

# Durability of concrete containing Recycled Asphalt Pavement (RAP)

Salma Jaawani<sup>1</sup>, Annalisa Franco<sup>1</sup>, Giuseppina De Luca<sup>1</sup>, Orsola Coppola<sup>1</sup>, and Antonio Bonati<sup>1</sup>

<sup>1</sup>Construction Technologies Institute of the Italian National Research Council, ITC-CNR, Via Lombardia 49, 20098 San Giuliano Milanese, Milan, Italy.

## Abstract

As the world moves towards new sustainable solutions, the use of recycled materials in concrete, whether it is for roads, structural or non-structural uses, becomes more indispensable. The aim of the study is to give an overview on Recycled Asphalt Pavement (RAP), a reclaimed material resulting from the milling of road/motorway surfaces. While different studies exist regarding the effect of RAP on the mechanical properties of concrete, limited research is available on the durability of concrete containing RAP. This paper presents a review of methods currently used to study durability aspects of RAP concrete in different applications, such as moisture, permeability, freeze-thaw, etc. and the open issues that need to be further investigated.

## 1 Introduction

Depletion of natural resources and the incredible amount of Construction and Demolition Waste (CDW) coming from the construction sector are the main reasons behind the recent strategy to use recycled aggregates as a partial or full replacement for natural aggregates in concrete. Among the different recycled materials, the use of aggregates coming from the milling of road surfaces, which constitute what is generally referred to as reclaimed asphalt pavement (RAP), is ever increasing. However, RAP use is still limited due to multiple standards' restrictions and to the fact that many aspects related to its performance are still not fully studied. The application of RAP is still limited to a re-use in road construction, and it is less studied for structural use in buildings. A limited use of RAP in structural concrete is due to the decrease of the mechanical properties of concrete containing RAP. Durability, which is strongly depending on the percentage of substitution of natural aggregates by RAP, is surely one aspect that needs to be further investigated. Therefore, this paper aims to give an overview on different conditioning methods that are currently considered to study the durability of RAP concrete. A definition of RAP is given and the recycled aggregate characteristics are described to underline the major issues that could be faced when used in concrete mixes. Durability is then analysed in terms of resistance to hygrothermal environments, evidencing the effect on parameters, such as the Retained Marshall Stability, the indirect tensile strength, the durability index. Another aspect of durability that is presented is related to the resistance of hardened concrete to freeze and thaw conditioning. Finally, other studies on durability are shown evidencing different types of conditioning and their results when different RAP percentages are used in concrete.

## 2 Reclaimed Asphalt Pavement (RAP)

### 2.1 Description and use of RAP

Recycled (or *reclaimed*) asphalt pavement is the name given to crushed, milled, pulverized, processed or/and unprocessed pavement materials containing asphalt and aggregates. These materials are generated when asphalt pavements are removed for reconstruction by milling from road/motorway surface. Reclaimed asphalt pavement consists of two components [1]:

- RAP aggregate, which is the aggregate part of the reclaimed asphalt;
- RAP binder that consists of the asphalt cement of the reclaimed asphalt.

The majority of RAP is usually destined to return to the roadway structure. This is due to the fact that RAP has its own grading curve characterized by a high percentage of fine and aged bitumen. For this reason this type of aggregate undergoes a sort of "closed cycle", returning again within the road construction, satisfying in this way the basic principles of circular economy [2].

In Italy, RAP is still not considered as a valuable resource. According to the Italian Roads and Bitumen Association (SITEB), Italy has made important progress in the reuse of milled asphalt on pavement roads. However, it still stands behind other countries in Europe. In 4 years, Italian roads have used from 20% (2014) to 25% (2018) of milled material recovery, compared to the European average of 60% [3]. In Italy, only 25% of the available milled asphalt is destined to be reused.

A possible reason behind the lack of use of RAP in structural concrete could be due to specific code restrictions and a decrease in mechanical properties like compressive strength, flexural strength, splitting tensile strength and a poor prediction of the behaviour of concrete containing RAP in terms of durability and exposure to critical conditions. The mechanical properties of RAP also depend on the original asphalt pavement type. Furthermore, both milling and crushing can cause some aggregate degradation [4].

Based on the studies investigated, a clear chemical composition of RAP still does not exist but according to Chyne [5], RAP is mostly composed of mineral aggregates, approximately 97% by weight, and the remaining is made of hardened asphalt cement. RAP has a similar chemical composition in comparison to that of natural aggregates and the major element compounds of RAP, in percentage by weight, are  $\text{SiO}_2$ ,  $\text{Fe}_2\text{O}_3$ ,  $\text{CaO}$  [5]. Another issue that is generally studied with reference to the chemical composition is the leaching of contaminants that could cause pollution while being carried by water after precipitation. Water carrying contaminants could infect surface waters or reach groundwater by infiltration. However, according to the studies of Brantley et al. [6], few pollutant chemicals leached from the RAP collected and none of organic chemicals or heavy metals was found. It is important to know that the models used to identify the behaviour of RAP when leaching were originally made for other types of aggregates [7]. For this reason, a deeper study is needed to prevent an overestimation of risks related to the leaching pollutants and consequently a better reuse of RAP.

## 2.2 Main characteristics of RAP influencing concrete properties

An appropriate use of reclaimed asphalt aggregates in concrete requires the study of their main characteristics. Among these, specific gravity and water absorption have a high influence on concrete. A low specific gravity indicates a high porosity, which results in poor durability and low strength of concrete [8]. The water absorption of aggregate represents the ability of RAP to absorb water and gives an idea of strength of aggregate: a high value of water absorption indicates high porosity of the aggregate, which make it unsuitable for concrete, unless found to be acceptable based on other tests like strength, hardness and impact. Based on several research studies [9-12], impurities negatively influence RAP aggregates, especially in terms of water absorption. Shape and dimensions are also important to design the mix and fix the w/c ratios for both asphalt mix and concrete for buildings. In terms of shape, for a higher workability, it is generally recommended to use rounded aggregates [10, 13, 14]. Flaky and elongated aggregates could lead to the production of concrete with segregation and poor surface finish, which will require a high cement and sand demand [10, 13, 14]. By influencing water demand, aggregates' shape plays a major role in the strength of hardened concrete. Another factor that influences the bond between aggregates and cement is the surface texture, whether it is rough or smooth [13-15]. For rough surfaces, the bond between cement and aggregates is strong and leads to good mechanical properties [15]. One of the most important physical characteristics of RAP aggregates is the crushing value (or resistance to fragmentation), which is a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load [8, 16-20]. Grading of aggregates is another important aspect as it influences various properties of concrete such as cohesion, water demand, workability, and strength [14, 21]. The percentage of substitution of natural aggregate by RAP aggregate is another aspect that influences the mechanical characteristics of the quality of hardened concrete. By increasing the percentage of substitution, most of the mechanical parameters of concrete decrease consequently. It must be said that the definition of the percentage of substitution depends mainly on the multiple limitations imposed by the standards that every country respects in order to assure a good performance of concrete also in terms of different exposure conditions. In this sense, one of the main mechanical characteristics that needs to be studied in a deeper way is durability, which is intended as the capability of maintaining the serviceability of a product, component, assembly, or construction over a specified time [22]. Durability studies depend majorly on the destination of use of the concrete containing RAP (roads, pavements, structural concrete, etc.). In the next chapter, an overview is given on the durability aspects necessary to define the suitability of RAP for the applications previously cited.

### 3 Durability of concrete containing RAP

Materials subject to the action of environmental factors such as temperature changes, air, and water are constantly amenable to effects on durability. When seasonal variation of temperature and moisture occurs, it is important to study the response of concrete mixes containing RAP to variation of moisture and freeze and thaw cycles [23]. Currently, the majority of studies on durability of concrete mixes relates to asphalt mixes [22, 24-34] as it can be seen in the next chapters. This is due to the fact that RAP is more likely to return to asphalt mixes. The research in terms of durability of structural concrete containing RAP [35, 36] is still nowadays poor and must be studied in deeper ways to allow structural and non-structural uses of concrete.

#### 3.1 Resistance to hygrothermal environments

In asphalt mixtures, aside from water and temperature actions, load conditions have a profound effect on the durability of asphalt concrete mixtures. In fact, the major contribution to the deterioration of pavements is predominantly related to traffic loading resulting in fatigue cracking, rutting (permanent deformation), and ravelling. However, when severe climate conditions are coupled with poor materials, the result is a degradation of asphalt concrete pavements under inadequate control [22]. The infiltration of water causes a loss of adhesion at the bitumen-aggregate interface and the strength of concrete decreases as it stopped to act as a coherent structural unit. The loss of strength and integrity of the asphalt pavement structure is the most serious consequence of stripping [24]. Stripping can take many surface forms during its development; by entering the interface, water can cause stripping in five different mechanisms: detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scour [22]. Similarly, infiltration of water can potentially contribute to corrosion of embedded steel reinforcement in reinforced concrete.

With the aim of studying the durability of concrete mixtures against the continuous and damaging effect of water and temperatures, researchers focused on concrete mixtures containing different percentages of screened RAP to define the most suitable percentage of RAP in relation of durability performance expressed in terms of resistance to water damage. In Alkawaaz et al. [24], virgin mixes were mixed with different percentages of RAP (5, 10 and 15% by weight of total mix). The specimens were then subjected to the Marshall test. The effects of water damage were studied by immersing the specimens in water at  $25^{\circ}\text{C} \pm 1^{\circ}\text{C}$  for 1, 4, 7, and 14 days [24]. The parameter used to define the resistance to water damage was expressed in terms of Retained Marshall Stability or "RMS" which is a ratio between the Marshall Stability for conditioned specimens and the Marshall Stability for unconditioned specimens, and it is an indicator of the durability potential. The durability potential of bituminous mixtures may be defined as the resistance of the mixture to the continuous and combined damaging effects of water. High durability potential usually implies that the mechanical behaviour of the mixture will endure for a long service life. An analysis of the results demonstrated that by increasing the immersion period, the durability potential reduces. When RAP content increases, the RMS values increase accordingly. This can be attributed to the increase in the stiffness of asphalt because of inclusion of RAP, which contains hardened asphalt that is more viscous than virgin asphalt [24]. In El-Hmrawey et al. [22] the same procedure was followed to define the RMS values with two main differences: the mixes were designed for a content of RAP of 0, 25, 50, 75 and 100%, for periods of immersion of 1, 3 and 7 days at  $60^{\circ}\text{C}$ . The test results showed that RAP has a significant effect on Marshall stability where the stability was increased by about 15%, 19% and 22.6% for 25%, 50% and 75% RAP content respectively, and was increased by about 10% for 100% RAP content [22].

A moisture sensitivity test was performed by Tabakovic et al. [34] in accordance with EN 12697-12 [37]. The percentages of RAP in the mixes were 0, 10, 20 and 30%. In this case, the objective was to determine the indirect tensile strength test (ITS) in accordance with EN 12697-23 [38]. The Irish National Roads Authority (NRA) [39] guidance values for water sensitivity tests (WSTs) suggest that wet to dry indirect tensile strength ratio values below 75% indicate moisture damage. From the results presented [34], it is evident that moisture damage is not an issue for the mixes containing 0%, 10%, and 20% RAP (ITS ratio of 93.4, 102.4 and 93.8%, respectively). With the inclusion of 30% of RAP in the mix, the ITS ratio decreases to below 90%, suggesting that further increases in RAP content could leave the mix vulnerable to moisture damage [34].

Another factor that is generally studied to demonstrate the effects of RAP on asphalt concrete mixtures durability is the Durability Index (DI), which is also a function of the Marshall Stability, and is a way to predict and control moisture damage in asphalt mixtures. The DI is defined as the sum of the

slopes of the consecutive sections of the durability curves, obtained representing the Marshall Stability as a function of the immersion times [24]. Low values of DI indicate a good performance against moisture attack. According to Alkawaaz [24], DI values obtained for mixes with different RAP contents (from 0.0% to 15% RAP) showed that the mixture containing 15% of RAP is the best one to endure for a long service life (lowest DI). In El-Hmrawey at al. [22], where a major content of RAP was implemented in the mixes, the mixtures containing 75% and 100% obtain higher total durability index values (34.24% and 36.62% respectively) compared with control mixtures, while mixtures of 25 and 50% RAP content achieved lower durability index (31.30% and 28.5% respectively). Therefore, El-Hmrawey at al. [22] concluded that the mixture containing 50% RAP is the best mixture to endure a long service life, while the mixture containing 100% RAP is the worst mixture to resist moisture damage.

### 3.2 Resistance to freeze-thaw cycles

Freeze-thaw (F-T) durability of concrete is a function of the pores. Air entrainment, which provides a closely spaced network of air voids that accommodate expanding pore water, greatly improves the resistance of concrete to freezing and thawing. For this reason, it must be considered during design phase.

The effect of F-T conditioning on high strength structural concrete containing RAP was studied in Thomas et al. [35]. In this study, different mixtures (25, 30, 35, 40, 45 and 50% RAP) were cured for 28 d and subjected to 300 cycles of freezing and thawing according to ASTM C 666, Procedure A [40]. The control mixture with 100% virgin coarse aggregate performed the worst under freeze-thaw cycling. The freeze-thaw durability improved with an increasing RAP content, up to about 35–40%, and decreased thereafter. The optimal performance in terms of durability factor (the relative dynamic modulus of elasticity following 300 cycles of freezing and thawing) was observed with 35% RAP, which exhibited a 300-cycle durability factor of 96%. The optimal performance in terms of residual compressive strength was observed with 40% RAP, which lost only 18% of its 28 days compressive strength after 300 cycles of freezing and thawing [35]. Similarly, in Brand et al. [41], the F-T durability of each mixture was determined by three replicate samples, according to AASHTO T161 Procedure A [42]. The F-T cycle alternates from a high temperature of 4°C to a low temperature of -18°C. At intervals no greater than 36 F-T cycles, the fundamental transverse frequency and specimen weight were measured. The test was completed once 300 freeze-thaw cycles were achieved. In this study, the mix containing 20% of fractioned RAP (FRAP) did not appear to be significantly affected. After 300 cycles, the durability factor was lower for the 50% FRAP mix than for the 35% FRAP mix, but the 35% FRAP mix experienced slightly greater mass loss than the 50% FRAP concrete. The results indicate that adding coarse FRAP to the concrete affected the freeze/thaw durability but not sufficiently to become a performance problem, assuming the concrete matrix was correctly air-entrained. A similar testing method was also applied by Berry et al. [36] to two different mixes containing 50% and 100% of RAP. Results showed a reduced freeze-thaw durability when RAP percentage increased from 50% to 100%, even if the behaviour under F-T conditioning was excellent for both concretes.

### 3.3 Other durability studies

Durability of concrete containing RAP is generally investigated also in terms of resistance to aggressive environments and temperature variations.

Chloride effect was investigated by Thomas et al. [35] in terms of chloride permeability, which is fundamental when concrete is destined to be coupled with steel. Chloride permeability is a function of porosity: low porosity and high tortuosity limit the diffusion of chlorides into the concrete matrix. When RAP is used as coarse aggregate, chloride can migrate through the concrete and potentially contribute to chloride-induced corrosion of embedded steel reinforcement. Chloride permeability was estimated by surface resistivity using a Wenner array probe in accordance with the specifications of AASHTO TP 95 [43]. Eight circumferentially spaced measurements were made on three replicate specimens per mixture. The surface resistivity of the control mixture was 34.1 k $\Omega$ -cm. With 25 and 30% RAP coarse aggregate, the surface resistivity reduced to 31.7 and 29.1 k $\Omega$ -cm, respectively. Even with the reductions in surface resistivity observed for mixtures including RAP, all mixtures exhibit low chloride permeability. It is important to note that these test results do not account for the fact that asphalt is exposed to de-icing salts during its service life, and RAP is therefore expected to contain some appreciable chloride content, which can be removed by washing. A chloride permeability test has been conducted by Brand et al. [41] to evaluate concrete permeability with the addition of fractioned RAP. The specimen was placed in contact with two solutions: a 3% sodium chloride (NaCl) solution (by mass) and a

0.3N sodium hydroxide (NaOH) solution. A 60V potential was applied, and the charge passed through the specimen was measured over a 6-hour duration because the chloride ion penetrability of the concrete can be evaluated based on the total charge passed in 6 hours. From the results of this study, the chloride penetrability did not appear to be affected by the presence of up to 50% coarse FRAP in the concrete, and the use of supplementary cementitious materials seems to help reducing the penetrability [41]. A chloride permeability test was also conducted by Berry et al. [36] to evaluate permeability differences between a mix containing 50% of RAP and a mix containing 100% of RAP. Results showed that little change in the permeability was registered with no evident difference between the two mixes.

When high strength concrete is used in transportation infrastructure, it becomes important to evaluate the coefficient of thermal expansion, as it affects the opening and closing of construction joints. Joint closure resulting from excessive thermal expansion leads to compressive stress development and potential cracking, resulting in a limitation for its service life [35]. In Thomas et al. [35], the coefficient of thermal expansion (CTE) of 28-d limewater cured cylinders was evaluated in a manner similar to that prescribed by AASHTO T 336 [44]. Three replicate specimens per batch were stored in a temperature-controlled chamber. The temperature was ramped from 10 °C to 50 °C and back to 10 °C in increments of 10 °C with a soak time of 30 min at each increment. The reported CTE is the average rate of change of axial strain as a function of temperature for three replicate specimens under increasing (10 to 50 °C) and decreasing (50 to 10 °C) temperature. Coefficients of thermal expansion for high strength concrete increased slightly as a result of the replacement of virgin coarse aggregate with RAP but in general the high strength and stiffness of the concrete matrix with respect to that of RAP material limit the expansion to within the typical range expected for conventional concrete.

#### 4 Discussion and Conclusions

The objective of the paper was to investigate the influence of RAP on durability of concrete under different aspects. It was noticed that test results found in literature are mainly focused on the re-use of RAP in asphalt mixtures with a poor interest to the use of RAP in structural concrete. The effects of RAP on the mixes are strongly dependent on the percentage of substitution. More precisely, it was observed that:

- The use of RAP is still limited due to the restrictions imposed by standards; thus, some of the characteristics of RAP needs to be studied with the proper method.
- The infiltration of water causes a loss of adhesion at the bitumen-aggregate interface and the strength of concrete decreases as it stopped to act as a coherent structural unit. The Retained Marshall Stability and the durability index are useful indicators to define the resistance of the mixture to the continuous and damaging effects of water and temperatures. An increase of RAP content produces an increase of RMS. Similarly, durability index showed higher values when RAP is included in higher percentages.
- Thanks to its low ability to hold extra moisture beyond the optimum moisture content, RAP is generally not affected by F-T conditioning, assuming the concrete matrix is correctly air-entrained. In high strength concrete, the freeze-thaw durability improved with an increasing RAP content to a limited degree.
- Adding RAP had no valuable effect on chloride permeability of concrete and the use of supplementary cementitious materials seems to help reducing the penetrability. This aspect becomes fundamental when concrete is destined to be coupled with steel.
- The large thermal expansion of the RAP coarse aggregate is restrained by the relative stability of the surrounding matrix, so that the CTE remains within the typical range expected for conventional concrete.
- A deeper investigation in terms of durability of structural concrete containing RAP is needed, as literature analysis showed a poor content of studies regarding the influence of RAP on the durability of structural concrete.

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