of their compositions as formulated in Redaelli et al. [12].

Mix designation	Material				
	Cement (kg/m^3)	Water (kg/m^3)	Plasticizer (kg/m^3)	Natural aggregate (kg/m^3)	AN RAP (kg/m^3)
L-N/P-N	357	161	6.5 (L)/9.8 (P)	1980 (100%)	-
L-R20/P-R20	357	161	6.1 (L)/9.2 (P)	1565 (80%)	391 (20%)
L-R40/P-R40	357	161	7.7 (L)/9.5 (P)	1153 (60%)	769 (40%)
L-R60/P-R60	357	161	8.7 (L)/9.9 (P)	756 (40%)	1134 (60%)
L-R80/P-R80	357	161	9.7 (L)/12.30 (P)	371 (20%)	1485 (80%)
L-R/P-R	357	161	10.6 (L)/7.1 (P)	-	1826 (100%)

(i.e., cement, water, natural aggregates, and plasticizers) were obtained from the Ecoinvent 3.8 database available on the SimaPro software. Data on RAP production were provided by Amplia Infrastructures S.p.A. The system boundary related to RAP production starts with the pre-treatment of crushing and sieving at Amplia Infrastructures plant, while maintenance road operations were excluded as part of the previous product system [24, 25]. RAP pre-treatments were performed by a diesel-powered machinery (CAMS CENTAURO 100/32) consuming 0.325 L/t_{RAP} of diesel fuel considering high productivity conditions. Moreover, a credit for the avoided production and transportation of natural aggregates due to RAP addition has been considered [26]. With the aim of providing a case study that can represent a real industrial case, data on materials transportation to the concrete batching plant were elaborated considering suppliers geographically close to Amplia Infrastructures plant in Anagni. A generic freight truck available on the Ecoinvent database was assumed as the means of transportation for each stage. Table 2 shows input data related to materials and transportation phases involved in concrete production. Lastly, a mixing plant working with 2.87 kWh for 1 m^3 of concrete was considered. The analysis was conducted adopting the ReCiPe 2016 method at midpoint level in hierarchist (H) perspective. Results are reported in terms of GWP impact category.

Results and Discussion

RAP characterization

The properties of the investigated RAP are shown in table 3, in terms of geometric density (ρ), water absorption (WA), total open porosity and contact angle values.

Both RAP shows comparable values of geometric density, with a slightly higher value for CRAP compared to FRAP. This could be related to a higher presence of the bituminous layer in the fine fraction related to a higher specific surface area of FRAP [27]. As expected, an opposite trend was observed for water absorption values, especially for the BO sample: the higher specific surface of the fine RAP involves a greater value of water absorption than coarse RAP [7]. However, this trend was not observable for AN RAP. In addition, comparing the obtained results with the ones reported in the published literature, contrasting data can be found [7]. This could be related to the water absorption test method: to reach the full saturation of the RAP particles, 72 hours were necessary due to the difficulty of reaching water penetration. This is probably due to the surrounding bituminous layer, which affects the effectiveness of conventionally adopted methods for natural aggregates. Thus, contact angle measurements were carried out with the aim of better elucidating RAP surface behavior and the results are reported in table 3. Both the samples exhibit a hydrophobic behavior of the surface, as static contact angle values of 130 - 135° were detected for both AN and BO samples. This behavior differs from natural concrete aggregates that exhibit hydrophilic behavior [28], with static contact angle value of 39 - 48° for granitic aggregates [29]. Lastly, total open porosity values (Table 3) of RAP are comparable along the two investigated samples. It can be noted a large variability of results due to the associated high standard deviations, indicating some heterogeneities between the different samples. Due to the slightly denser nature of AN RAP, this sample was selected as aggregate for preparing concrete mixes discussed in the next paragraph. With this purpose AN RAP was further analyzed by SEM observations reported in figure 2. It is revealed the stratigraphy of RAP particle consisting of natural aggregates of different particle sizes embedded in a bituminous layer. This observation highlights the high variability of this material in terms of composition, shape,

Table 3: Physical properties of the investigated RAP.

RAP type	Water absorption (%)		Geometric density (g/cm^3)		Total open porosity (%)	Contact angle (°)
	FRAP	CRAP	FRAP	CRAP		
AN	0.81	0.81	2.24	2.46	5.4 ± 1.7	135
BO	2.01	1.32	2.23	2.37	6.5 ± 1.9	130

Table 2: Materials and transportation phases considered in the LCA analysis.

Material	Material dataset (Ecoinvent 3.8 database)	Origin	Destination	Distance (km)
CEM II/A-LL 42.5 R	Cement, alternative constituents 6 - 20%	Cement supplier	Concrete batching plant	10.2
Water	Tap water	-	Concrete batching plant	-
Plasticizer	Polycarboxylates, 40% active substance	Supplier	Concrete batching plant	20.0
Gravel	Gravel, crushed	Quarry	Concrete batching plant	27.3
Sand	Sand	Quarry	Concrete batching plant	27.3
AN RAP	-	Amplia Infrastructures plant	Concrete batching plant	0.9

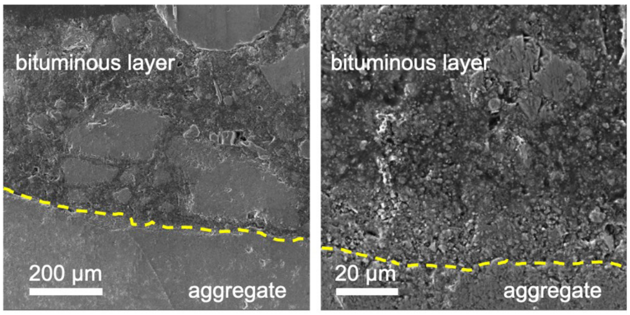

Figure 2: SEM observation of the polished cross-section of AN RAP at different magnifications.

dimension and bitumen content.

Concrete microstructure analysis

MIP results are reported in figure 3. In detail, figure 3a shows an increase in total open porosity when RAP is added as aggregate for both L and P concretes. L concrete porosity linearly increases from L-N (8.6%) to L-R60 (20.6%) and then slightly decreases for L-R80 (16.9%) and L-R (15.5%). P samples containing RAP exhibit rather similar porosity values considering the associated standard deviation, with a slight increase in porosity for P-R concrete (17.4%). The obtained results show some irregularities with the addition of 80% and 100% of RAP and L-R60 and P-R are the most porous samples of their series. The pore size distribution of L and P concretes are reported in figure 3b and figure 3c, respectively. A similar pore distribution is observed with average pore size between 0.01 and 0.1 µm for both L and P concretes. Especially in L concrete, more macropores were detected in the samples containing RAP with a concentration up to 80% than in the reference sample with only natural aggregates. To conclude, it can be stated that independently from the applied cement, RAP replacement induces an increase in porosity, that can mostly double the open porosity values already with 60% RAP replacement.

SEM observations in figure 4 show the interface between cement paste and natural aggregate (Figure 4a) and between cement paste and RAP (Figure 4b). Fragments of L-N concrete (Figure 4a) and L-R20 concrete (Figure 4b) are selected as representative samples. A good adhesion between cement paste and natural aggregate is observed, whereas discontinuities and voids are clearly visible at the interface between cement paste and RAP, regardless of the RAP content and the cement type. The scarce adhesion is mainly related to the hydrophobicity of RAP surfaces previously discussed [31].

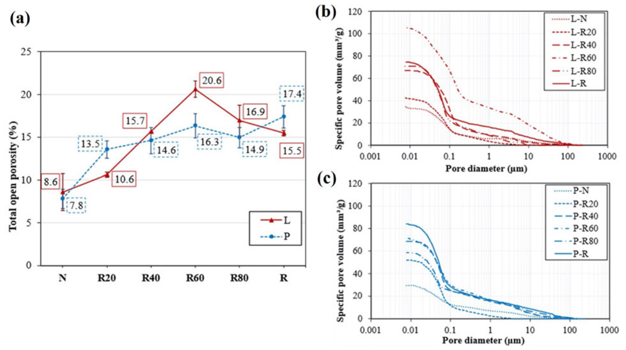

Figure 3: Total open porosity and pore size distribution of concretes by MIP: **(a)** total open porosity of L and P concrete as the amount of RAP increases; **(b)** pore size distribution of L concrete; and **(c)** pore size distribution of P concrete.

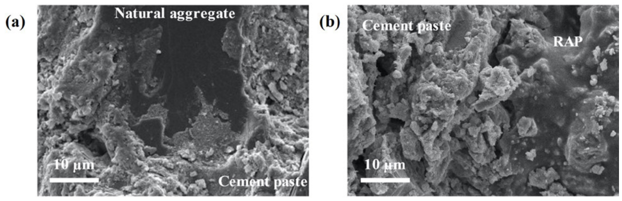

Figure 4: SEM observations: **(a)** interface between cement paste and natural aggregate in L-N concrete and **(b)** interface between cement paste and RAP in L-R20.

LCA analysis

The first results of LCA analysis are summarized in table 4 in terms of reduction in GWP impact category for L concretes. Compared to natural aggregate, GWP contribution of RAP is significantly lower, especially considering the credit for the avoided production and transportation of natural aggregate. Increasing the RAP content in the mix leads to a progressive reduction in the CO_2 emissions of concrete up to a reduction of 12% for 100% RAP replacement. Among all the materials necessary to produce concrete, it was found that the most impactful material in terms of CO_2 emissions is cement, accounting for about 90% of the total impact of each mix. Whether water has an almost negligible impact, plasticizer has a significant influence in the assessment of GWP, even if its amount was very small (0.3 - 0.4 wt.% over concrete). As reported in literature, RAP can affect the workability of fresh concrete [7]. In addition, addiction of plasticizer may be required, and its impact linearly varies according to its dosage in mixture.

Table 4: Percentages of the reduction in GWP related to the RAP replacement. These values were calculated with the respect of concrete with 100% natural aggregate (N).

	L concrete					
	N	R20	R40	R60	R80	R
GWP reduction (%)	0.0	3.4	5.6	8.0	10.3	11.9

Conclusions

In this work, the suitability of RAP as concrete aggregate replacement was evaluated in terms of microstructure and sustainability performances. The conclusions are addressed as follows:

- RAP characterization showed that the bituminous layer induces a rough and porous surface and hydrophobic behavior, which differs from natural aggregates for concrete;
- MIP analysis on concretes highlighted a general increase in total open porosity in samples containing RAP. Pozzolanic cement-based concretes exhibit similar porosity values when the RAP content increases,

suggesting a similar microstructure among samples. Regardless of the cement type, some irregularities encountered for samples with 80% and 100% RAP may discourage the use of high percentages of RAP in concrete mixes. Morphological observations pointed out voids and discontinuity at the interface between cement paste and RAP probably due to RAP hydrophobicity. This result may affect the higher porosity of concrete with RAP and consequently their overall mechanical performances; and

- The first results on LCA analysis proved the sustainability of concrete containing RAP. GWP decreases gradually as the amount of RAP in the mix increases, to a reduction of about 12% for CEM II-based concretes with 100% RAP, respectively.

Finally, in order to perform a complete assessment of this material with the final application in the field of construction materials, long-term durability tests are fundamental and need to be compared with traditional concrete with 100% natural aggregates, in terms of frost resistance and corrosion performances of the steel rebars in reinforced concrete. As a final step, a scale up process in a real production site can assess the potentialities of these materials in an industrial production process.

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Conflict of Interest

None.

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