Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Performance and environmental analysis of Reclaimed Asphalt Pavement (RAP) concrete produced in industrial environment

G. Masi, A. Michelacci, S. Manzi, A. degli Esposti, B. De Pascale, A. Bonoli &
M.C. Bignozzi
Department of Civil, Chemical, Environmental and Materials Engineering, University of Bologna, Bologna, Italy

ABSTRACT: This study aims at evaluating the performances of reclaimed asphalt pavement (RAP) as concrete aggregate replacement in terms of mechanical and physical properties and environmental analysis. RAP concrete production was scaled up and it occurred in an industrial environment (CTI, Imola, Italy) by preparing a 3.5 m^3 concrete casting. A partial aggregate replacement of 40% of RAP was fixed to ensure acceptable workability and mechanical performance. For comparison's sake, the same concrete mix with 100% natural aggregates was also tested. Concrete performances in terms of mechanical and physical properties were checked initially after 7 and 28 days of curing. Environmental analysis of RAP concrete was also carried out using Life Cycle Assessment (LCA) analysis applying a "cradle-to-gate" approach. All the realistic input data collected from the industry plant were considered. Durability tests are ongoing and freezing-thawing resistance and exposure to salt spray chamber on unreinforced and reinforced concrete specimens will be evaluated. As main outcomes, even if inferior mechanical properties were obtained in terms of compressive, tensile strength and elastic modulus values, a relevant reduction (average value of 15%) of environmental impacts was found especially related to global warming potential, terrestrial ecotoxicity, human non-carcinogenic toxicity and fossil resource scarcity. This study is set in the framework of "Sustainable concrete made with recycled asphalt pavement (RAPCON)" project (2020–2023), funded by Cariplo Foundation under the "Circular Economy for a sustainable future" call (2019).

1 INTRODUCTION

In order to improve the environmental sustainability of concrete, several routes have been and are currently investigated. Mainly the use of supplementary cementitious materials (SCMs) or alkali activated binders as cement replacement or the recycling of construction and demolition waste (CDW) as aggregate replacement, as well as the combination of these strategies, have shown promising results (Boobalan *et al.*, 2022). As aggregates usually represent about the 80% of a concrete mix and are the mostly used materials after water, using recycled aggregates from CDW is a promising route to improve concrete sustainability (de Brito and Kurda, 2021). Among the others, reclaimed asphalt pavement (RAP) has been widely studied as potential concrete aggregate from CDW (Debbarma, Selvam and Singh, 2020; Nandi and Ransinchung, 2021). RAP consists of natural aggregates covered by a bituminous layer and dust film, and it is derived from demolition and milling processes during asphalt pavement maintenance (Singh, Ransinchung and Kumar, 2017). A recent study has highlighted the suitability of RAP as recycled concrete aggregate thanks to its good dimensional stability and freezing and thawing resistance (Masi *et al.*, 2022). However, the presence of the bituminous layer can hinder the overall performances of concrete at the fresh and hardened state.

DOI: 10.1201/9781003323020-344

Increasing the RAP content in concrete mix induces a decrease in the mechanical performance due to moderate adhesion between the bituminous layer and the cement binder (Huang, Shu and Li, 2005; Al-Oraimi, Hassan and Hago, 2009; Hossiney, Tia and Bergin, 2010; Brand and Roesler, 2017). Other studies have highlighted the negative effect of RAP in the workability of fresh concrete (Huang, Shu and Burdette, 2006; Al-Oraimi, Hassan and Hago, 2009). Thus, a preliminary characterization protocol of RAP as concrete aggregate is fundamental to ensure the final concrete performance (Masi *et al.*, 2022). On the other hand, the use of RAP as concrete aggregate can improve some mechanical and durability properties, such as toughness and freezing and thawing resistance, respectively, due to different pore size distribution and the presence of the bituminous layer (Huang, Shu and Li, 2005; Huang, Shu and Burdette, 2006; Abraham and Ransinchung, 2019). The limited use of this type of CDW as recycled concrete aggregate is surely related to the lack of specific guidelines and standards and also to limited systematic information related to the environmental sustainability of RAP when used as concrete aggregate replacement (i.e., life cycle assessment (LCA)). Few studies are currently available in literature reporting LCA analyses and are mainly related to specific applications such as concrete slab production (Shi, Mukhopadhyay and Zollinger, 2018), precast concrete blocks (Nandi and Ransinchung, 2021) and cement-based pavement layers (Bressi, Primavera and Santos, 2022).

So, this study investigates the mechanical performances (i.e., compressive, tensile strength and elastic modulus) and their correlation with some physical properties (i.e., geometric density and open porosity) of a concrete mix produced by 40% RAP as replacement for concrete aggregates. A reference concrete mix (with 100% natural aggregates) was also prepared and tested for comparison purpose. All concrete mixes were prepared in a real industrial environment (CTI, Imola, Italy) by formulating 3.5 m^3 for each investigated mix. In addition, the main environmental impacts for both the investigated concrete are studied using LCA analysis, applying a “cradle-to-gate” approach and considering 3.5 m^3 concrete mix as the functional unit. All the input data for the LCA analysis have been kindly provided by CTI industrial plant, so as to build a realistic case study that well simulates the production of RAP-based concrete. This study reports the first results of the task related to the “validation in industrial relevant environment” of the project “Sustainable concrete made with recycled asphalt pavement” (RAP-CON, 2020-2023) granted by Fondazione Cariplo (“Circular Economy for a sustainable future” call, 2019).

2 MATERIALS AND METHODS

2.1 *Materials*

For preparing concrete mixes, CEM III/A 42.5 R was used together with superplasticizer (MasterEase 7007, Master Builder solution) as admixture. Natural siliceous aggregates were used with a maximum dimeter of 16 mm. The applied RAP was kindly provided by CTI with a maximum diameter of 16 mm. Figure 1 reports images of RAP stored in the CTI plant and their particle size distribution.

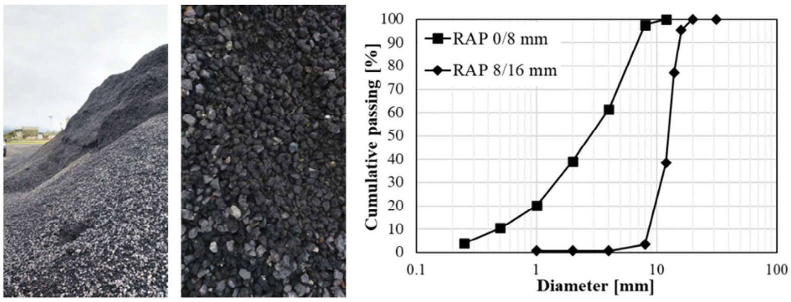

Figure 1. Images of RAP in the industrial plant and particle size distribution of the used RAP.

2.2 *Mix design and sample preparation*

Concrete mixes were prepared in CTI industrial plant located in Imola (Bologna,Italy). Two different concrete mixes were formulated by using 100% natural aggregates (CNAT used as reference mix) and a 40% RAP replacement (CRAP). Both these mixes were prepared in order to produce 3.5 m^3 concrete using the mix design reported in Table 1. The material dosage was designed in order to produce both CRAP and CNAT characterized by C32/40 strength class and a S4 slump class. For both the mixes, the water (considering both the added water and the humidity of the aggregate) to cement ratio (W/C) was kept constant and equal to 0.448. After mixing procedures, slump test was carried out to validate the targeted slump class (S4) and values of 170 and 185 mm were measured for CRAP and CNAT, respectively. Then, fresh concrete was cast in sample holders and compacted by using concrete vibrator. Lastly, curing was performed for 7 and 28 days at 20 °C with a relative humidity of 95%. For this study, the following samples were used for each mix and curing time: 10 cubic samples (with the edge of 150 mm) for compressive strength and geometric density measurements, 3 cylindric sample (with 150 mm diameter and 300 mm height) for tensile strength and other 3 cylindric samples (with the same dimensions) for elastic modulus determination.

Table 1. Mix design for producing 1 m^3 of concrete.

	Material dosages (kg/m^3)					
	Cement	Water	Additives	Gravel	Sand	RAP
CNAT	375	127	3.86	971	840	-
CRAP	380	137	3.58	461	628	696

2.3 *Characterization*

Geometric density was calculated by dividing the dry mass of cubic sample by its geometric volume. The reported results are an average of at least 3 repeated measurements.

Mechanical performances of CRAP and CNAT samples were evaluated in terms of compressive, tensile splitting strength and elastic modulus measurements. Compressive strength was determined in accordance with the EN 12390-3 standard (*EN 12390-3 Testing hardened concrete: compressive strength of test specimens*, 2019) as the ratio of the maximum load at failure and cross-sectional area of the cubic specimen. The reported results are the average of 10 measurements on cubic samples (L=150 mm). Tensile splitting strength was performed on 2 cylindrical samples (D=100 mm and H=200 mm) according EN 12390-6 standard (*EN 12390-6 Testing hardened concrete: tensile splitting strength of test specimens*, 2009). Elastic modulus was measured in accordance with EN 12390-13 (*EN 12390-13 Testing hardened concrete: determination of secant modulus of elasticity in compression*, 2013) on 3 cylindrical samples (D=150 mm and H=300 mm).

Lastly, to determine the open porosity and the average pore diameters of the two concrete mixes at the different curing time, mercury intrusion porosimetry (MIP) using Pascal 140 and 240 instruments (Thermo Fisher Scientific). MIP analyses were performed onto concrete samples of about 1 cm^3 (avoiding external surfaces) in triplicate.

2.4 *Life Cycle Assessment (LCA)*

LCA analysis was carried out using Simapro 9.2 software in accordance with ISO 14040 standard series (*ISO 14040 Environmental management - life cycle assessment - principles and framework, 2006th ed.*, 2020). The objective of the analysis is the evaluation of the environmental impact of a cement mix produced in an industrial scenario applying 40% RAP as replacement for natural aggregate, compared with a control mix made with 100% natural aggregate. The system boundary is set on a "cradle-to-gate" approach (i.e., from materials extraction/production to concrete production at the batching plant). In details, the RAP production phases take into account the impacts related to the treatments (crushing and screening) at the CTI plant, while milling and transportation to the CTI plant of asphalt waste are not considered in the analysis because they are part of the previous product system (Santos, Flintsch and Ferreira, 2017; Vandewalle *et al.*, 2020). The functional unit (FU) used in the present study is 3.5 m^3 of concrete. Data on the impacts generated by extraction/production of materials commonly used in concrete (i.e., cement, water, natural aggregates, and plasticizers) were obtained from the Ecoinvent 3.8 database available on the SimaPro software. The transportation conditions considered for each material are based on CTI suppliers. Materials were modeled starting from the inventory data and some specific data were implemented using information from CTI, as reported in Table 2.

Table 2. Materials used in investigated concrete mixes and their transportation distances considered in the analysis.

Material	Material dataset	Origin	Destination	Transportation dataset	Distance (km)
CEM III/A 42.5 R	Cement, blast furnace slag 36-65%	Cement supplier	CTI Batching plant	Transport, freight, lorry	60
Water	Tap water	-	CTI Batching plant	-	-
Plasticizer	Polycarboxylates, 40% active substance	Supplier	CTI Batching plant	Transport, freight, lorry	214
Gravel	Gravel, crushed	Quarry	CTI Batching plant	Transport, freight, lorry	18
Sand	Sand	Quarry	CTI Batching plant	Transport, freight, lorry	18

Since CTI also operates in the field of pavements, the company directly recovers waste generated from the milling of pavements following maintenance work. Waste is crushed and screened with a diesel-powered machinery (CAMS CENTAURO 100/32) consuming 0.325 L/t_{RAP} of diesel under conditions of high productivity. The processed waste is known as RAP, ready to be used as recycled aggregate. Both RAP processing and concrete production take place in the CTI plant. To enhance the use of RAP as natural aggregate replacement for concrete production, a credit for the designed system has been considered (Pantini, Borghi and Rigamonti, 2018) as shown in Table 3. More specifically, the use of 40% of RAP in concrete mixture avoids not only the use, but also the production of 2356 kg of natural aggregate (1614 kg of gravel and 742 kg of sand) for 3.5 m^3 of concrete and its transportation from the quarry to the CTI plant.

A mixing plant working with about 10 kWh for 3.5 m^3 of concrete was considered as the last step in concrete production. The method used for the analysis is ReCiPe 2016 at the midpoint level in hierarchist (H) perspective, which addresses 18 impact categories.

3 RESULTS AND DISCUSSION

3.1 *Concrete properties*

First results of mechanical performance and physical properties of CRAP and CNAT after 7 and 28 days of curing are reported in Table 3.

In general, CRAP exhibits inferior mechanical properties in terms of compressive, tensile strength and elastic modulus compared to CNAT. This is related to the porosity of the samples, as shown by the reduction in geometric density related to the use of RAP as aggregate replacement. On the other hand, considering the different curing time, while CNAT reaches compressive strength slightly higher than 40 MPa (the strength target of the mix design)

Table 3. Mechanical and physical properties of concrete made with natural and RAP aggregates after 7 and 28 days of curing.

Sample	Geometric density (ρ, g/cm^3)	Compressive strength (R_c, MPa)	Elastic modulus (E_d, GPa)	Tensile strength (f_t, MPa)	Open porosity (%)	Median pore diameter (μm)
CNAT-7	2.21±0.04	41±2	29.2±0.5	3.2±0.2	10.9±0.5	0.025±0.001
CRAP-7	2.03±0.01	25±2	21.6±0.1	2.6±0.3	19±4	0.17±0.06
CNAT-28	2.20±0.03	52±3	43±3	2.9±0.4	9.8±0.2	0.021±0.001
CRAP-28	2.02±0.01	34±1	26±5	2.3±0.2	18±2	0.09±0.06

already after 7 days of curing, CRAP shows slightly lower values than expected even after 28 days. This result is also partly related to a small addition of water (about 30 L for the whole 3.5 m^3 mix) during the concrete preparation for workability reasons even if the overall W/B ratio (considering both the added water and aggregate humidity) does not change. More in detail, while tensile strength values can be considered constant for both the concrete mixes and considered curing time, compressive strength and elastic modulus values exhibit a significant increase for both CRAP and CNAT passing from 7 to 28 days of curing: CRAP exhibits a compressive strength of 25 MPa after 7 days and 34 MPa after 28 days, representing an increase of 36%, and an elastic modulus of 22 GPa and 26 GPa after 7 and 28 days, respectively, representing a 20% increase. CNAT shows compressive strength values of 41 and 52 MPa for 7 and 28 days, respectively (a correspondent increase of 27%) and elastic modulus values of 29 GPa after 7 days and 43 GPa after 28 days, representing a 47% increase. These inferior mechanical performances measured for this mix where 40% RAP has been used are quite expected results based on the literature analysis (Huang, Shu and Li, 2005; Al-Oraimi, Hassan and Hago, 2009; Hossiney, Tia and Bergin, 2010).

More interestingly, Table 3 also reports the outcomes of the MIP measurements in terms of open porosity and median pore diameters. For both 7 and 28 days of curing, open porosity measured for CRAP is higher than the ones measured for CNAT. These results well highlight that CRAP is more porous and characterized by larger pores. This difference in pore size distribution is an important key in terms of durability. In fact, pore size distribution towards larger pores induces a decrease in the crystallization pressure of water or salts when samples are exposed to freezing and thawing or salt crystallization cycles (Scherer, 1999). Therefore, these results are quite encouraging regarding durability tests in terms of frost resistance that are currently ongoing, indicating that probably CRAP will show good durability performance in this regard (Thomas, Fellows and Sorensen, 2018). However, due to the fact that RAP is partially replaced as concrete aggregate and is distributed more or less evenly throughout the concrete, a dedicated investigation is currently ongoing to validate the durability performance in terms of frost resistance.

3.2 *LCA analysis*

The environmental impacts related to both the analyzed mixes are reported in Table 4.

Four categories show significant impact values: global warming potential (GWP), terrestrial ecotoxicity (TE), human non-carcinogenic toxicity (HNCT) and fossil resource scarcity (FRS). CRAP exhibits variations equal to -5% in GWP, -18% in TE, -15% in HNCT and -12% in FRS compared to CNAT. Generally, the production of 3.5 m^3 of CRAP shows lower values than CNAT for each of the considered impact categories, with an average reduction of about 15%. Thus, the 40% of RAP in the concrete mix brings significant benefits, as remarked in Figure 2.

The impact related to each input data was evaluated for both CNAT and CRAP for the 4 categories in which concrete is most impactful (Figure 3): raw material production, power consumption (electricity) for concrete mixing, all the considered transportation phases and the credits related to avoided use of natural aggregates.

Table 4. Results of LCA analysis in terms of the 18 impact categories addressed by the Recipe midpoint (H) method for 3.5 m^3 of concrete made with natural aggregate (CNAT) and concrete containing 40% of RAP in mixture (CRAP).

Impact category	Unit	CNAT	CRAP
Global warming potential (GWP)	kg CO_2 eq	7.71×10^{2}	7.33×10^{2}
Stratospheric ozone depletion (SOD)	kg CFC11 eq	1.30×10^{-4}	1.09×10^{-4}
Ionizing radiation (IR)	kBq Co-60 eq	4.23×10^{1}	3.67×10^{1}
Ozone formation - Human health (OF1)	kg NO_x eq	$1.49\times10^{\circ}$	$1.30\times10^{\circ}$
Fine particulate matter formation (FPMF)	kg PM2.5 eq	6.40×10^{-1}	5.60×10^{-1}
Ozone formation - Terrestrial ecosystems (OZ2)	kg NO_x eq	$1.51\times10^{\circ}$	$1.32\times10^{\circ}$
Terrestrial acidification (TA)	kg SO_2 eq	$1.67\times10^{\circ}$	$1.51\times10^{\circ}$
Freshwater eutrophication (FE)	kg P eq	1.50×10^{-1}	1.30×10^{-1}
Marine eutrophication (MEu)	kg N eq	1.00×10^{-2}	1.00×10^{-2}
Terrestrial ecotoxicity (TE)	kg 1.4-DCB	1.77×10^{3}	1.45×10^{3}
Freshwater ecotoxicity (FE)	kg 1.4-DCB	1.24×10^{1}	1.06×10^{1}
Marine ecotoxicity (MEc)	kg 1.4-DCB	1.70×10^{1}	1.45×10^{1}
Human carcinogenic toxicity (HCT)	kg 1.4-DCB	2.05×10^{1}	1.50×10^{1}
Human non-carcinogenic toxicity (HNCT)	kg 1.4-DCB	3.10×10^{2}	2.65×10^{2}
Land use (LU)	m^2a crop eq	1.24×10^{1}	$9.90\times10^{\circ}$
Mineral resource scarcity (MRS)	kg Cu eq	$3.93\times10^{\circ}$	$3.72\times10^{\circ}$
Fossil resource scarcity (FRS)	kg oil eq	1.04×10^{2}	9.12×10^{1}
Water consumption (WC)	m^3	$8.65\times10^{\circ}$	$5.24\times10^{\circ}$

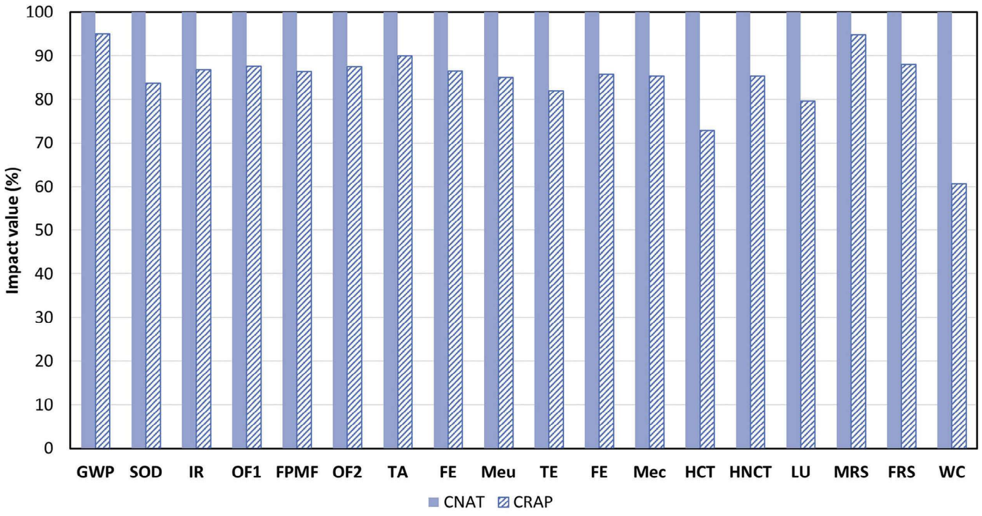

Figure 2. Impact categories addressed by the Recipe midpoint (H) method for 3.5 m^3 of concrete made with natural aggregate (CNAT) and concrete containing 40% of RAP in mixture (CRAP). Results are shown according to internal normalization.

Firstly, cement production is the most critical stage for most of the total impact of each category: it is responsible of about the 90% of CO_2 emissions for both concrete mixes, where a 5% reduction of GWP category was measured in CRAP due to RAP incorporation. Transportation is the most relevant stage after cement production. Thus, a unique RAP processing and concrete batching plant is a favorable condition (as in the considered industrial plant). In addition, the advantage associated with the reduction of natural aggregate in mixture is greatly appreciated in TE category. In HNCT and FRS categories, natural aggregate production follows cement in impact. Water and RAP production exhibit almost no impact, but they were still reported for completeness. Lastly, the registered impact reduction for CRAP is mainly due to the avoided use of natural aggregates (Pantini, Borghi and Rigamonti, 2018).

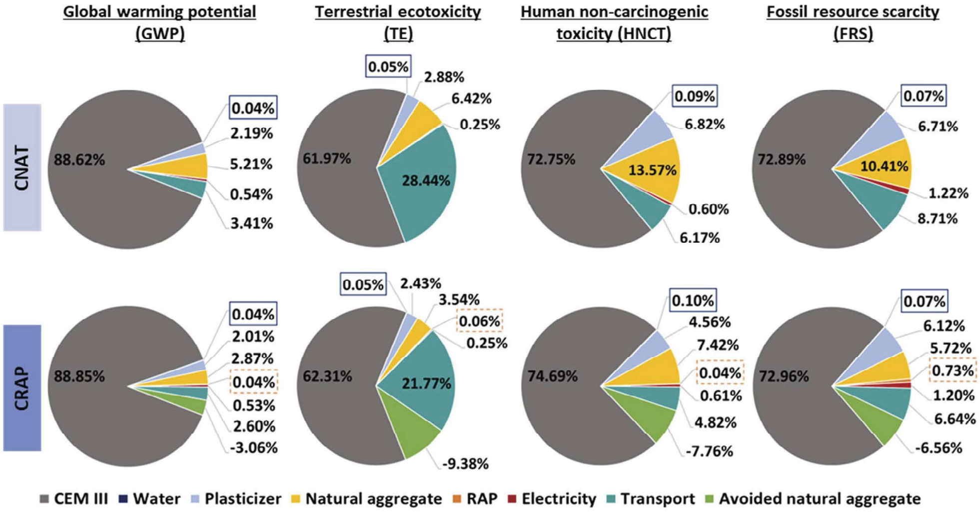

Figure 3. Impact assessment for each input data: CEM III (blast furnace slag cement), water (framed with a continuous blue line), plasticizer, natural aggregate (sand and gravel), RAP (framed with an orange dotted line), electricity for concrete mixture, transport (as the total transport of all materials involved in concrete production) and the avoided natural aggregate (due to the use of RAP as recycled aggregate).

4 CONCLUSIONS

This study reports preliminary results in terms of mechanical and physical properties, as well as the environmental assessment by life cycle analysis (LCA) of concrete mixes prepared in a real industrial environment by partially replacing natural aggregates with Reclaimed Asphalt Pavement (RAP). In this study, a 3.5 m^3 concrete mix with a replacement of 40% RAP has been evaluated. The main results can be drawn as follows:

- concrete with 40% RAP exhibits inferior mechanical properties in terms of compressive, tensile strength and elastic modulus for both 7 and 28 days compared to concrete with 100% natural aggregate (reference mix). These findings are mainly related to higher porosity of the mix with RAP incorporation as highlighted by the lower geometric density and MIP analysis results. In addition, incorporation of RAP as concrete aggregates also induces higher average pore diameters of one order of magnitude for both considered curing times.
- The incorporation of RAP (40%) induces a beneficial effect in terms of environmental impacts, as highlighted by LCA analysis. Especially for the most significant impact categories for concrete production, such as global warming potential, terrestrial ecotoxicity, human non-carcinogenic toxicity and fossil resource scarcity, a relevant reduction has been measured of an average value of 15%. Surely, increasing the RAP replacement a more significant reduction in the environmental impacts can be measured. However, higher RAP amount can strongly hinder the mechanical performances of resulting concrete. Thus, a complete characterization in terms of materials and environmental performance is a fundamental approach for sustainable building materials designing.

ACKNOWLEDGEMENTS

This study was carried out in the framework of RAPCON ("Sustainable concrete made with recycled asphalt pavement") project (2020–2023), under the "Circular Economy for a sustainable future" call (2019) funded by Cariplo Foundation. The authors would like to acknowledge Eng. Luca Guardigli (CTI, Imola) and Mr. Paolo Carta (University of Bologna) for their precious help in preparing and testing concrete samples.

REFERENCES

Abraham, S. M. and Ransinchung, G. D. R. N. (2019) 'Pore Structure Characteristics of RAP-Inclusive Cement Mortar and Cement Concrete Using Mercury Intrusion Porosimetry Technique', *Advances in Civil Engineering Materials*, 8(3), p. 20180161. doi: 10.1520/acem20180161.

Al-Oraimi, S., Hassan, H. F. and Hago, A. (2009) 'Recycling of reclaimed asphalt pavement in Portland cement concrete', *Journal of Engineering Research*, 6(1), pp. 37–45. doi: 10.24200/tjer.vol6iss1pp37-45.

Boobalan, S. C. *et al.* (2022) 'Studies on green concrete – A review', *Materials Today: Proceedings*. Elsevier Ltd, 65, pp. 1404–1409. doi: 10.1016/j.matpr.2022.04.392.

Brand, A. S. and Roesler, J. R. (2017) 'Bonding in cementitious materials with asphalt-coated particles: Part I – The interfacial transition zone', *Construction and Building Materials*. Elsevier Ltd, 130, pp. 171–181. doi: 10.1016/j.conbuildmat.2016.10.019.

Bressi, S., Primavera, M. and Santos, J. (2022) 'A comparative life cycle assessment study with uncertainty analysis of cement treated base (CTB) pavement layers containing recycled asphalt pavement (RAP) materials', *Resources, Conservation and Recycling*, 180. doi: 10.1016/j.resconrec.2022.106160.

de Brito, J. and Kurda, R. (2021) 'The past and future of sustainable concrete: A critical review and new strategies on cement-based materials', *Journal of Cleaner Production*. Elsevier, 281, p. 123558. doi: 10.1016/j.jclepro.2020.123558.

Debbarma, S., Selvam, M. and Singh, S. (2020) 'Can flexible pavements' waste (RAP) be utilized in cement concrete pavements? – A critical review', *Construction and Building Materials*. Elsevier Ltd, 259, p. 120417. doi: 10.1016/j.conbuildmat.2020.120417.

EN 12390-13 Testing hardened concrete: determination of secant modulus of elasticity in compression (2013).

EN 12390-3 Testing hardened concrete: compressive strength of test specimens (2019).

EN 12390-6 Testing hardened concrete: tensile splitting strength of test specimens (2009).

Hossiney, N., Tia, M. and Bergin, M. J. (2010) 'Concrete containing RAP for use in concrete pavement Mitigation of Cracking in Concrete View project Concrete Containing RAP for Use in Concrete Pavement', *International Journal of Pavement Research and Technology*, 3(5),pp. 251–258. Available at: https://www.researchgate.net/publication/290031177.

Huang, B., Shu, X. and Burdette, E. G. (2006) 'Mechanical properties of concrete containing recycled asphalt pavements', *Magazine of Concrete Research*, 58(5), pp. 313–320. doi: 10.1680/macr.2006.58.5.313.

Huang, B., Shu, X. and Li, G. (2005) 'Laboratory investigation of portland cement concrete containing recycled asphalt pavements', *Cement and Concrete Research*, 35(10), pp. 2008–2013. doi: 10.1016/j.cemconres.2005.05.002.

ISO 14040 Environmental management - life cycle assessment - principles and framework, 2006th ed. (2020).

Masi, G. *et al.* (2022) 'Assessment of reclaimed asphalt pavement (RAP) as recycled aggregate for concrete', *Construction and Building Materials*. Elsevier Ltd, 341(February), p. 127745. doi: 10.1016/j.conbuildmat.2022.127745.

Nandi, S. and Ransinchung, G. D. R. N. (2021) 'Performance evaluation and sustainability assessment of precast concrete paver blocks containing coarse and fine RAP fractions: A comprehensive comparative study', *Construction and Building Materials*. Elsevier Ltd, 300, p. 124042. doi: 10.1016/j.conbuildmat.2021.124042.

Pantini, S., Borghi, G. and Rigamonti, L. (2018) 'Towards resource-efficient management of asphalt waste in Lombardy region (Italy): Identification of effective strategies based on the LCA methodology', *Waste Management*. Elsevier Ltd, 80, pp. 423–434. doi: 10.1016/j.wasman.2018.09.035.

Santos, J., Flintsch, G. and Ferreira, A. (2017) 'Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability', *Resources, Conservation and Recycling*. Elsevier B.V., 116, pp. 15–31. doi: 10.1016/j.resconrec.2016.08.025.

Scherer, G. W. (1999) 'Crystallization in pores', *Cement and Concrete Research*, 29(8), pp. 1347–1358. doi:10.1016/S0008-8846(99)00002-2.

Shi, X., Mukhopadhyay, A. and Zollinger, D. (2018) 'Sustainability assessment for portland cement concrete pavement containing reclaimed asphalt pavement aggregates', *Journal of Cleaner Production*. Elsevier Ltd, 192, pp. 569–581. doi: 10.1016/j.jclepro.2018.05.004.

Singh, S., Ransinchung, G. D. and Kumar, P. (2017) 'An economical processing technique to improve RAP inclusive concrete properties', *Construction and Building Materials*. Elsevier Ltd, 148, pp. 734–747. doi: 10.1016/j.conbuildmat.2017.05.030.

Thomas, R. J., Fellows, A. J. and Sorensen, A. D. (2018) 'Durability analysis of recycled asphalt pavement as partial coarse aggregate replacement in a high-strength concrete mixture', *Journal of Materials in Civil Engineering*, 30(5), pp. 1–7. doi: 10.1061/(ASCE)MT.1943-5533.0002262.

Vandewalle, D. *et al.* (2020) 'Assessment of eco-friendly pavement construction and maintenance using multi-recycled rap mixtures', *Recycling*, 5(3), pp. 1–21. doi: 10.3390/recycling5030017.