

Review

# Limitations on the Use of Recycled Asphalt Pavement in Structural Concrete

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**Abstract:** Recycled materials from construction and demolition waste, such as recycled concrete aggregate, recycled brick aggregate, or recycled asphalt coming from the milling of road/motorway surfaces, are the key for a sustainable production of concrete. This paper reviews in particular the use of recycled asphalt pavement (RAP) aggregates in the production of concrete for structural uses. An overview is initially presented to describe the different areas of use of RAP, its definition and the limitations imposed by codes and standards. Relatively to the experimental data provided by the literature, a comparison with the Italian minimum requirements is also provided. Lastly, the influence of RAP on the characteristics of concrete such as compressive strength, flexural strength, Young's Modulus and a study of durability are presented to define the possible applications of RAP in structural concrete in relation to the current allowable percentage of substitution.

**Keywords:** recycled asphalt pavement; recycled aggregate; structural concrete; circular economy; sustainability; characterization; limitations; standards



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## 1. Introduction

The new approach in the engineering field is focused on sustainability by aiming at new solutions able to reduce the greenhouses emissions in the environment; the civil engineering cannot be excluded and it has to contribute to the 2050 decarbonization challenge. Concrete, which is the most widely used construction material, is also one with the largest impact on the environment due to the production and demolition processes. The high embodied energy required throughout the concrete production, implies the well-known “greenhouse gas emissions” problem, especially CO<sub>2</sub>. According to Pavlu [1], the majority of energy consumption for concrete production is connected with the production of cement that requires 90% of total embodied energy of concrete. Furthermore, most of the global greenhouse gases emissions, especially SO<sub>x</sub>, which are responsible of acidification, are originated from the production of concrete. Moreover, if on one side, the concrete production is connected to a high energy consumption, on the other side demolition of concrete structures causes large amounts of waste. Most of the overall waste is due to Construction and Demolition Waste (CDW) that represents 25–30% of the total amount of material waste on earth [1]. Only in Europe, it is possible to count about 800 million tons of CDW per year, i.e., around 32% of the total waste generated [2]. CDW contains multiple and different materials, although concrete and bricks constitute the highest percentage. According to the EU Waste Strategy [2], it is fundamental to find a way to re-use aggregates deriving from CDW and to reduce the amount of unused and deposited materials. Among the different recycled aggregates that replace, partially or fully, the natural ones in concrete, the recycled (or reclaimed) asphalt pavement (RAP), obtained from milling of road surfaces, is gaining a high interest as an effective approach for recycled CDW utilization and reduction of natural resources depletion. Large amounts of recycled asphalt are still deposited on landfills and mostly remain unused [1]. The majority is generally returned to an asphalt

structure. In the last few years, researchers [3–5] have investigated the possible use of reclaimed asphalt pavement in structural concrete by studying its influence on hardened concrete properties, such as compressive strength, flexural strength, elastic modulus and splitting tensile strength.

This paper aims to give an overview of the current applications of RAP aggregates in the construction sector, focusing on their use in structural concrete. A definition of RAP is provided with special attention paid to the production, chemical composition and possible leaching issues. Considering the real exploitation of this recycled material, the analysis of the current standards and regulations for the characterization of RAP aggregates and the possible barriers on their use in concrete is presented. Last but not least, the influence of RAP on concrete performance is analysed to investigate the current state of the art and to point out future research directions.

## 2. Applications and Use of RAP Worldwide

The majority of RAP is usually destined to return to the roadway structure. This is due to the RAP grading curve, which is characterized by a high percentage of fine and aged bitumen [6]. 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 the circular economy [7]. Indeed, when properly crushed and screened, RAP consists of high-quality and well-graded aggregates coated by asphalt cement that can be used in hot asphalt mix, cold asphalt mix, and asphalt concrete production for base and sub-base construction. In the last few years, studies have been conducted in order to prove the suitability of RAP, also for the production of structural concrete [3–5,8–17]. Unfortunately, only a few results on the use of RAP in structural concrete are available. The analysis of the state of the art evidenced that the majority of papers investigate the use of RAP in asphalt mixture [6,18–49] for roads and pavements. Considering the (not-exhaustive) list of examined papers (Table 1), more than half discuss the use of RAP in asphalt mixtures.

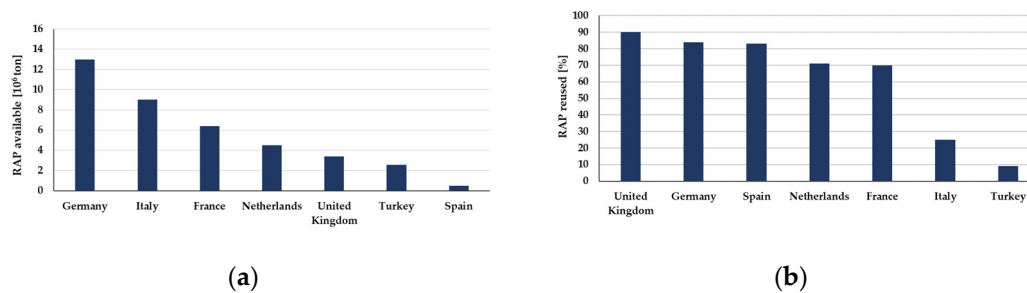
**Table 1.** Use of RAP in different fields and the main research results.

Applications	% of Papers (N <sub>tot</sub> = 46 Papers)	Main Conclusions
Pavements/roads [6,18–49]	72%	<ul style="list-style-type: none"> <li>Compressive strength, splitting tensile strength, flexural strength and elastic modulus decreases as the percentage of RAP increases.</li> <li>Higher content of RAP negatively influences the fatigue resistance.</li> <li>Higher percentage of RAP negatively influences compressive strength, splitting tensile strength, flexural strength and elastic modulus.</li> </ul>
Structural use [3–5,8–17]	28%	<ul style="list-style-type: none"> <li>Durability studies on the effect of RAP on concrete are still missing.</li> </ul>

According to [38], the percentage of RAP used in hot and warm mix asphalt (HMA/WMA) and cold mix asphalt (CMA) in Europe, respectively 51.4% and 3.81%, is significantly higher than the RAP percentage used for other purposes, such as coarse aggregate in structural concrete (about 2%). Furthermore, the amount of RAP deposited on landfills is still high (9.63%), surpassing the percentage of RAP used for structural concrete.

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, increasing it from 20% (2014) to 25% (2018) (see Figure 1) [50]. However, Italy still stands behind other countries in Europe that boasts an average of 60% [50]. The countries considered to be the most virtuous, on the other

hand, are the United Kingdom (90%), Germany (84%), Spain (83%), and the Netherlands (71%) [50].



**Figure 1.** SITEB analysis on RAP in Europe: (a) RAP available in each country; (b) Percentage of reused RAP [50].

In the United States, the discrepancy between the use of RAP in HMA/WMA and for the other purposes is even more significant, since the percentage of RAP destined to the production of HMA/WMA reaches the 81.3% of the total production of RAP [51].

The still limited use of RAP in road construction is justified by the reduced mechanical properties of asphalt mixes containing this recycled material. Indeed, replacing virgin aggregate by RAP in asphalt mix can cause a decrease in compressive strength, flexural strength, splitting tensile strength and modulus of elasticity [23,29,30,39]. When included in asphalt mix, RAP also influences fatigue and thermal cracking resistances [38] while showing an increase in the stiffness compared to a mix with virgin aggregates. According to Hossiney et al. [23], who performed a finite element analysis to determine the maximum flexural stress in typical concrete pavements in Florida under critical temperature and load conditions, the resulting maximum stress to flexural strength ratio for RAP concrete decreases as the RAP content increases (maximum reduction of about 27%), when compared to that of a reference concrete with no RAP. A lower stress–strength ratio means a higher number of stress cycles to failure as well as a better performing concrete. In addition, thanks to the presence of a thin film of asphalt layer on the RAP aggregate, the energy absorption capacity and flexural toughness of the concrete can improve significantly [11].

In the construction of roads, worldwide regulations remain strict on the use of RAP as a substitute aggregate, limiting it to a range between 5% and 50% [26].

Similarly, a possible reason behind the lack of usage of RAP in structural concrete could be due to the specific code restrictions, to a decrease in mechanical properties like compressive strength, flexural strength, splitting tensile strength and to a poor prediction of the behaviour of concrete containing RAP in terms of durability or when it is exposed to aggressive environments. These aspects will be better studied in the following sections.

### 3. Quality and Homogeneity of RAP Aggregates

#### 3.1. Definition and Origin/Production of RAP Aggregates

Recycled 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 the road/motorway surface. A reclaimed asphalt pavement consists of two components [34]:

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

As both components have a great impact on the performance and the mixture of concrete, the amount of RAP content is still limited by the maximum amount of aggregate and binder allowed in the mixture. The properties of RAP are largely dependent on the properties of both the original aggregate and the binder.

Based on the studies investigated, the chemical composition of RAP derives from the type of pavement, which in turn depends on the type of parent rock of the aggregate. For

this reason, a petrographic analysis is required. Coppola [3] just refers to a petrographic analysis without indicating the relative results, while Chyne et al. [33] reported a chemical composition of the RAP aggregate studied, which is shown in Table 2 as a result of the X-ray fluorescence tests. RAP contains mineral aggregates up to 97% by weight and the remainder is made of hardened asphalt cement. RAP has a similar chemical composition in comparison to that of natural aggregates. It was observed that the major element compounds of RAP, in percentage by weight, are SiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, CaO [33]. The asphalt in RAP is a viscoelastic material, whose properties depend on temperature and the loading conditions. As the RAP is exposed to the environment, oxidation causes two conversion processes in the aged asphalt: (i) oils in resins; and (ii) resins in asphaltenes. The viscosity increases with the RAP binder content and it plays a major role in terms of workability. A decrease in the viscosity of the bitumen allows a better workability of the mixes. Consequently, when the RAP is included as an aggregate in the concrete, the properties of the latter, such as creep and shrinkage, get affected.

**Table 2.** Chemical composition of RAP [33].

Element	Test Result (% by Weight)
SiO <sub>2</sub>	38
Fe <sub>2</sub> O <sub>3</sub>	26.8
CaO	16.3
Al <sub>2</sub> O <sub>3</sub>	11
SO <sub>3</sub>	2.9
TiO <sub>2</sub>	1.8
K <sub>2</sub> O	1.73
MnO	0.585
SrO	0.37
CuO	0.13
V <sub>2</sub> O <sub>5</sub>	0.11
BaO	0.2
Re <sub>2</sub> O <sub>7</sub>	0.06
ZrO <sub>2</sub>	0.055
ZnO	0.045

The mechanical properties of RAP also depend on the original asphalt pavement type. There can be significant differences between asphalt concrete mixes, since the aggregates in surface course must have high resistance to abrasion to contribute to acceptable friction resistance properties: these aggregates may be of higher quality than the aggregates in binder course applications, where polishing resistance is not fundamental. Furthermore, both milling and crushing can cause some aggregate degradation [51]. The particle size distribution of milled or crushed RAP varies in accordance with the type of equipment used to produce the RAP, the type of aggregate in the pavement, and whether any underlying base or subbase aggregate has been mixed in with the RAP during the pavement removal [51]. Asphalt pavement is generally removed either by milling (which can remove up to 50 mm thickness in a single pass) or by full-depth removal (using a rhino horn on a bulldozer and/or pneumatic pavement breakers) [51]. The crushed material is conveyed to a facility for processing. At this facility, the RAP undergoes a series of operations, including crushing, screening, transporting and stacking. Especially during the stacking phase, an aspect that is generally investigated regards the potential environmental risks related to a possible leaching of pollutants of RAP. In the time frame between transportation and storage, precipitation could fall on the RAP stocked on landfills, resulting in contaminants leaching from the RAP itself. Water-carrying contaminants could pollute surface waters or reach groundwater by infiltration. As a consequence of infiltration, it must be said that there is an important relationship between asphalt age and properties, such as penetration and viscosity. As asphalt ages and is exposed to the elements, it tends to harden and become brittle, resulting in an increase in viscosity and a decrease in penetration. For

this reason, when evaluating the potential of a waste material to leach chemicals to the environment, a number of approaches may be employed. The study reported by Brantley et al. [42] found that few pollutant chemicals leached from the stocked RAP and no organic chemicals or heavy metals were found. This indicates that RAP, under most regulatory policies for beneficial reuse of waste in the environment, would pose a minimal risk from a leaching standpoint. Risk evaluation tools, like IWEM (US EPA's Industrial Waste Management Evaluation Model) used by Spreadbury et al. [43], could be used to provide estimates on the content of chemical compositions and to evaluate what types of controls may be necessary to verify potential environmental risks. Such estimates can then be supported by field monitoring in order to make definitive conclusions on the actions to be taken. The use of IWEM in Spreadbury's study identified, however, some limitations when simulating highly soluble ("wash-off") constituents that leach in the short-term and quickly deplete from RAP in the long-term, which could lead to an overestimation of the potential risk. A deeper study of factors that affect RAP leaching, methods of test, and risk assessment approaches can result in a better implementation of RAP and in a maximization of RAP reuse without any type of pollution risk on environment and human health.

In Italy, the leaching test becomes fundamental to define the "bituminous conglomerate granulate" stated in the Ministerial Decree n°69 of 28 March 2018 [52]. In this sense, it is important to distinguish the "bituminous conglomerate" and the "bituminous conglomerate granulate": the first one indicates the unprocessed waste material, while the second one is the definition given to the end of waste (EOW). The EOW material is the waste material that has been processed and has undergone one or more recycling processes in order to be used as recycled aggregate. The recycling process includes [53]:

- Crushing, aimed at obtaining a reduction in the size of the waste;
- Separation, to eliminate unwanted materials in the final product;
- Screening, aimed at separating the grains based on their size to obtain homogeneous particle size fractions.

According to the Italian Ministerial Decree n°69 [52], once the bituminous conglomerate undergoes the recycling process, it must be declared as "granulate of bituminous conglomerate". This happens when the following requirements are fulfilled.

- The bituminous conglomerate granulate can be used in bituminous mixtures obtained by hot/cold mixing system, and for the production of aggregates to be used in road construction [54].
- The requirements indicated by the standards EN 13242 [54] or EN 13108-8 [55] should be respected (as a function of the intended use).
- The following actions (defined in Annex 1 of the Ministerial Decree) should be carried out:
  - a visual check on the incoming material;
  - an asbestos test, a polycyclic aromatic hydrocarbon (PAH) test and a leaching test, whose results are then compared with the limits reported in the Ministerial Decree;
  - characteristics such as grading (EN 933-1 [56]), petrographic description (EN 932-3 [57]) and content of extraneous material (maximum equal to 1% in mass content) should be defined. These will be included in a Declaration of Conformity, which is the document that confirms that the granulate fully respects what is established in the Ministerial Decree.

EN 12620 [58], which is the harmonised European standard for aggregate for use in concrete (more details will be presented in the following sections), is not recalled in the Ministerial Decree, posing therefore a limit to the use of the bituminous conglomerate granulate in the building sector. This means that, currently, the bituminous conglomerate granulate can only be used in road construction, causing, therefore, a strong limitation and barrier on further implementations of this recycled material in structural concrete.

### 3.2. Characterization of RAP Aggregates According to Existing Standards for Different End-Use Application

The construction sector is closely regulated by standards, regulations and design codes, which cover different levels of the commercialization and the use of innovative materials in the national and international market. The Construction Products Regulation (CPR) EU 305/2011 [59] sets up harmonised conditions for the marketing of construction products on the EU market. The reference documents for the CE marking of a product are the harmonised technical specifications, i.e., harmonised standards (hENs) and European Assessment Documents (EADs), which are published in the Official Journal of the European Union (OJEU). When a product is covered by a harmonised standard the manufacturer shall draw up a Declaration of Performance (DoP) when such a product is placed on the market (CPR, Art. 4). Through the DoP the manufacturer assumes responsibility for the conformity of the product with the declared performance values, which are assessed according to the methods reported in the specific harmonised standard.

When it comes to aggregates, there are different harmonised standards for their CE marking and therefore their commercialisation. A list is reported in Table 3. All standards generally foresee the use of recycled aggregates and are the result of the Mandate M/125 [60], which is the mandate of the European Commission to CEN [61] (European Committee for Standardization), and CENELEC [62] (European Committee for Electrotechnical Standardization) concerning the execution of standardisation work for harmonised standards on aggregates. The harmonised standards include a list of essential characteristics that define the properties of the product, which have influence on the basic requirements of the construction work (*BWR*, see CPR, Annex I). Each essential characteristic has to be determined according to the test method reported in the specific hEN in relation to the intended use of the product.

The study of the existing hENs, including the use of recycled aggregates, allows us to discuss the possible application of RAP as an aggregate for different intended uses in the construction sector. A summary is reported in Table 3. Except for EN 12620 [58], which is specific for aggregate for concrete and will be studied in more detail in Section 3.3, a general overview will be given for each analysed standard.

In the harmonised European standard EN 13139 [63], which specifies the properties and the characteristics of aggregates and fillers obtained from natural, artificial or recycled materials to be used for mortars, some limitations for the use of RAP have been found. Aggregate size could constitute the main limit to the non-suitable use of RAP in the mix for mortars because RAP is generally not homogeneous and could not respect the grading requested by the standard. It should also be pointed out that in EN 13139 [63] there are no indications for recycled aggregates in the evaluation of total sulphur content. Furthermore, the content of organic material in the aggregates shall not influence the setting speed of the mortar by extending its time by more than 120 min. In terms of mechanical properties, the compressive strength of the specimens shall not decrease by more than 20% after 28 days, and this could be a limitation considering that a decrease in compressive strength has in general been evidenced for mortar containing RAP depending on the percentage of substitution [40,41]. All these aspects are relevant for the inclusion of RAP in the scope and, consequently, for the application, of this standard. Similarly, EN 13043 [64] specifies the properties of aggregates and fillers obtained from natural or recycled materials for use in bituminous mixtures and in surfaces for roads, airports and other areas subject to traffic. More precisely, this standard does not concern the use of RAP in milled bituminous conglomerates, thus imposing its exclusion if it is used as an aggregate (Table 3).

**Table 3.** Harmonised European standards and possible limitations for RAP aggregates.

European Standard	Title	RAP Use [Y/N]	Possible Limitations for RAP Aggregates
EN 12620	Aggregates for concrete	Y	See Section 3.3 of this paper
EN 13055-1	Lightweight aggregates Part 1: Lightweight aggregates for concrete, mortar and grout	N	Not applicable (RAP density higher than that foreseen in the Scope)
EN 13055-2	Lightweight aggregates—Part 2: Lightweight aggregates for bituminous mixtures and surface treatments and for unbound and bound applications	N	Not applicable (RAP density higher than that foreseen in the Scope)
EN 13139	Aggregates for mortar	Y	<ul style="list-style-type: none"> <li>Aggregate size should be homogeneous.</li> <li>No references for recycled aggregates in total sulphur content.</li> <li>Setting speed should not exceed 120 min.</li> <li>Compressive strength of mortar specimen should not decrease more than 20% after 28 days.</li> </ul>
EN 13043	Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas	N	<ul style="list-style-type: none"> <li>Aggregate shape should be predominantly round for a better workability.</li> <li>Aggregates' affinity with bituminous binder.</li> <li>A clear definition of chemical composition and coarse contaminants is requested.</li> </ul>
EN 13242	Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction	Y	<ul style="list-style-type: none"> <li>Recycled aggregates should respect the maximum values for water soluble sulphate content.</li> <li>Setting speed should not exceed 120 min.</li> <li>Compressive strength of mortar specimen should not decrease more than 20%.</li> </ul>
EN 13450	Aggregates for railway ballast	Y	No limitations
EN 13383-1	Armourstone—Part 1: Specification	Y	No limitations

Among the other harmonised standards listed in Table 3, EN 13242 [54] specifies the properties of aggregates obtained through a natural or industrial process or recycled for unbound materials and bound with hydraulic binders, for use in civil engineering works and road construction. By analysing the requirements reported in the standard, attention should be paid to the aggregate size, the content of water-soluble sulphate and the content of organic material, the latter to be evaluated according to EN 1744-1 [65]. Furthermore, the percentage of aggregates should not influence the setting speed of the mortar by extending its time by more than 120 min and the compressive strength of the specimens should not decrease for more than 20% after 28 days, similarly to what is reported in EN 13139 [63]. As mentioned previously, a deeper experimental investigation should be conducted to analyse if the inclusion of RAP in the mix design as an aggregate could influence the setting speed of the mortar and the compressive strength of the specimens. The standard EN 13242 [54] is generally associated to EN 11531-1 [66], which gives more indications on the classification of soils, on the designation of aggregates and their unbound mixtures, and on the criteria for compliance verification when used in civil engineering works and road construction. The other standards reported in Table 3, including the use of recycled aggregates, do not present any particular limitation to the use of RAP in the construction of railways (EN 13450 [67]), or for protective works as armourstone (EN 13383-1 [68]).

When focusing on aggregates for concrete, EN 12620 [58] is the reference document for the characterisation and consequent CE marking of aggregates and EN 13055-1 [69] is the reference for lightweight aggregates for concrete. In Italy, the Technical Standard for Construction Works (NTC 2018 [70]), which is a national law, completely refers to EN

12620 [58] or EN 13055-1 [69] for the characterization of aggregates for structural concrete. If RAP aggregates do not fall in the scope of one of the two standards, it is not possible to apply them in structural concrete. Both standards give a description of the most important characteristics of the natural aggregate and, in particular, EN 12620 [58] covers aggregates having an oven-dried particle density greater than  $2.00 \text{ Mg/m}^3$  for all types of concrete, including concrete in conformity with EN 206 [71], concrete used in roads and in other pavements and for precast concrete products. Furthermore, regarding the recycled aggregate, EN allows wider range with densities higher than  $1.50 \text{ Mg/m}^3$ . The European standard EN 13055-1 [69] covers, instead, lightweight aggregates for concrete, i.e., aggregates having particle densities not exceeding  $2.00 \text{ Mg/m}^3$ . According to Chyne et al. [33], the bulk density of RAP aggregate falls between  $1.94 \text{ Mg/m}^3$  and  $2.30 \text{ Mg/m}^3$ , which therefore excludes the use of EN 13055-1 [69]. More details on EN 12620 are discussed later on in Section 3.3.

As seen, the cited standards, although they do not fully cover the RAP, give harmonised methods for the assessment of the properties of the aggregate that can serve as a basis for the characterisation of RAP aggregates. Generally, the majority of these standards include geometrical, physical and chemical properties and, specifically, specific gravity, water absorption, bulk density, abrasion resistance, crushing strength and impact resistance.

Studies have demonstrated that RAP aggregate has a lower specific gravity and water absorption [4]. A low specific gravity indicates a high porosity, which results in poor durability and a lower strength of concrete. Based on several research studies [1,6,38,72], impurities negatively influence RAP aggregates, especially in terms of water absorption. Moreover, a differentiation in fine and coarse aggregate is highly recommended to define the characteristics [23,73]. 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 [6,74,75]. Flaky and elongated aggregates could lead to the production of concrete with segregation and a poor surface finish, which will require a high cement and sand demand [6,74,75]. 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 [32,74,75]. For rough surfaces, the bond between cement and aggregates is strong and leads to good mechanical properties [32]. In the case of aggregates with smooth surfaces, it is necessary to wash it well and to clean the aggregates before use to avoid a poor bond between aggregates and cement [74,75]. 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 [4,8,16,44–46]. As an alternative to the crushing value, the aggregate impact value gives a relative measure of the resistance of an aggregate to a sudden shock or impact [33]. Properties like crushing, impact and abrasion resistance do not usually exceed the limits imposed by the standards expected for the use of recycled aggregates when compared to virgin aggregates, especially if they are used for concrete pavement applications [33]. According to Okafor [4], the British testing method prescribed in BS 812-3 [76] to determine the crushing and impact value for assessing the strength of aggregate is not suitable for RAP. A more adequate testing method should be developed to define the strength value of RAP in order to not overestimate or underestimate one of the most important characteristics of the RAP aggregate [4]. The same problem could be faced when the European testing method for crushing and impact value (EN 1097-2 [77]) is used, since it is comparable to that proposed by the British standard. Grading of aggregates is another important aspect as it influences various properties of concrete such as cohesion, water demand, workability, and strength [3,75]. RAP aggregates should be well graded and consistent in their grading, especially because gradation is related to the percentage of the substitution of natural aggregates by recycled aggregates in



concrete, which, in turn, it is strongly dependent on by the exposure class and the strength class of concrete for the majority of countries, as will be shown in the following sections.

### 3.3. Minimum Requirements in Italy for RAP Aggregates to Be Used in Concrete

As mentioned previously, the harmonised standard EN 12620 [58] contains all the essential characteristics with the relative test methods necessary for the assessment of aggregates for concrete. In Italy, the national law for construction (NTC 2018 [70]) imposes the use of this harmonised standard for the qualification of all types of aggregates and refers to the minimum requirements included in the national standards UNI 8520-1 [78] and UNI 8520-2 [79], which are strictly connected to EN 12620 [58]. The list of essential characteristics according to EN 12620 and the relative requirements set up by UNI 8520-1/2 [78,79] is reported in Table 4. Among all the essential characteristics reported in Table 4, a higher focus will be given to the most influential characteristics of the aggregates on the performance of concrete, i.e., the aggregate size, shape and density, resistance to fragmentation (crushing value), and water absorption. Other properties, like durability against freeze–thaw and volume stability, are surely important; however, no information has been found in the literature for RAP aggregates according to the European methods.

Starting from aggregate size, EN 12620 [58], in terms of coarse aggregates, requires respecting a ratio between the maximum sieve size ( $D$ ) and the minimum sieve size ( $d$ ) equal to 1.4. From the experimental data drawn up from literature [23], it can be noticed that this ratio is generally respected in RAP aggregates. Furthermore, it is known that the distribution of particle size becomes important when the aggregate is used in concrete and it influences its water demand, cohesion, bleeding and the segregation phenomena [75]. In the characteristics related to the grading analysis, it must be evidenced that in UNI 8520-2 [79] there are no references for recycled aggregates origins, which can be considered a limit when trying to prove the different grading size of the aggregate.

Aggregate shape is also decisive for workability. Rounded aggregates generally allow a better workability. For this reason, it is important to define the flakiness (FI) [80] and the shape index (SI) [81] of aggregates to prevent any workability issues like the production of concrete with segregation and high sand demand. Low values of FI indicates a low proportion of elongated aggregates, while high values of FI indicates a high proportion of elongated aggregates. Data from literature [6,44] evidence high variability and this is probably due to the origin of RAP. For this reason, and as it can be seen in Table 4, FI varies from 9% to 20%.

Aggregate specific gravity can be defined as the weight ratio between aggregate and water at similar volumes [6]. The specific gravity of aggregate will affect the value of density. In RAP materials that contain aggregate and aged bitumen, the density of RAP will be affected by their components and composition. It can be understood that the presence of aged bitumen will reduce RAP density. In UNI 8520-2 [79], in terms of density, there is a clear specification for recycled aggregates based on “type A” and “type B”, which differ from each other in the percentage content by mass. Generally, the minimum density requirement (in terms of oven-dried particle density) is  $1700 \text{ kg/m}^3$  and from the values reported in the papers analysed [3,6,23], RAP aggregates have a density between  $2186$  and  $2371 \text{ kg/m}^3$ . These results demonstrate that RAP density respects the minimum requirements established in Italy.

**Table 4.** Comparison between essential characteristics according to EN 12620, minimum requirements for application in Italy and experimental values from literature.

Essential Characteristics	Clause in EN 12620	Property	Testing Method	Symbol/Category	Italian Requirements (*) (UNI 8520-2)	NOTES (*)	Experimental Values from Literature
Particle shape, size and density	4.2	Aggregate size	EN 933-1 [56]	d/D	EN 12620 §4.2 [58] D/d ≥ 1.4 For concrete classes ≥ C12/15 at least 2 fractions of aggregates are necessary		D/d = 5.26 D/d = 21.2 [23]
	4.3	Grading	EN 933-1 [56]	G <sub>xx</sub>	For concrete classes ≥ C30/37 more than 2 fractions of aggregates are necessary		-
	4.4	Flakiness index	EN 933-3 [80]	FI <sub>xx</sub>	No specific limits (value defined in design phase)		20.73% [6] 9% [44]
		Shape index	EN 933-4 [81]	SI <sub>xx</sub>	No specific limits (value defined in design phase)		-
	5.5	Oven-dried particle density	EN 1097-6 [82]	ρ <sub>rd</sub>	Aggregate type A: ρ <sub>rd</sub> ≥ 2100 kg/m <sup>3</sup> Aggregate type B: ρ <sub>rd</sub> ≥ 1700 kg/m <sup>3</sup>	For RA, refer to oven-dried particle density ρ <sub>rd</sub>	2371 kg/m <sup>3</sup> (EN 1097-6) [3] 2186–2259 kg/m <sup>3</sup> (ASTM C127) [23] 2245 kg/m <sup>3</sup> (IS 2386-3) [6] (**)
5.6	Bulk density	EN 1097-3 [83]	ρ <sub>b</sub>	Not mentioned in UNI 8520-2 [79]		1940–2300 kg/m <sup>3</sup> [39]	
Cleanliness	4.6	Fines	EN 933-1 [56]	F <sub>xx</sub>	UNI 8520-2 Table 2 [79]	No indications for coarse RA	-
	4.5	Shell content	EN 933-7 [84]	SC <sub>xx</sub>	Not mentioned in UNI 8520-2 [79]	Not suitable for RAP	-
Resistance to fragmentation/crushing	5.2	Resistance to fragmentation	EN 1097-2 §5 [77]	LA <sub>xx</sub>	For R <sub>ck</sub> ≥ C50/60: category ≤ LA <sub>30</sub>	Testing method not suitable for RAP	28.1–29.6% (ASTM C131) [8,16] 24–27 (EN 1097-2) [44–46]
		Resistance to impact	EN 1097-2 §6 [77]	SZ <sub>xx</sub>	No specific limits	Testing method not suitable for RAP	4.3–33% [33]

Table 4. Cont.

Essential Characteristics	Clause in EN 12620	Property	Testing Method	Symbol/Category	Italian Requirements <sup>(*)</sup> (UNI 8520-2)	NOTES <sup>(*)</sup>	Experimental Values from Literature
Resistance to polishing/abrasion/wear	5.4.1	Resistance to polishing	EN 1097-8 [85]	PSV <sub>xx</sub>	No specific limits		50% [47]
	5.4.2	Resistance to surface abrasion	EN 1097-8 [85] Annex A	AAV <sub>xx</sub>	Option NR (no requirements) not admissible for concrete under abrasion. Minimum category defined by designer.		-
	5.3	Resistance to wear	EN 1097-1 [86]	MDV <sub>xx</sub>	Option NR (no requirements) not admissible for concrete under abrasion. Minimum category defined by designer.		-
Composition/content	8.1	Petrographic description (more consolidated for NA)	EN 932-3 [57]		Defined only for NA (UNI 8520-2 Table 1 [79])		*No declared values* No gypsum, amorphous silica or pyrite content in RAP used in [5].
	5.8	Constituents of coarse recycled aggregates	EN 933-11 [87]	% content	No specific limits		
	6.2	Water-soluble chloride ion content	EN 1744-1 §7 [65]	% content	Content ≤ 0.03%	For all types of aggregate	*No declared values* EN 12620 limitations satisfied according to [3].
		Acide-soluble chloride ion content	EN 1744-5 [88]	% content	Content ≤ 0.03%	For RA, content must be defined by designer	
	6.3.1	Acide-soluble sulfate	EN 1744-1 §12 [65]	AS <sub>xx</sub>	Value ≤ 0.2% [AS <sub>0,2</sub> ]		*No declared values* EN 12620 limitations satisfied according to [5].
	6.3.2	Total sulfur	EN 1097-6 [82]	S Declared value	No specific limits for RA	Only for NA and blastfurnace slags	

Table 4. Cont.

Essential Characteristics	Clause in EN 12620	Property	Testing Method	Symbol/Category	Italian Requirements <sup>(*)</sup> (UNI 8520-2)	NOTES <sup>(*)</sup>	Experimental Values from Literature
	6.3.3	Water-soluble sulfate	EN 1744-1 §10 [65]	SS <sub>xx</sub>	Value ≤ 0.2% [SS <sub>0.2</sub> ]	For RA	*No declared values* EN 12620 limitations satisfied according to [5].
	6.4.1	Constituents which alter the rate of setting and hardening of concrete - humus content - mortar specimen test	EN 1744-1 §15.1 [65] EN 1744-1 §15.3 [65]		Requirements of EN 12620 [58] §6.4.1 shall be satisfied: negative colorimetric tests or compliant results in mortar tests.		-
	G.4	Lightweight organic contaminators	EN 1744-1 §14.2 [65]		For ordinary concrete: ≤ 0.1% For concrete for aesthetic purpose and paving: < 0.05%		-
	6.4.1	Influence on initial setting time of cement (RA)	EN 1744-6 [89]	A	t <sub>e</sub> ≤ 10 min [A10]		-
Volume stability	5.7.2	Volume stability—drying shrinkage	EN 1367-4 [90]	% WS	No specific limits		-
	6.4.2	Dicalcium silicate disintegration	EN 1744-1 §19.1 [65]		Only for blastfurnace slag		-
	6.4.2	Iron disintegration	EN 1744-1 §19.2 [65]				
Water absorption	5.5	Expansion of steel slag	EN 1744-1 §19.3 [65]	V <sub>x</sub>	Only for blastfurnace slag		1.7–2.5% (EN 1097-6)
	5.5	Water absorption	EN 1097-6 [82]	WA <sub>24</sub> Declared value	For XF classes: WA <sub>24</sub> ≤ 1% For XF classes: If WA > 1% the class of resistance to freeze must be declared according to EN 1367-1		[3,44] 1.9–2.08% (ASTM C127) [8,23] 1.51% (IS 2386-3) [6]

Table 4. Cont.

Essential Characteristics	Clause in EN 12620	Property	Testing Method	Symbol/Category	Italian Requirements <sup>(*)</sup> (UNI 8520-2)	NOTES <sup>(*)</sup>	Experimental Values from Literature
Durability against freeze-thaw	5.7.1	Freeze-Thaw resistance	EN 1367-1 [91]	F <sub>xx</sub>	For XF classes: category $\leq$ F <sub>2</sub>		-
	5.7.1	Magnesium sulfate soundness	EN 1367-2 [92]	MS <sub>xx</sub>	For XF classes: Category $\leq$ MS <sub>25</sub>		-
	Not included in EN 12620	Freeze-Thaw resistance in the presence of salt (NaCl)	EN 1367-6 [93]	FEC <sub>xx</sub>	Category must be declared for XF2 and XF4		-
Resistance to polishing/abrasion/wear	5.4.3	Resistance to abrasion from studded tyres	EN 1097-9 [94]	AN <sub>xx</sub>	No specific limits		-
Durability against alkali-silica reactivity	5.7.3	Alkali-silica reactivity	UNI 8520-22 [95]		No limits for RA	UNI 8520-2 [79] Table 1 only refers to NA	-

<sup>(\*)</sup> NA= Natural Aggregates; RA= Recycled Aggregates <sup>(\*\*)</sup> When not directly provided,  $\rho_{rd}$  was calculated with the following formula:  $\rho_{rd} = \rho_{ssd} / (1 + WA/100)$ , where  $\rho_{ssd}$  represents the saturated and surface dried particle density and WA the water absorption in (%).

Another important aspect of aggregates is the resistance to fragmentation, determined in terms of the Los Angeles (LA) value, which corresponds to the percentage of the initial mass which has passed the 1.6 mm sieve after degradation in a horizontal drum for a specific number of revolutions (500). A low LA value indicates that the material has a high abrasion resistance. Conversely, a high LA value indicates that the material has a low abrasion resistance [8,16,44–46]. The binding requirement is when the aggregate is destined to be used in C50/60 concrete. In this case, the maximum LA value should be less or equal to  $LA_{30}$ , which means that the resistance to fragmentation expressed with the Los Angeles coefficient shall be  $LA \leq 30$ . When evaluated with EN 1097-2 [77], the range of LA values was shown to be between 24 and 27 [44–46]. However, the LA value is heavily dependent on the quality of RAP used, especially its origin, which suggests that an appropriate selection is required in order to avoid a weak mechanical performance. Experimental values evaluated in accordance with American standards (ASTM C131 [96]) were also analysed: the Los Angeles abrasion resistance value for coarse RAP was found to be less than 38%, which implies that RAP does not have a uniform hardness [97]. However, it has to be said that testing the resistance to fragmentation with different test method standards [98] can reveal different results, which may be not directly comparable.

As regards the study of composition/content in Coppola et al. [3], the petrographic analysis was conducted following EN 932-3 [57] and it showed no gypsum, amorphous silica or pyrite content in the RAP aggregate used. The chemical composition was also studied by Coppola [3] in terms of sulfate, sulfur and soluble chloride contents according to EN 1744-1 [65] and it was reported that the values were lower than the limits defined by EN 12620. However, the obtained values were not reported in this study, and therefore a direct comparison between the minimum requirements reported in UNI 8520-2 and chemical composition values was not possible.

The water absorption of aggregate represents the ability of RAP to absorb water and gives an idea of the strength of aggregate: a high value of water absorption indicates high porosity of the aggregate, which make it unsuitable for concrete, unless it is found to be acceptable based on other tests like strength, hardness and impact [75]. UNI 8520-2 [79] only gives indications on absorption when the exposure class is for freeze/thaw risk, requiring a further examination of freeze and thaw when the value of water absorption is higher than 1%. From the analysis conducted on RAP aggregates in different studies, it was shown that the lowest value of water absorption for RAP is 1.51% [6] when determined through the Indian IS standard method, while with American ASTM method the value falls between 1.9 and 0.08% [8,23]. When using the European method of testing, water absorption presents an even higher value, which is about 2.5% [3]. Specific gravity and water absorption can be found in the same list of essential characteristics of EN 12620 [58] and are both tested with European method 1097-6 [82]. This suggests that the European testing method might be more conservative than the other international testing methods.

Crossing all the information on aggregates for concrete that can be found in EN 12620 [58] and the minimum requirements for Italian standards described in UNI 8520-1/2 [52,53], that are enforced by the Italian law (NTC 2018 [70]), many characteristics are not fully covered by clear indications when it comes to recycled aggregates, even more so for a bituminous aggregate.

When a product is not covered or not fully covered by a harmonised standard, i.e., the performance in relation to its essential characteristics cannot be entirely assessed according to an existing harmonised standard, a possible solution for its qualification could be the drafting of a European Assessment Document (EAD). This document allows the CE marking of the product on the basis of a European Technical Assessment (ETA, see Section 3.2). Article 19 of CPR establishes the cases in which this can occur:

- absence of harmonised standard: the product does not fall within the scope of any existing harmonised standard;

- assessment method not adequate: for at least one of the essential characteristics of the product, the assessment method provided for the harmonised standard is not appropriate;
- absence of assessment method: the harmonised standard does not provide for any assessment method for at least one of the essential characteristics of the product.

For example, as mentioned previously in Section 3.2, the testing method for the evaluation of crushing resistance does not appear to be suitable for RAP aggregates, which therefore need to be studied in a deeper way in terms of essential characteristics and their assessment method. A specifically developed EAD could therefore indicate the cited characteristic and define a more adequate method for its assessment. In this way, a manufacturer can CE-mark its product and commercialize it in the European market.

In Italy, the qualification is mandatory for structural products and materials. As a matter of fact, according to Chapter 11 of NTC 2018 [70], structural products and materials must be qualified under the responsibility of manufacturers and three different situations can occur: (i) materials and products that, for the specific intended uses, fall in the scope of harmonised standards so that the CE marking is mandatory; (ii) materials and products whose qualifications can follow the procedures indicated in the standards itself (i.e., steel rebars or concrete, to cite some); (iii) materials and products which do not fall in the previous cases, and for which the manufacturer must CE-mark on the basis of the relative ETA or, equivalently, has to obtain a Certificate of Technical Assessment (CVT in Italian), the latter issued by the President of the Superior Council of Public Works, on the basis of specifically developed guidelines.

The development of an EAD could therefore be a possible way for material qualification if the use of RAP is foreseen for structural elements.

#### 4. Mechanical Behaviour of Concrete Containing RAP

Many studies (see Table 1) were conducted on concrete with RAP aggregates and with different percentages of substitution. It is well known that a higher substitution of natural aggregate with RAP aggregate influences the strength of concrete [19]. In the production of concrete for constructions, the RAP aggregates used are more likely to be coarse, since fine aggregates affect workability [21].

The results on fresh concrete show that both air content and unit weight of concrete mixes with RAP do not vary significantly with the RAP content percentage; slump slightly increases with increasing RAP content. In terms of workability, RAP aggregate mixes are easily mixed compared to natural aggregates ones and this is probably due to the presence of oil traces [3].

Hardened concrete characteristics were analysed in terms of compressive strength, flexural strength, split tensile strength and elasticity modulus, and the main results are shown in the following paragraphs.

##### 4.1. Compressive Strength

Different studies show that RAP has a negative influence on compressive strength: a higher percentage of substitution leads to a decrease in compressive strength [4,11,15]. Nevertheless, the use of 25–50% RAP coarse aggregate in high strength concrete mixture ensures compressive strengths in the range of 29.6–47.6 MPa [99]. In Okafor [4], compressive tests were conducted after 7, 28 and 90 days on two different mixes of concrete containing RAP aggregate (1:2:4 and 1:3:6 by weight of cement, sand and RAP aggregate with w/c ratios of 0.50, 0.60 and 0.70) and the compressive strength was in general lower than that of a reference concrete with no RAP, but with the same proportions of constituents at all ages. However, in all the cases studied, the compressive strength was increasing with age. The reduction was less for the mix 1:3:6, being on average 4.2 MPa the difference in strength for w/c = 0.50. Furthermore, by increasing the w/c ratio (from 0.50 to 0.70), the reduction of compressive strength between the concrete mix containing RAP aggregate and the reference concrete was even lower (1.5 MPa as average difference). Okafor also

observed that failure in the compression of RAP concretes was dominated by a breakdown in the bond between the aggregates and the attached old asphalt-mortar without any apparent crushing of the aggregate, while for the natural aggregate concretes of similar mixes, crushing of aggregate was more evident.

Hossiney et al. [23] confirmed the low influence of w/c ratios on compressive strengths, showing almost constant values at 0.43, 0.48 and 0.58 with 40% percentage of substitution of RAP.

From the analysis conducted, it may be inferred that the correlation of compressive strength of concrete with mechanical properties of aggregate is not very significant. The physical properties, like the void ratio and aggregate gradation, also have a very small correlation with compressive strength of concrete. On the contrary, the specific gravity of aggregates has a higher correlation with the compressive strength of concrete [15].

#### 4.2. Flexural Strength

Similarly to compressive strength, the flexural strength decreases as the content of RAP increases. According to Hossiney et al. [23], the percentage of reduction in flexural strength of the concrete containing RAP is lower than the corresponding percentage of reduction in compressive strength: a mix containing 40% RAP and w/c equal to 0.53 exhibits a reduction of 37% if compared to a mix containing virgin aggregates, while in terms of compressive strength, the same mix showed a reduction of 52% (values at 28 days). According to Okafor [4], flexural strength values of a concrete mix containing RAP is lower than that of a reference concrete (28% lower on average at 28 days). Moreover, it was noticed that the increase in w/c did not result in any significant effects on flexural strength, due to the fact that the bond strength of the asphalt-mortar attached to the aggregate, which is directly related to the flexural strength, and remained unchanged [4]. This was also confirmed by the studies of [23].

In another type of application where RAP was used as a coarse aggregate for a pavement quality concrete, Paluri et al. [27] noticed that a concrete with up to 30% of RAP aggregate had a flexural strength higher than 4.5 MPa, which is the minimum required for flexural strength of pavement concrete according to the IS Standards [100] to avoid both rheological and mechanical underperformance.

According to Coppola [3], with the 20% RAP aggregate, although the concrete flexural strength was 14% lower than the mix without RAP, the flexural toughness was 48% higher compared to that of standard concrete.

#### 4.3. Modulus of Elasticity and Splitting Tensile Strength

The percentage of substitution of natural aggregates by RAP aggregate also influences the modulus of elasticity: by increasing the percentage of substitution, the modulus of elasticity decreases. The variations of w/c ratios are limited by the fact that the modulus of elasticity is sensitive to the increase in the w/c ratio [3]. The higher the RAP replacement, the lower the Young's modulus. However, studies demonstrate that by reducing the w/c ratio (from 0.53 to 0.45) [3], it is possible to achieve a similar Young's modulus between concrete, with a 15% substitution of RAP and a reference concrete with no RAP.

Similarly to the other mechanical parameters, splitting tensile strength was also investigated and it can be demonstrated that an increase in RAP content causes a decrease in splitting tensile strength [11,16,23]. The rate of strength reduction in the split tensile strength for RAP mixtures can be significantly lower than that of the compressive strength [11]. After 28 days, the reduction of compressive strength of concrete containing RAP was 58.7% of that of the reference concrete, while the reduction in the split tensile strength was 95.3% [11].

#### 4.4. Durability

The implementation of RAP in concrete needs to be investigated from another perspective, which is its intended use in buildings: is RAP concrete suitable for structural



applications or does the strength reduction limit it to non-structural applications? Recent research [5] suggests that RAP concrete may retain sufficient strength for structural applications if high strength concrete mixture designs are used. For high strength concrete applications, durability must be proven, and an evaluation of Alkali Silica Reactivity (ASR), chloride permeability, freeze–thaw durability, and coefficient of thermal expansion is essential.

In terms of concrete durability, ASR is considered a deleterious reaction between the alkaline pore solution of concrete and various metastable forms of silica contained in aggregates [101]. In particular, ASR of RAP aggregate has been investigated by Berry et al. [49] by using the methods reported in ASTM C1260 [102]. In this standard, ASR is studied in terms of the expansion of mortar bars at 80 °C at 14 days and an expansion of more than 0.20 percent is considered potentially deleterious [49]. From the results reported in [49], the expansion of the bars was around 0.23 percent, therefore exceeding the limit posed by the standard. However, it must be said that during the testing phase, the elevated temperature affected the bituminous material on the RAP aggregates by causing its stripping from the exterior of the mortar bars and the formation of a slick on the top of the solution [49]. For this reason, ASTM C1260 [102] results are a poor indicator of ASR vulnerability for RAP aggregates. Similarly, Brand et al. [48] reported that the expansion is due to the elevated temperature in the NaOH solution and in order to mitigate this expansion, multiple solutions, such as the use of supplementary cementitious materials and/or a low-alkali cement, should be considered [48]. However, according to Brand et al. [48], the test for ASR revealed that RAP aggregates were non-reactive. Furthermore, in [33,39], it was reported that thanks to an increase in the RAP binder content, which causes an increase in viscosity, it was possible to reduce the alkali–silica reactions in RAP aggregates.

Chloride permeability is a function of porosity and pore connectivity, and, specifically, low porosity and limited pore connectivity reduces the diffusion of chlorides into the concrete matrix. The permeability of asphalt is much higher than that of even low-quality concrete [5]. This could be problematic if the concrete obtained with the utilization of RAP is destined to be coupled with steel reinforcement, since the inclusion of RAP could limit the resistance to chloride permeability [5]. However, results reported by [5] indicate that the chloride permeability of high strength concrete, estimated by surface resistivity using a Wenner array probe in accordance with the specifications of AASHTO TP 95 [103], is unaffected by the replacement of up to 50% of natural coarse aggregate with RAP [5].

Unlike chloride permeability, freeze–thaw durability in concrete is a function of the pore structure [5]; specifically, good freeze–thaw durability requires pores of sufficient size and connectivity to allow pore water to expand as it freezes without exerting pressure on the matrix. Air voids facilitate the expansion of pore water, which provides a great resistance of concrete to freezing and thawing. The presence of RAP aggregates improves freeze and thaw resistance to a limited degree, because RAP is not distributed in a uniform way and spacing remains too large for any significant improvement in freeze–thaw durability [5]. Brand et al. [48] reported that an excellent freeze–thaw durability is exhibited for normal concrete with 0 and 20% RAP coarse aggregate, while Berry et al. [49] showed a reduced freeze–thaw durability when the percentage of RAP was increased from 50% to 100%. The optimal RAP percentage of replacement in terms of freeze–thaw durability for high strength concrete is instead 35% by mass [5].

The coefficient of thermal expansion of concrete has a significant influence on the opening and closing of construction joints and it is therefore of interest in transportation infrastructures. Asphalt materials have a high thermal expansion, which could lead to a high coefficient of thermal expansion of concrete containing RAP. Hossiney et al. [23] determined coefficients of thermal expansion for normal strength concrete with RAP coarse aggregate, and reported an increase of up to 10% when 40% of virgin coarse aggregate was replaced with RAP. According to Thomas [5], the coefficient of thermal expansion of high strength concrete is minimally affected by the replacement of up to 50% of natural coarse

aggregate with RAP. With 35–40% RAP, the coefficient of thermal expansion is higher than the high strength concrete, with 100% of natural aggregate.

In [5], other parameters, such as the initial rate of absorption and capillary absorption coefficient, were studied and the results demonstrate that these parameters decrease with the increase in RAP aggregate content: both the initial rate of absorption and capillary absorption decreased by 50% for a mix containing 75% of RAP in relation with a mix with only virgin aggregates. A decrease in sorptivity parameters is due to the clogging of pores with drying before the absorption process.

An investigation into durability is essential to define the possible behaviour of concrete if coupled with steel reinforcement or used under critical temperature conditions, in order to define the most suitable applications: further studies are therefore needed to cover the gaps found in the literature.

#### 4.5. Influence of the Percentage of Substitution of RAP on the Mechanical Properties of Concrete

The percentage of substitution of natural aggregate by RAP aggregate plays a major role in the quality of hardened concrete, because it influences its mechanical characteristics, as was largely discussed in the previous sections. By increasing the percentage of substitution, most of the mechanical parameters of concrete decreases consequently. However, it must be said that there are standard limitations to the percentage of the replacement of natural aggregates by bituminous aggregates. These limitations are mentioned in EN 206, Annex E [71], which includes the percentage of substitution as a function of the concrete exposure class for the two types of aggregates defined by EN 12620 (Type A and Type B, see Section 3.3).

Table 5 shows the percentage of substitution according to EN 206 as a function of the type of aggregate, the aggregate size and the concrete exposure class. For an aggressive class of exposure, the percentage of substitution is zero.

**Table 5.** Percentage of substitution of natural aggregate by bituminous aggregates ( $R_{a1}$ ,  $R_{a5}$ ) according to EN 206 as a function of the exposure class.

Reference Standard	Aggregate Type	Aggregate Size	Exposure Class			
			X0	XC1, XC2	XC3, XC4, XF1, XA1, XD1	All Other Exposure Classes <sup>(a)</sup>
EN 206:2021	Type A <sup>(a)</sup> ( $R_{a1-}$ )	$\geq 4$ mm	50%	30%	30%	0%
	Type B <sup>(b)</sup> ( $R_{a5-}$ )	$\geq 4$ mm	50%	20%	0%	0%

<sup>(a)</sup> Type A recycled aggregates from a known source may be used in exposure classes, to which the original concrete was designed with a maximum percentage of replacement of 30%. <sup>(b)</sup> Type B recycled aggregates should not be used in concrete with a compressive strength  $> C30/37$ .

In Germany, the percentage of substitution is defined, similarly to EN 206, as a function of the aggregate type, aggregate size and the concrete exposure class (see Table 6). The German Code of Practice (DAfStb Guideline [104]) allows us to use a maximum of 45% of the total aggregates as recycled aggregates larger than 2 mm for concretes with a strength class lower than C30/37. By comparing what is reported in EN 206 and the percentages allowed in Germany, it may be noticed that for the same type of aggregate and in the same class of exposure, the percentage is higher. This allows us to affirm that in Germany, the limitations on the use of bituminous aggregate are less restrictive.

**Table 6.** Percentage of substitution of natural aggregate by bituminous aggregates in Germany.

Country	Aggregate Type	Aggregate Size	Exposure Class		
			WO, XC1 WF, XC1-XC4	WF, XF1, XF3	WF, XA1
Germany	Type 1 <sup>(a)</sup> ( $R_{a1-}$ )	$\geq 2$ mm	45%	35%	25%
	Type 2 <sup>(b)</sup> ( $R_{a1-}$ )	$\geq 2$ mm	35%	20%	25%

<sup>(a)</sup> Type 1: concrete chippings. <sup>(b)</sup> Type 2: building chippings.

Table 7 reports the percentages of substitution for the United Kingdom, as a function of the class of use of concrete and the class of resistance of concrete. The classification is also based on the class of use of concrete. The use of 100% replacement is allowed for concretes with a strength class lower than C16/20 and a maximum of 20% is allowed for concrete used in reinforced or prestressed concrete. In the remaining uses, the percentage of replacement allowed is zero. In the British standards, it was observed that the recycled aggregates referred to are grouped in two different categories: recycled concrete aggregate (RCA) and recycled aggregate (RA), which includes bituminous aggregates. There is not a clear distinction based on the origin of the aggregates.

**Table 7.** Percentage of substitution according to British standards (BS 8500-2) [105].

Type of Aggregate	Class of Use of Concrete	Types of Class of Use of Concrete	Class of Resistance of Concrete	Percentage of Substitution of Aggregates	Applications
RA	GEN	GEN 0	C6/8	100%	Trench fill, unreinforced
		GEN 1	C8/10		
		GEN 2	C12/15		
		GEN 3	C16/20		
	RC	RC20/25	C20/25	20%	Reinforced concrete
		RC25/30	C25/30		
		RC28/35	C28/35		
		RC30/37	C30/37		
		RC32/40	C32/40		
		RC35/45	C35/45		
	RC40/50	C40/50	0%		
FND		FND2	C25/30	0%	Foundation in aggressive ground
		FND2Z	C25/30		
		FND3	C25/30		
		FND3Z	C25/30		
		FND4	C25/30		
		FND4Z	C25/30		
		FND4M	C25/30		

Additional specification requirements and permitted applications to be assessed on a case-by-case basis.

In Italy, the Technical Standards for Construction Works (NTC 2018 [70]) do not give indication on the percentage of substitution of aggregates originated from recycled asphalt: the document only refers to waste coming from demolition and the waste of concrete. Furthermore, as was said before, the standard refers generally to the harmonised European standard EN 12620 for the qualification of coarse recycled aggregate for concrete.

Differently to the NTC 2018, the previous version of the standard published in 2008 (NTC 08 [106]) referred clearly to EN 8520-1/2 [78,79] in the definition of additional chemical and physical requirements that recycled aggregate should respect in the function of the intended use of concrete, the maximum percentage of substitution and the class of resistance of concrete. In particular, for the maximum percentage of substitution, EN 8520-2 refers to UNI 11104 [107] for additional information compared to those reported directly in NTC 08. The additional information on recycled aggregate is currently missing in the new standard NTC 2018 and the reference to UNI 11104 can only be inferred because EN 8520-2 is only considered a useful reference by NTC 2018. Therefore, it cannot be certainly said whether UNI 11104 is a mandatory reference and therefore a regulatory gap exists in the current law which should be further investigated.

Despite the issue just evidenced, the percentage of replacement indicated in UNI 11104 is a function of the type of aggregate, the class of resistance of concrete and the class of exposure (Table 8). The use of 100% replacement is allowed for concretes with a strength class lower than C8/10. If one refers to UNI 11104 to define the percentage

of substitution, the Italian limitations are more restrictive than the European ones: for example, the maximum percentage of substitution for a concrete with a class of resistance lower or equal to C30/37 and an exposure class X0 is 30% for UNI 11104 [107] while it can reach 50% for European standard when a “type A” aggregate is used. Experimental studies are needed in support of a possible use of a higher percentage of substitution than what is indicated in the Standards to take advantage of RAP aggregates and to avoid the deposition of unused material that could fit the minimum requirements requested in concrete.

**Table 8.** Maximum percentage of substitution in Italy (UNI 11104).

Country	Type of Aggregate	Class of Resistance	X0	XC1 XC2XC3	XC4	XS1	XS2XS3	XD1	XD2	XD3	XF1	XF2XF3XF4	XA1	XA2	XA3
Italy	Type A (Ra <sub>1</sub> -)	≥C12/15	60%	–	–	–	–	–	–	–	–	–	–	–	–
		≤C20/25	30%	30%	–	–	–	20%	–	–	–	20%	20%	–	–
		≤C30/37	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
	Type A, B (Ra <sub>1</sub> - and Ra <sub>5</sub> -)	≤C45/55	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
		C8/10						100%							

## 5. Discussion and Conclusions

In this paper, an overview on RAP aggregate as a possible substitute for natural aggregates in structural concrete is given. The analysis of the studied papers evidenced that nowadays it is more likely to use RAP in asphalt mixes for road and pavements, rather than as an aggregate in concrete mixtures for buildings. Beyond the mechanical limitations that include the decrease of parameters such as compressive strength, flexural strength, splitting tensile strength and modulus of elasticity as the percentage of replacement of RAP increases, the main reason behind the limited use of RAP as a recycled aggregate in concrete is due to the multiple barriers, mainly related to the existing Standards which are enforced by national laws and are generally developed for natural or the most-known recycled aggregates. Despite the Italian and European legislation pushes towards the prudent and rational use of environmental resources, bureaucracy and prejudice of technicians and designers still hinder the development of asphalt recycling, therefore limiting its use. From the study carried out into the limitations on the use of RAP, it is clear that a major investigation on RAP is required to deepen the knowledge in the following aspects:

- The chemical composition of RAP shall be given in order to have a better knowledge of the constituents that have a certain influence on its mechanical performance.
- While applying the existing test methods, their reliability when used to study the characteristics of RAP aggregates shall be assessed: as showed in the paper, some test methods foreseen by standards are indeed not fully suitable for RA and therefore RAP (e.g., crushing and impact testing method, leaching test, petrographic description).
- The inclusion of RAP in standards must be revised, as it was observed that a gap in the inclusion of bituminous aggregate is present and recycled aggregates are not fully covered by some standards.
- If used in concrete for buildings, RAP durability shall be investigated to have a better indication of the possible use of concrete containing RAP, especially if coupled with steel and if used in critical conditions.
- Further experimental studies on the percentage of substitution in concrete are needed to verify the limitations indicated in the standards with respect to the maximum percentage of replacement of natural aggregate by recycled aggregates allowed nowadays, and also as a function of the concrete exposure class.
- In Italy, the use of RAP as a recycled aggregate is definitely more limited due to various restrictions imposed by current laws.

A possible solution to the different barriers encountered could be the development of a European Assessment Document (EAD) that includes essential characteristics not completely covered by European harmonised standards and suitable assessment methods for RAP, or new essential characteristics not foreseen by current standards. Starting from a deeper study of the material, which is indeed needed to cover some of the aspects already

analysed, the document could help to overcome some of the limitations and could pave the way for a real exploitation of RAP aggregate in the construction sector.

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