Materials Reports: Solidwaste and Ecomaterials
Journal Homepage: www.sciopen.com/journal/3078-4093

Original Research Report

Waterproofing concrete with reclaimed asphalt pavement

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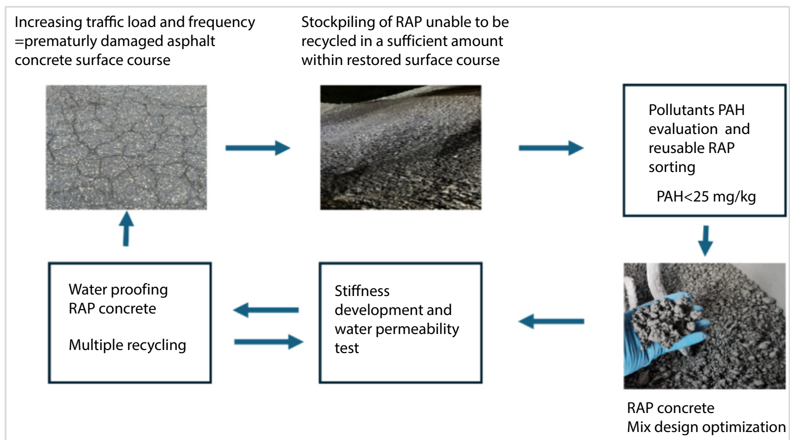
Abstract: The amount of reclaimed asphalt pavement (RAP) after roadway milling procedures is high, and it cannot be completely recycled within asphalt. Therefore, to save landfill space, the recycling of uncontaminated RAP aggregates within concrete was deeply studied. The combination of two blended cements and the addition of 30% RAP to replace natural aggregates allowed an appropriate control of the early strength and stiffness development of the RAP concrete. The strength values remained in the range of 36–43 MPa up to 60 d, and the modulus of elasticity was between 27500 MPa and 28500 MPa. The control of these two parameters within the early hydration stage and the RAP addition was essential to avoid the formation of microcracks and to obtain waterproof concrete. The fine RAP component allowed adequate densification and the production of watertight recycled concrete. The leaching tests indicated a very low environmental risk with respect to the pollutant release.



Keywords: asphalt, waste, concrete, water, impermeability

Citation: A. Krattiger, A. Terminio, C. Paglia. Waterproofing concrete with reclaimed asphalt pavement. *Materials Reports: Solidwaste and Ecomaterials*, 2025, 1: 9520006. https://doi.org/10.26599/MRSE.2025.9520006.

1. Introduction

The sustainability of the construction industry has been a growing requirement in recent decades. This is mainly due to the increase in the global temperature and the CO_2 emissions. The depletion of natural resources and the increasing demand for construction materials caused by the rapid urbanization in the last 20 years[1] force industries to find alternatives and close recycled loops of the materials. Construction and demolition waste (CDW) is a major resource to be exploited. Concrete and masonry represent the major types of waste[2]. In China, bricks, blocks, concrete, mortar, and masonry account for 90% of the total construction and demolition waste[3]. The European Commission targets a recovery rate of 70% for the CDW[4]. Therefore, a great effort needs to be made in the reuse and recycling of construction materials.

Most pavements with high-speed traffic worldwide are composed of asphalt, and the United States[5] as well as the eastern countries, such as India, are rarely an exception to this asphalt-based pavement system[6]. They are flexible and guarantee appreciable riding comfort and safety. The macro texture of asphalt is not very different from that of concrete. Stone aggregates are surrounded by a binder. In the asphalt

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Received 3 August 2024; Received in revised form 10 October 2024; Accepted 18 October 2024

pavement, the bituminous binder is present in a percentage of 5%–6% by weight (Fig. 1a), while in the concrete, the cementitious binder accounts for a percentage varying from 10% to 15% by weight. On the other hand, the maximum aggregate size of asphalt may reach 22 mm, and the aggregates may be harder, while in concrete, the maximum size may reach 32 mm. The granulometric curves are also slightly different between the two materials, depending on the asphalt layer considered. More chipped-angular aggregate shapes are preferred to achieve the load-bearing capacity of the asphalt layers, while a more rounded shape is used for concrete to increase the workability[7].

The rapid degradation of asphalt pavement[8], especially of the surface course, and the milling procedure cause a high amount of reclaimed asphalt pavement (RAP) materials. The RAP is obtained by milling procedures that may include the surface layer of a pavement structure or a full-depth reclamation that can involve a full depth down to 30 cm and below. Different granulometries, shapes, agglomerations, and dimensions can be obtained depending on the material type and milling procedure. The coarser component (>8 mm) generally exhibits a high angularity and less bituminous materials (Fig. 1a). The finer component (<8 mm) shows more bituminous materials (Fig. 1b). The RAP aggregates indicate a lower specific gravity[9] (1.9–2.3 g cm^{-3}) compared to the common natural aggregates(2.6–2.8 g cm^{-3})[10]. The RAP humidity content may vary from 5% to 8% depending on the stone materials and the storage situation[11]. The chemical composition of RAP is similar to that of natural aggregates with respect to the SiO_2, Fe_2O_3, and CaO[12], being composed of more than 94% of natural aggregates.

The RAP waste is usually recycled within bituminous pavements along the surface courses, bases or subbases[13]. The RAP percentage allowed depends on the country and type of asphalt layer, with an increase in the allowable addition up to 100% for the base courses. With time, the durability of the surface layers is more critical due to the hardened bituminous material aged in contact with oxygen and humidity[14]. Generally, cracking is the most frequent form of damage in asphalt pavements and it mainly occurs in the winter. On the contrary, the higher temperature form of damage, namely rutting, is a permanent deformation that mainly takes place in the summer[15].

The recycling of RAP within cementitious mixtures, such as in mortar[16] or concrete[17], is also possible. The RAP fractions are used in concrete. A few concrete mixtures are produced with the combination of more fractions[18]. The fresh-state characteristics of the mixture highly depend on the RAP shape and dosage. Low dosages increase the slump. The full replacement of natural aggregates with fine RAP decreases the slump, while the slump is lowered with coarse RAP aggregates [17]. The investigations are mainly focused on concrete pavements containing RAP[19]. The presence of a bituminous binder around RAP aggregates needs to be carefully kept under control at high service temperatures due to possible creep phenomena. On the other hand, the combination of asphalt and cementitious materials is a practice that takes place in the pavement sector to increase the stiffness of the surface layers. The fine-grained mortar percolated within the voids of the porous surface asphalt layers may exhibit a compressive strength of the system up to 9 MPa, although a slight decrease in the resistance to the freezing action may occur. The thermal excursions artificially caused by thunder/shower tests and the exposure of the specimens for 7 h at 60 °C and subsequently for 30 min to rain for 20 cycles promote an exudation of the bituminous binder, especially along the cementitious-bituminous interface. The adhesion along this interface seems questionable with a temperature increase. The relatively sharp chemical distinction between bituminous and cementitious materials may affect the bond in the medium term, especially during the cyclic changes of the environmental conditions[20]. Furthermore, the application technique and the lack of void filling may cause rutting and premature cracking in heavily loaded static areas, such as truck parking lots[21].

On the other hand, the concrete with up to 50% replacement levels of natural aggregates by RAP may maintain similar properties to the reference concrete[22], although the general lowering of the compressive strength—due to the weak adhesion of the bituminous film with the cementitious

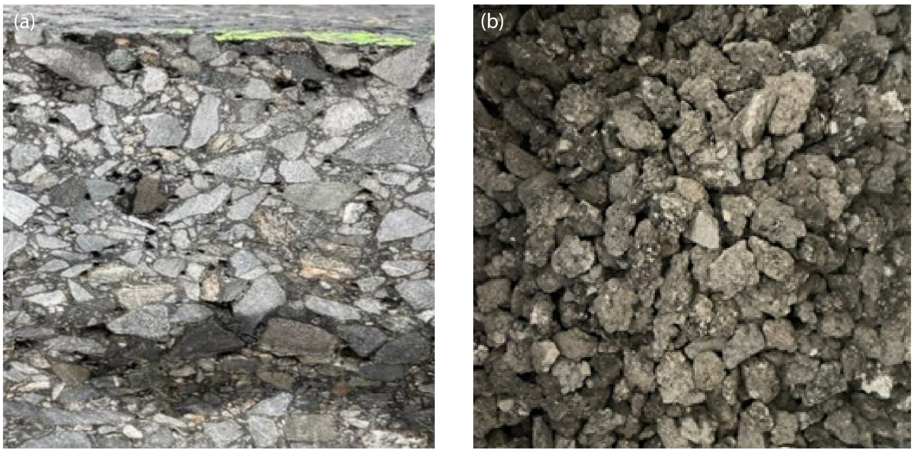

Fig. 1. (a) Asphalt macro texture of a highway lane surface course more than 20 years old with a maximum aggregate size of 22 mm. (b) Reclaimed asphalt pavement aggregates after the milling procedure of a highway surface course with a maximum aggregate size of 22 mm.

matrix—may be mitigated by removing the dust particles from RAP after the milling procedure[23]. The addition of coarse[22] or fine[24] RAP aggregates affects the mixture properties. Compressive strength, tensile strength and flexural strength may exhibit some reduction, with these latter properties being less influenced by the RAP addition. Nevertheless, a sufficient content of intermediate particles (2–10 mm) promotes the formation of a dense RAP concrete matrix with a positive influence on the mechanical properties. A reduction of the modulus of elasticity may also be seen[25]. Moreover, the addition of RAP aggregates, which exhibit a thin bituminous film around the aggregates, increases the toughness of the concrete[26].

The substitution of natural aggregates with RAP in concrete or roller-compacted concrete[27] is mainly investigated for pavement applications, probably because RAP derives from asphalt pavements. Nonetheless, the use of RAP in concrete provides interesting results with respect to the mechanical properties. These positive characteristics may be further investigated for applications in the building sector, although durability features are not yet well clarified. In this context, the long-term behavior of RAP concrete is necessary and provides useful information for infrastructure and buildings. The replacement of 30% natural aggregates with RAP in conventional concrete exhibits a positive influence on the mechanical and durability properties. The low presence of RAP particle agglomeration improves the water and the chloride permeability resistance[28]. Mortar mixes exhibit an initial decrease in the water capillary adsorption as the RAP percentage increases, despite the apparent higher porosity of RAP-containing mixes as compared to the reference. This is caused by the partial melting and pore filling of the bituminous materials during the preparation of the specimens for sorptivity tests[29]. Recently, the preparation temperature of specimens was lowered to below 48 °C, since bituminous exudation takes place at 60 °C. The permeability of concrete containing fine and coarse aggregates appears higher than that of concrete with the fine or coarse components added individually. Agglomeration of the fine components may also change the permeability properties. The porosity increase in RAP concrete may reach 14% and is caused by the weak and porous interfacial transition zone of the bituminous-rich aggregates and the cementitious material, although the chloride penetration seems to be reduced as compared to the reference concrete[30]. Conversely, the addition of 25%–50% RAP to high-strength concrete does not significantly affect the chloride penetration[31]. Fly ash may be added to fill the voids and obtain a denser matrix[32]. A reduction in the porosity would linearly lower the water adsorption for RAP concrete[33]. This fact significantly affects the durability properties. The high porosity resulting from the addition of RAP may positively affect the resistance to freeze and thaw, but adversely influence the carbonation resistance. Nevertheless, all these durability parameters, as for the mechanical properties, also depend on the mix design optimization, and further studies are required[34]. The freeze/thaw resistance in high-strength concrete may not be positively affected by the presence of RAP, because the pore spacing is too large for getting sufficient connectivity to accommodate the expansion of water to ice[31]. On the contrary, an excellent freeze/thaw resistance exists for conventional concrete with RAP addition up to 20%[35]. The alkali-silica reaction may also be a partial issue in RAP concrete, although accelerated tests requiring an increase in the temperature to about 50 °C [36] are not reliable, because of the softening of the bituminous compounds in concrete. Therefore, RAP concrete is still highly under investigation, and its application as structural concrete may actually exhibit some limitations[37]. The standards in the different European countries may slightly differ in the allowable percentage of RAP substitution of natural aggregate in concrete up to 30% depending on the exposure class in Germany[38], up to 20% for reinforced concrete in the UK, while a more stringent regulation is applied in Italy, which largely limits the use of RAP in concrete applications[39]. In Switzerland, the RAP content in concrete is largely limited[40] and recycled concrete with a bituminous content lower than 1% is required. On the other hand, the environmental regulation[41] does not mention the RAP as a possible reusable material in concrete but treats it as a waste unbound material with severe pollutant limits. Therefore, as in other countries, the legal situation appears rather unclear and should be clarified according to the technical and scientific evolution.

In this context, the use of RAP concrete as a structural component or for producing concrete with improved properties, especially water tightness, is poorly investigated. Waterproof concrete is particularly important in buildings, where the buried foundations are often or even constantly in contact with groundwater. Therefore, this work aims to analyze the replacement of natural aggregates with RAP in concrete and to study its performance, particularly the waterproof properties and leaching behavior.

2. Experimental procedure

The watertightness of concrete foundation wall elements of buildings is mainly achieved by using concrete wrapped with a bituminous coating on its surface. This procedure is applied to the constantly buried parts of the structures, which are often in contact with the groundwater. More recently, concrete technology development allows concrete to be cast with high watertightness performance. The use of supplementary cementitious materials, such as silica fume or fly ash, promotes the formation of a dense structure with a further increase in the waterproof property. The increased demand and pressure on the construction sites, the need for casting and concrete hardening speed, as well as the requirement to comply with the durability exposure classes, force us to produce concrete with faster early strength development. In the cases where junction spacing is not adequate or high masses need to be cast, premature cracking appears. The cracks are mainly caused by a difficult control of the curing and the shrinkage as well as too-high early stiffness of the concrete.

The abundance of RAP waste, the high impermeability of the bituminous fraction, the high thermal expansion of the bituminous component and the likelihood of obtaining an increase in the waterproof property, due to the closing porosity action of the fine RAP, as well as the slight increase in the concrete ductility, trigger the present experimental investigations.

The mix designs to attain a waterproof concrete are multiple, and the main one is used. Several parameters are regulated to attain adequate workability. The main mix design is shown in Table 1. Two C25/30 concretes with different siliceous-calcareous aggregate origins (Mix 1 and Mix 2) and one C30/37 concrete (Mix 3) are tested[42].

The workability of both mixtures exhibits a C3 consistency, and the workability loss within 60 min after the preparation of the blends is limited and remains within the C3 consistency class. The compressive strength is measured on 150-mm cubes after 7, 28, 60 d of hydration at a loading speed of 0.6 MPa s^{-1} [43], and the curing of the specimens takes place at 20 ± 2 °C. The indirect tensile strength is measured after 28 d of hydration[44]. The modulus of elasticity is tested after 28 d[45].

The water impermeability is measured by putting 150-mm concrete cubes under pressure after 28 d of hydration. The surface exposed to the water needs to be roughened by brushing. The three concrete specimens for each blend are placed in the device (Fig. 2). The surface to be tested is subjected to a water pressure of 500 ± 50 kPa for 72 ± 2 h. After the tests, the specimens are broken into two halves perpendicular to the surface exposed to water. Once the specimens are sufficiently dry, the vertical water penetration profile through a sealed circular zone of 75 mm is marked. The deepest penetration value is recorded with a precision of ± 1 mm[46].

The hydraulic shrinkage is measured after 90 d[47]. The accelerated carbonation resistance is tested after 28 d in a climate chamber with 4% CO_2 concentration and 65% relative humidity for 56 d[48]. The chloride penetration resistance is measured after 28 d by applying a potential difference between an anode and a cathode steel plate and forcing the chlorides to migrate within the specimens[49].

The RAP allowed to be recycled is based on the content of two main parameters concerning the pollutants, such as the aliphatic hydrocarbons C10–C40 and the polyaromatic hydrocarbons PAH, which must remain below the required limits. To clarify the environmental pollution potential of the blends containing RAP, leaching tests are also performed. Tests were conducted on the milled asphalt RAP (RA 0/22 mm) granules, the concrete Drytech R with 30% RAP in substitution of the natural aggregates, and the concrete CPN C with 25% recycled concrete Drytech R 0/22 mm.

Table 1. Main dosages for the preparation of the mixtures.

Parameters	Values
Concrete compressive strength class	C25/30 C30/37
Exposure class	XC4 accelerated carbonation resistance level
Maximum aggregate size	32 mm
Chloride content (% cement mass)	<0.10
Cement type	(50%) CEM II A/LL 42.5 N + (50%) CEM IV/A (V) 32.5 N LH-SR
Cement dosage (kg m^{-3})	>280; Total 320 kg m^{-3}
Water cement/ratio	<0.50
Workability	S4/F4
Superplasticizer type (%)	Dryfluid SF® 0.8–1.2
RAP content (%)	30

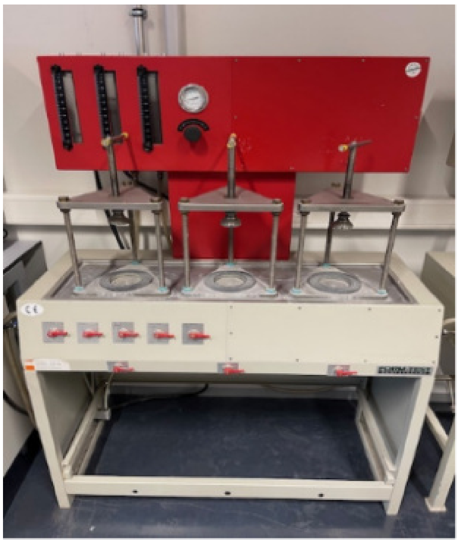

Fig. 2. Water permeability device.

3. Results and discussion

3.1. Reclaimed asphalt pavement

The milled reclaimed asphalt pavement (RAP) aggregates are analyzed for the granulometric distribution and exhibit an aggregate size range of 0–22 mm, with approximately 60% of the aggregates below 8 mm grain size (Fig. 3a). The total water adsorption of the aggregates is 20.0, 21.9 and 22.1 L m^{-3}[50]. The C25/30 mixtures in the fresh state exhibit a density varying from 2301 kg m^{-3} to 2327 kg m^{-3} up to 2330 kg m^{-3}[51]. The occluded air content ranges from 1.5% to 2%[52], and the water/cement ratio ranges from 0.47 to 0.48.

3.2. Mechanical performance

The compressive strengths of the three main concretes were 25–29 MPa at 7 d, 32–40 MPa at 28 d, and 39–43 MPa at 60 d (Fig. 3b). This progressive and controlled strength development reduces the risk of shrinkage cracks while maintaining sufficient strength, in spite of the general trend to lower compressive strength with the addition of RAP[22,24] in concrete. A strength increase is generally observed from 7 d to 60 d. However, the strength development occurs in a controlled manner due to the blending of the two main composite cements with a conventional strength development. This fact allows it to reach usable strength at an early age by maintaining a strength ⩽ 40 MPa at a later stage up to 60 d. A controlled strength development, particularly at an early age, is decisive for concrete that needs to be waterproof. A too-rapid strength increase is often observed for conventional concrete exposed to the atmosphere and values well beyond 50 MPa are observed after 60 d. In these cases, the tensile stress

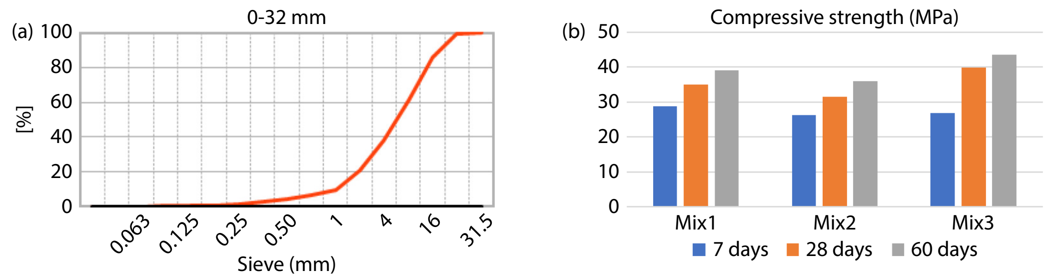

Fig. 3. (a) Sieve curve of the RAP component 0–22 mm. (b) Compressive strength of the C25/30 and C30/37 concretes.

and consequently the risk of crack formation increase. Cracks may exhibit an uncontrolled size of 0.145–0.300 mm, in spite of the care in the curing processes. Cracking may also extend several meters in length along the base foundation floors. Fine cracks (0.050–0.100 mm) may not significantly affect the durability of concrete exposed to atmospheric conditions. However, under water pressure, similar or higher crack widths may adversely affect the waterproof properties of the concrete placed on site. Waterproof concrete is a special cementitious material that is supposed to spend most of its service life buried in the ground. It is not exposed to very variable temperature conditions. The changes occur mainly in the humidity and groundwater contact. To maintain the impermeability over time, the first weeks during placement are decisive, and a controlled strength as well as a microstructural development that accommodates the hydration products to fill the porosity completely is a relevant requirement. Compared to the mechanical properties, the compressive strength of standard concrete C30/37 with a water-cement (*w/c*) ratio of 0.48–0.52 for the optimized mixture without mix design corrective measures, exhibits a mean value of 49.6±0.6 MPa and changes to the C45/55 concrete. The concrete C30/37 with a *w/c* ratio of 0.45 exhibits a value of 65±0.6 MPa and changes to the C 65/75 concrete at hydration beyond 28 d, with a density of 2348±0.07 kg m^{-3}.

The modulus of elasticity can also be controlled with the proper mix design (Fig. 4a). The compressive strength and the stiffness are also influenced by the addition of 30% RAP (by weight). The replacement of natural aggregates with RAP significantly decreases the strength, especially at high dosages beyond 30%[25]. However, at dosages up to 30%, the RAP may help to control the stiffness of the concrete. A modulus of elasticity below 30000 MPa is a good premise to avoid premature cracking caused by excessive concrete rigidity.

The indirect tensile strength exhibits values ranging from 2.7 MPa to 2.9 MPa and up to 3.4 MPa (Fig. 4b). In the standard C30/37 concrete, the value used for calculating shrinkage reinforcement size to counteract indirect tensile strength is generally 2.9 MPa. This allows maintaining a general flexibility of the cementitious material and controlling tensile stresses that may arise after placing operations and during service life at a later stage.

3.3. Permeability to water

The water permeability exhibits very low values. The required limit of the penetration depth for watertight concrete is set at 30 mm. The specimens exhibit penetration depth values from 11 mm to 18 mm (Table 2).

The C25/30 and C30/37 concretes added with 30% RAP exhibit a higher waterproof capability. The combination of cements (50% CEM II A/LL 42.5 N and 50%CEM IV/A (V) 32.5 N) allows the concretes to attain both a reasonable and moderate early-age strength development and a dense microstructure as well as a high water tightness. The addition of supplementary cementitious materials contributes to the densification of the cementitious matrix[32]. Similarly, the blended cements increase the resistance to aggressive agents contained in polluted subsoil and wastewater, reduce the hydration heat, and promote adequate pore refinement, which closes the porosity of the concrete within an appropriate timespan of 28 d. Furthermore, the combination of the two blended cements allows an appropriate control of the strength and rigidity development of the concrete, and an adequate densification and water tightness within 28 d of hydration.

The addition of RAP particles allows control of the indirect tensile strength and reduces the *w/c* ratio by improving the water tightness[28]. The addition of 30% RAP in concrete appears to be an optimum maximum dosage, although generally, the RAP content may go up to 50% by weight[22]. A reduction in the porosity and the water adsorption for RAP concrete[32] is observed with the 30% RAP addition. The pore interconnectivity that may enhance the freeze/thaw resistance of

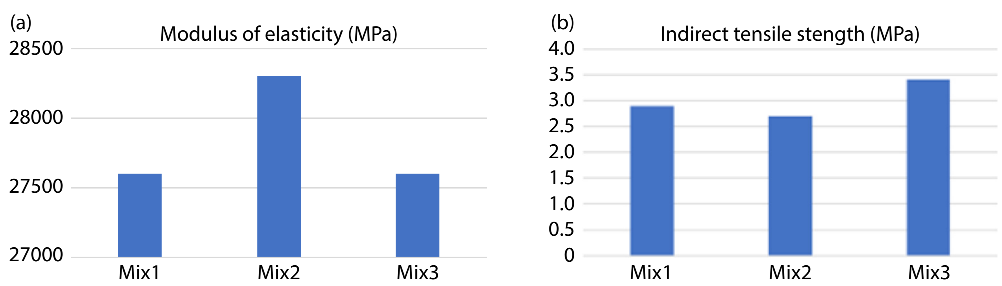

Fig. 4. (a) Modulus of elasticity and (b) indirect tensile strength of the concrete mixtures.

Table 2. Water penetration depth of the RAP concrete mixtures.

Mix 1 (C25/30)	Mix 2 (C25/30)	Mix 3 (C30/37)	Limit for waterproof concrete
17 mm	18 mm	11 mm	30 mm

RAP concrete[35] is not observed in this case. In fact, the durability properties largely depend on the mix design and not solely on the presence of RAP. In spite of some skepticism about the application of RAP concrete for structural components[37], the two cement components and the 30% RAP concrete exhibit a good compromise between mechanical properties development and waterproof capability. This latter feature is particularly present in the RAP concrete that exploits the impermeable nature of the bituminous material around the natural aggregates to limit water entrance. Furthermore, a general good adhesion between the bituminous materials and cement mortars may be seen on a microstructural level[20] and maintain a low porosity along the interface (Fig. 5). All these features indicate a positive use of RAP in concrete, in spite of the large limitations on the use of RAP in cementitious materials on a European level[38,39,40].

3.4. Durability and dimensional stability

The chloride penetration resistance under the application of an electric field indicates values ranging from 10×10^{-12} m^2 s^{-1} to $6\times10^{-12}\pm 1.1\times10^{-12}$ m^2 s^{-1} for the Drytech Concrete R® C30/37 at 60 d. The data are generally below the required limit for chloride-resistant concrete with a maximum set limit of 10×10^{-12} m^2 s^{-1}. The poor interface zone that may occasionally occur between bituminous-rich aggregates and the cementitious materials[29] does not affect the resistance to chloride penetration, which remains high. The accelerated carbonation coefficients vary from 3.6 mm/year$^{0.5}$ to 3.8 mm/year$^{0.5}$ and are below the limit of 4.5 mm/year$^{0.5}$. On the other hand, it is important to emphasize that buried reinforced concrete exhibits relatively low carbonation over time[53], although this also depends on concrete quality. However, carbonation is not a main critical factor for the durability of buried structures. More relevant is the control of hydraulic shrinkage. The values need to remain below 0.47‰ after 90 d. The measured values of the mixtures range from 0.46‰ (Mix 1) to 0.34‰ ± 0.01‰ (Mix 2). The shrinkage values appear to be adequately low. Moreover, the moderate strength development and the controlled rigidity contribute to lowering the shrinkage risk, along with adequate curing and an adequate junction pattern for large structures.

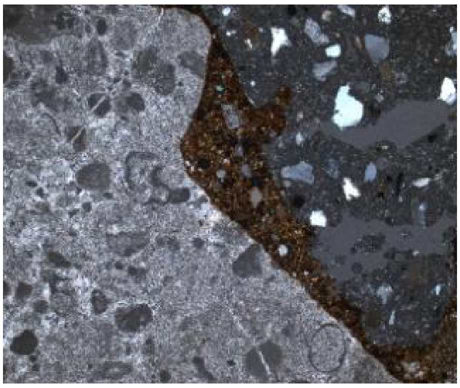

Fig. 5. Good interface adhesion between bituminous and cementitious materials. (Picture horizontal length: 500 mm)

3.5. RAP pollutants

A main issue with using RAP in concrete is determining the environmental pollution potential. The polycyclic aromatic hydrocarbons (PAH) of the bituminous material must remain below some levels, typically 250 mg kg^{-1}, and the C10–C40 hydrocarbons were below 500 mg kg^{-1}. Additionally, the content of heavy metals must remain below some limits that depend on international and local regulations. The latter may refer to the unbound materials prior to disposal and not to the cementitious bound status[44]. Therefore, the RAP concrete is exposed to 24-hour eluate leaching tests and controlled with respect to a wide range of leached pollutants[44] (Table 3).

During the tests, a comparison was also made between concrete containing 30% RAP and concrete with a 2-mm bituminous membrane with the primer underneath. The latter exhibits a higher solid residue after filtration at 105 °C. The content was 860 mg L^{-1} and was classified as a special landfill deposit class. The combination of concrete with a bituminous membrane is a typical waterproof system conventionally used to seal the buried reinforced concrete parts of buildings from water infiltration.

The last two columns exhibit the limits for inert unbound material disposals and the material reuse limits for clinker and concrete production. The RAP-recycled concretes exhibit lower concentrations of organic carbon, heavy metals, cyanides, sulfide, sulfite, N- and P-compounds, C10–C40, and sum PAHs than the required limits. Thus, by using RAP with C10–C40 and sum PAHs pollutant content below the limits and the bound-state RAP within the concrete, it is possible to obtain a very low environmental risk. Unlike asphalt, which is directly exposed to atmospheric and rainy conditions, potential pollutants are bound within the cementitious system.

The coarse RAP aggregates from 8 mm to 22 mm are relatively easy to be mechanically treated. The bituminous part can be largely reduced, and the cleaned aggregates exhibit a residual bituminous content below 1%, so that they can be easily reused as asphalt or concrete aggregates. The fine RAP aggregates with diameters ranging from 0 mm to 8 mm must be treated chemically to remove the old stiff residual bituminous materials. The latter procedure has a high environmental impact, because the chemically treated bituminous residues are supposed to be transported to the incineration plants. On the other hand, these fine RAP aggregates are particularly adequate within recycled RAP concrete, since they contribute to closing the porosity and producing waterproof RAP concrete.

4. Conclusions

The use of RAP allows the production of concrete with adequate early strength and stiffness development. The combination of the two blended cements provides appropriate control of the strength and rigidity development of the concrete at an early stage and an adequate densification of the matrix.

Table 3. Pollutant concentration of the eluates from the mixtures after the leaching tests.

Chemical parameter (mg kg^{-1})	Milled asphalt RAP (RA 0/22 mm) granulates	Concrete Drytech R with 30% RAP	Concrete CPN C with 25% recycled concrete Drytech R 0/22 mm	Reference limit for disposal[44] Type B	Reference limit for waste reuse for the clinker and concrete production[44]
Organic sum HC-index C10–C40 (mg L^{-1})	2600	<0.2	<0.2	500	3000
Aliphatic HC C5–C10 (mg L^{-1})	<0.5			10	100
Organic carbon TOC400	2.9			2	5
Heavy metals					
Chromium-VI ICP (induced coupled plasma)	0.02			0.1	
Antimony	<2			30	30
Arsenic	4	11		30	30
Lead	12	13		500	500
Cadmium	<0.5	<0.5		10	5
Chromium	19	38		500	500
Cobalt	<30	<30			250
Copper	23	24		500	500
Molybdenum	<10	<10			
Nickel	20	34		500	500
Mercury	<0.1	<0.1		2	1
Zinc	33	80		1000	2000
Tin	<2	3			100
Volatile organic compounds					
Benzene (dw)	<5	<0.005	<0.005	1000	1000
Sum BTEX (dw)	180			10000	10000
Sum CS (dw)	<20			1000	10000
Sum PCBs (AHR/AltIV)	<0.05			1	10
PAH					
Benzol (a) pyrene (dw)	0.54	0.06	0.21	3	3
Sum PAHs EPA	7.7	0.05	0.16	25	250
Nitrite (mg L^{-1} as NO_2)		0.142	0.06	1	1
Ammonium (mg L^{-1} as NH_4)		0.21	0.08	0.50	
Ammonium (mg L^{-1} as NH_4^+)		0.16	0.07	0.50	
Dry residue (after filtration, 105 °C)		454		500	
DOC (mg L^{-1})		4.4	6.4	20	20

The dense microstructure seems to be enhanced by the fine RAP aggregates, which fill the porosity and significantly increase the water tightness of the RAP concrete within 28–60 d of hydration. In this context, the bound state of the RAP within the cementitious matrix largely reduces the leaching of environmental pollutants.

Author contribution statement

Andreas Krattiger: Conceptualization, Data analysis, Practical implementation. **Andrea Terminio:** Concrete technology, Mix design optimization, Pollutant analysis, RAP concrete mechanical and durability tests. **Christian Paglia:** Data analysis, Manuscript writing.

Declaration of competing interest

Christian Paglia is an Editorial Board Member for *Materials Reports: Solidwaste and Ecomaterials* and was not involved in the editorial review or the decision to publish this article. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Andreas Krattiger is employed by Drytech SA, and Andrea Terminio was the Head of Swiss Beton Technology SA.

Acknowledgements

The authors gratefully acknowledge support from the technicians of Drytech SA, Swiss Beton Technology SA, and the Institute of Materials and Construction, SUPSI.

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