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The Impact of Recycled Concrete Aggregate on the Stiffness, Fatigue, and Low-Temperature Performance of Asphalt Mixtures for Road Construction

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Abstract: The need for road (re)construction materials is constantly growing. At the same time, there is a limited quantity of new, high-quality materials available and a buildup of secondary/recycled construction materials. One possible solution may be the use of recycled concrete aggregate (RCA) in asphalt mixtures instead of natural aggregate (NA), which also promotes economic and environmental sustainability. The potential use of fine and coarse RCA in road asphalt mixtures is analyzed in this work. Nine asphalt mixtures were tested for base course layers, where RCA was used as a NA substitute. The impact of the quantity of RCA (up to 45% by mass) on the resulting physical and mechanical properties of asphalt mixtures was investigated, and consequently compared with the properties of a reference control mixture produced with NA only. Results reveal that the addition of RCA requires higher bitumen in comparison to the control mixture (up to 1%). Consequently, mixtures with RCA had 15–20% lower stiffness and up to 26% higher critical fatigue strain value (ε_6). Although RCA mixtures contained more bitumen, their low-temperature resistance was slightly inferior compared with the control mixture (failure temperatures were up to 4.3 °C higher). In conclusion, asphalt mixtures with up to 45% RCA can be used without substantially reducing performance.

Keywords: asphalt mixture; recycled concrete aggregate; complex modulus; fatigue resistance; low-temperature resistance

1. Introduction

Each year, more than 26 billion tons of natural aggregate are consumed by the construction industry worldwide [1]. The European production of primary aggregates (sand, gravel, and crushed rock) is estimated to be around 2.3 billion tons annually [2]. Over time, this high degree of consumption will inevitably lead towards a deficiency of natural high-quality aggregate—a problem that is already present in many countries, especially in highly developed urban areas (e.g., the Netherlands imports natural aggregate). At the same time, construction and demolition (C&D) waste disposal is becoming an increasing global challenge.

A reasonable starting point in resolving these problems is seen in recycling C&D waste, especially demolished concrete waste, referred to as recycled concrete aggregate (RCA). The rate of C&D waste recycling in European countries varies widely; Denmark, the Netherlands, Estonia, and Germany recycle over 80% of their C&D waste, while some countries reuse less than 10% [3], and for others appropriate data are not even available.

Considering that the European production of hot and warm mix asphalt in 2017 was equal to 296.7 million tons [4] and that asphalt concrete typically consists of 90–95% aggregate (by weight), there is great potential for the application of RCA in asphalt road mixtures.

Any demolished concrete waste can be successfully utilized, assuming that the necessary crushing, cleaning, and sieving are done properly. In general, RCA has the same macrostructure as its parent concrete, consisting of two phases: the cementitious matrix and the natural aggregate particles. Previous studies have confirmed that the cementitious matrix has a higher porosity than natural aggregate, which is the main cause of a number of unfavorable properties of RCA: lower density and higher water absorption, reduced mechanical properties [5,6], increased fine particles content, and higher Los Angeles (LA) coefficient [7]. In spite of this, there are some advantages from the concrete crushing process, such as the particularly rough surface texture, sharp edges, and favorable shape of RCA particles [8]. In general, these properties of RCA lead to improved interaction and increased surface friction between the aggregate particles, as proven by El-Tahan et al. [9]. Natural aggregate exhibits a significantly lower specific surface compared with RCA, as shown by scanning electron microscopy results [10]. The increased specific surface of RCA and the presence of the porous cementitious matrix are the main reasons for increased water/bitumen absorption in comparison with natural aggregate.

RCA is typically used for cement concrete production as a substitute for natural aggregate, but also for unbound base and sub-base layers and for soil stabilization [11]. Recently, the application of RCA in asphalt mixtures has been gaining more attention. However, the relevant research has mostly focused on the impact of RCA quantity and particle size distribution on the optimum bitumen content (OBC), as well as on the water sensitivity [9,12–14], stiffness [15–17], and rutting of asphalt mixtures [13,16,18].

Several previous studies have demonstrated a correlation between the quantity of RCA used in asphalt mixtures and the OBC value. Generally, a higher RCA content leads to a higher OBC in asphalt mixtures because of the porous structure of RCA particles. The current experience regarding the use of RCA in asphalt mixtures shows that the maximum particle size and the percentage of applied RCA are two key factors influencing asphalt mixture stiffness. Wong et al. [19,20] showed that the stiffness of asphalt mixtures made with 100% fine RCA (particle diameter $\leq$ 4.75 mm) was higher than the stiffness of the control mixture. However, the substitution of coarse natural aggregate (particle diameter > 4.75 mm) with RCA decreased the stiffness of the asphalt mixtures [20,21], in contrast to the results obtained by Alvarez et al. [15]. As far as the mixtures with a total natural aggregate substitution (both fine and coarse RCA) are concerned, the higher RCA content decreased the stiffness of asphalt mixtures [18,22,23]. In their study, Wong et al. [19] reported that the application of a filler originating from RCA did not significantly influence the asphalt mixture stiffness. Additionally, Nwakaire et al. [24] used RCA obtained from high-quality concrete (with a compressive strength of 60 MPa) and concluded that, beyond 40% RCA, the resilient modulus decreased sequentially.

When considering fatigue resistance, the results of previous studies [10,20,25–27] indicate that the addition of RCA as a filler or fine aggregate ($\leq$4.75 mm) improved fatigue resistance, whereas mixtures with full replacement of natural aggregate with RCA, and those with partial replacement with coarse RCA, had poorer fatigue resistance than the control mixtures.

Pérez et al. [28], Wu et al. [29], Bhusal and Wen [17], and Hou et al. [14] concluded that adding RCA decreases the fatigue resistance of asphalt mixtures, regardless of the type. Contrary to these conclusions, Pasandín and Pérez [30] found that the fatigue resistance of a base course mixture made with RCA performed better than a control mixture made with natural aggregate. The same conclusion was made by Nwakaire et al. [24], who tested a stone mastic asphalt mixture, attributing its behavior to the higher OBC of RCA mixtures when compared to the control mixture. The effect of coarse RCA (>4.75 mm) on the fatigue resistance of asphalt layers was also investigated by Pasandín and Pérez.

The authors tested a control mixture against mixtures with 5%, 10%, 20%, or 30% RCA. In order to improve the RCA quality, the RCA was heated for 4 h at a temperature of 170 °C [31], or coated with a bitumen emulsion before mixing the asphalt [32]. The obtained results revealed that the amount of RCA used did not significantly affect the asphalt fatigue resistance.

So far, only a limited number of studies have examined the low-temperature cracking resistance of asphalt mixtures with RCA. Bhusal and Wen [17] carried out indirect tensile tests (IDTs) at a temperature of −10 °C and at a controlled displacement rate of 50.8 mm/min. Tests were performed on asphalt mixtures for wearing courses, containing 0–100% RCA. The results showed that a greater RCA content decreased the tensile strength, obtained by using IDT. Other authors [10,33,34] demonstrated that the addition of RCA decreased the low-temperature cracking resistance of base course asphalt mixtures. The three-point bending test was performed on 250 × 30 × 35 mm beams at a temperature of −10 °C and a controlled displacement rate of 50 mm/min. Contrary to this, Sun et al. [26] concluded that adding fine RCA improved low-temperature cracking resistance. Zhang et al. [35] also showed that the fracture load of asphalt mixtures made with up to 50% coarse RCA, obtained from low-strength concrete, increased at a temperature of 0 °C.

After reviewing the relevant research studies, it is evident to us that the RCA content and particle size distribution have a crucial impact on the performance of asphalt mixtures. In most studies, the stiffness of asphalt mixtures for wearing courses was determined by including only a combination of fine and coarse RCA. A significantly smaller number of studies were focused on asphalt mixtures for base courses, made with either fine or coarse RCA. Furthermore, there is limited research available on testing the fatigue and low-temperature cracking resistance of asphalt mixtures containing RCA.

In view of this, the main research objective of this study was to evaluate the application of RCA in road asphalt mixtures. In this regard, the impact of RCA quantity and particle size distribution (i.e., the replacement of conventional aggregate with coarse RCA, with fine RCA, and with both coarse and fine RCA) on the physical and mechanical properties of road asphalt mixtures is investigated, in particular RCA effects on stiffness, fatigue, and low-temperature cracking resistance.

2. Materials and Test Methods

A conventional asphalt mixture used for base course layers of the type AC 22 base 50/70 was selected for this study, enabling lower bitumen content and higher possible RCA content compared with conventional asphalt wearing course mixtures. The other reason for this selection was the less strict technical requirements for base course materials, since RCA's mechanical properties were expected to be poorer than those of natural crushed aggregate (NA).

2.1. Material Composition and Sample Preparation

RCA used in this study was obtained from concrete slabs that were replaced during the renovation of a tram rail substructure. The slabs were covered by an asphalt top layer, which protected them from environmental impact and slowed down the carbonation process, resulting in a relatively high pH value (10.7 and 11.8 for fractions 4/8 mm and 8/16 mm, respectively, according to EN 16192:2013/EN 12457(1−4):2008. After more than three decades of service life, the reclaimed concrete still had considerable mechanical properties (the cores taken from the structure were of compressive strength class C35/45) and high purity: after the crushing and separation processes, the obtained RCA contained 98% concrete, 1.2% asphalt, and 0.8% brick debris.

The control mixture, denoted as E, contained mineral filler (5%), 0/4 mm (41%), 4/8 mm (15%), 8/16 mm (24%), and 16/22.4 mm (15%) NA fractions. The final aggregate particle size distribution curve, as well as curves of RCA and NA fractions used in this study, are displayed in Figure 1. For all the mixtures prepared in this study, natural crushed limestone was used as the virgin aggregate.

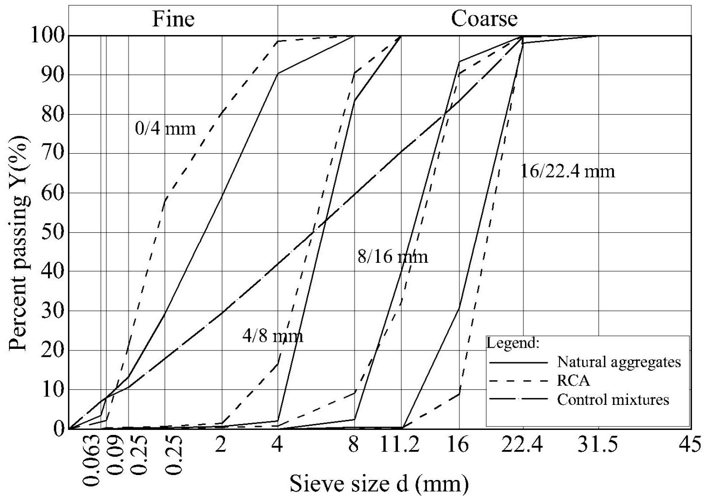

Figure 1. Particle size distribution curves of final aggregate mixture, RCA, and NA fractions.

The particle size distribution of the asphalt mixtures with RCA was approximately the same as for the control mixture. The physical and mechanical properties of the aggregates used are shown in Table 1. As expected, RCA had lower density, lower resistance to crushing, and inferior abrasion characteristics, but significantly higher water absorption values compared with the natural aggregate. However, the equivalent value of the LA coefficient was lower than 30, even for the aggregate mixtures with the highest RCA content, which meets the technical specifications for bituminous base layers for medium traffic loading [36].

Table 1. Physical and mechanical properties of aggregates.

Test	Standard	Unit	RCA		NA	
			Fine	Coarse	Fine	Coarse
Apparent specific gravity	EN 1097-6	(kg/m^3)	2645	2667	2717	2743
Bulk specific gravity SSD		(kg/m^3)	2512	2532	2650	2731
Bulk specific gravity		(kg/m^3)	2430	2450	2580	2724
Water absorption		(%)	3.4	3.2	0.4	0.2
Los Angeles abrasion	EN 1097-2	(%)	-	31.5	-	26.1

Limestone filler and plain bitumen of the type 50/70 were used in all asphalt mixtures.

The quantity of RCA was set to a maximum of 45% of the aggregate mixture, in order to limit the potential influence of RCA's inferior mechanical properties on the performance of asphalt mixtures. Additionally, the need for an excessive increase in the bitumen content was avoided. As can be seen from Figure 2, nine asphalt mixtures containing RCA were divided into three groups. In the first group, only fine RCA (0/4 mm) was used, whereas in the second group only the coarse aggregate (4/22.4 mm) was used. The third group included mixtures with a combination of both fine and coarse aggregate. Each of the first three groups was additionally divided into three subgroups, including 15%, 30%, or 45% RCA. All asphalt mixtures were labeled accordingly: for example, label F-45 describes the asphalt mixture in which 45% of fine NA (41% of 0/4 mm fraction) was substituted by RCA, giving a replacement rate of 18.5% in the final mixture. The total RCA contents in mineral aggregate mixtures are shown in Table 2.

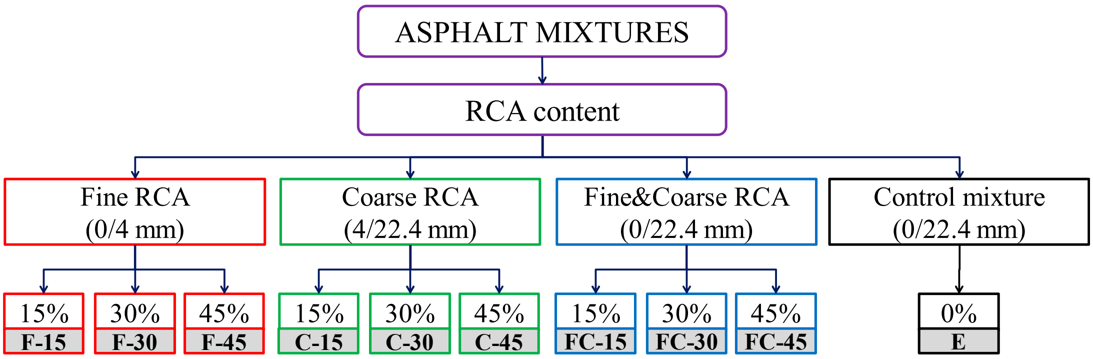

Figure 2. Labels of asphalt mixtures.

Table 2. Total RCA content in mineral aggregate mixtures.

Mix	E	F-15	F-30	F-45	C-15	C-30	C-45	FC-15	FC-30	FC-45
RCA (%)	0	6.2	12.3	18.5	8.9	17.7	26.6	15	30	45

The optimum bitumen content (OBC) of each mixture was obtained by performing the Marshall mix design procedure (European Standard EN 12697–34:2012) at a temperature of 150 °C and with a compaction energy of 2 × 50 blows. The target air void content was set to 5.2%, which allowed for the comparison of OBC obtained for different mixtures. The volumetric properties of asphalt mixtures are given in Table 3. It can be concluded that a higher amount of RCA resulted in a higher OBC, as a consequence of the higher porosity and surface area of RCA (Figure 3). This trend is more noticeable in mixtures with fine RCA (F mixtures), then in mixtures with coarse RCA (C mixtures). As expected, the highest OBC values were found for asphalt mixtures, with the highest RCA content in the final asphalt mixture (FC mixtures). The higher porosity and surface area of RCA resulted in a decrease in the effective bitumen content involved in the coating of aggregate particles. Consequently, air voids increased, whereas voids in mineral aggregate and voids filled with bitumen decreased [22,37,38]. Considering that the quantity of bitumen absorbed by the aggregate is equal to approximately half of the water absorbed [39] (Table 1), the effective bitumen contents were estimated (Table 3) based on the water absorption (Table 1) and RCA content (Table 2).

Table 3. Volumetric properties of asphalt mixtures.

Mixture Type	Optimum Bitumen Content	Air Voids	Voids in Mineral Aggregate	Voids Filled with Bitumen	Effective Bitumen Content
	OBC	AV	VMA	VFB	(%)
	(%)	(%)	(%)	(%)	
E	3.4	5.2	13.5	61.0	3.26
F-15	3.5	4.9	13.4	63.2	3.27
F-30	3.5	4.6	13.0	64.9	3.18
F-45	3.6	5.4	14.0	61.1	3.18
C-15	3.4	5.0	13.2	61.9	3.13
C-30	3.5	5.6	14.0	59.6	3.10
C-45	3.5	5.4	13.8	60.6	2.97
FC-15	3.6	5.3	13.9	62.1	3.24
FC-30	3.9	5.4	14.7	63.0	3.32
FC-45	4.4	4.5	15.0	69.6	3.60
Specification [36]		3–6	N/A	55–74	

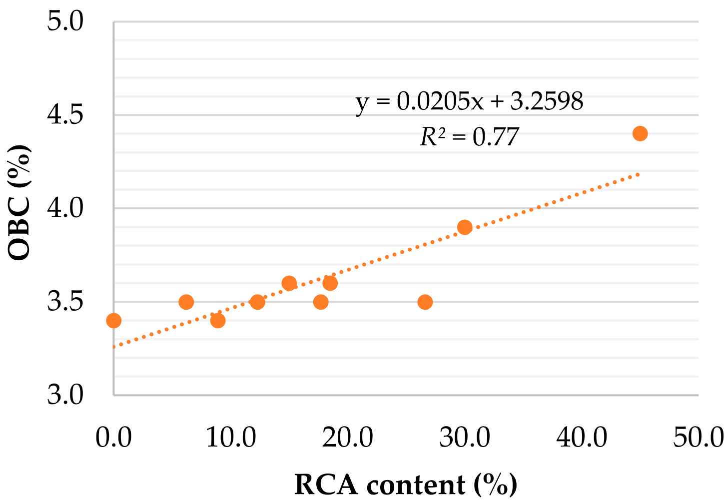

Figure 3. Optimum bitumen content as a function of RCA content.

After the mixing process, all mixtures were preheated prior to the compaction at a temperature of 170 °C for 90 min. Subsequently, they were compacted in a specially prepared polygon, using a one-ton roller compactor (see Figure 4). From the asphalt mixture slabs (500 × 500 × 70 mm), prismatic specimens were cut with final dimensions of 50 × 60 × 400 mm for stiffness and fatigue resistance determination, and of 50 × 50 × 160 mm for low-temperature cracking resistance.

Figure 4. Asphalt mixture laying and compaction.

2.2. Complex Modulus and Fatigue Resistance Determination

The complex modulus and the fatigue resistance of the asphalt mixtures were tested by using a four-point bending beam test (4PBB) in strain-controlled mode, according to European Standards EN 12697–26:2018, Annex B, and EN 12697–24:2018, Annex D, respectively (see Figure 5).

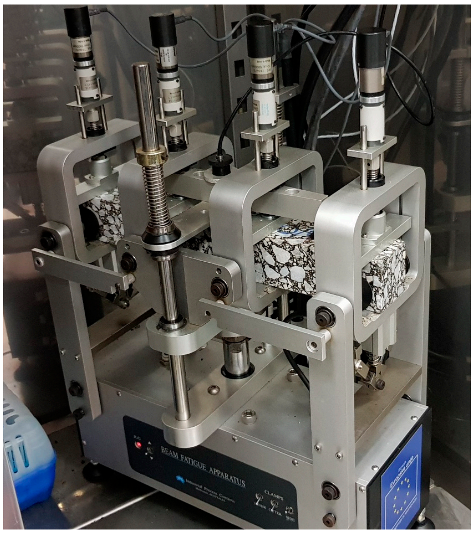

Figure 5. 4PBB device used for complex modulus and fatigue testing.

The complex modulus values were measured using a constant strain amplitude of 50 µm/m at several test temperatures (5 °C, 15 °C, or 25 °C) and frequencies (0.1, 1, 5, 8, or 10 Hz).

A strain-controlled fatigue test was performed at three different strain amplitudes (130, 200, and 300 µm/m), at a single temperature of 20 °C and at a fixed frequency of 10 Hz, according to European Standard EN 12697−24:2018. Before being loaded, the specimens were conditioned for 2 h at a constant testing temperature. To determine the number of loading cycles until failure, the conventional failure criterion was adopted (EN 12697−24:2018), i.e., when a 50% decrease in the initial complex modulus (measured after 100 loading cycles) occurs.

In order to obtain the fatigue functions for all tested mixtures, three strain amplitudes were considered with at least three test replicates (resulting in nine asphalt samples for one asphalt mixture, and 90 asphalt samples in total). Strain amplitudes were defined so that fatigue failure occurs in the range from 10^4 to 2×10^6 loading cycles.

2.3. Resistance to Low-Temperature Cracking

The resistance to low-temperature cracking of asphalt mixtures was determined using the Thermal Stress Restrained Specimen Test (TSRST), according to European Standard EN 12697−46:2013.

During TSRST, the specimen is held at constant length by using a closed-loop system, while its temperature decreases from an initial temperature of 20 °C with a constant cooling rate of T = −10 °C/h. Due to the prohibited thermal shrinkage, the specimen is subjected to an increasing cryogenic tensile stress. The test ends at a minimum test temperature of −40 °C or at failure, when the cryogenic stress reaches the tensile strength of the asphalt specimen. The test result is the functional dependency of cryogenic stress to temperature, failure temperature, and tensile strength. The test setup for the TSRST is shown in Figure 6.

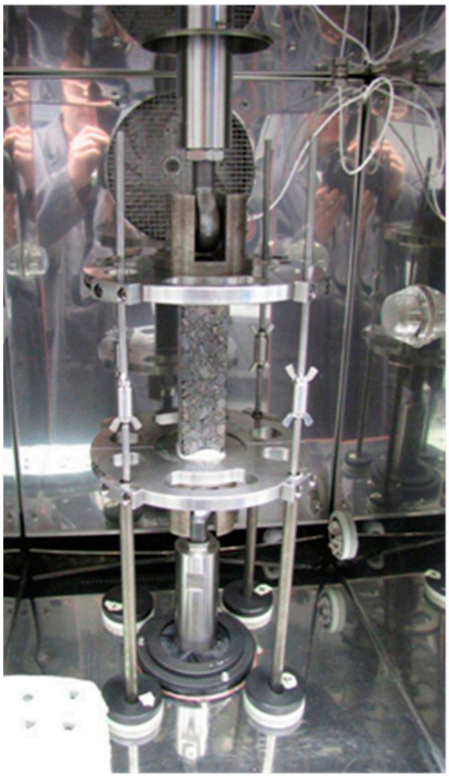

Figure 6. TSRST device used for determining low-temperature cracking resistance.

3. Results and Discussion

3.1. Complex Modulus

Based on the complex modulus values at different temperatures and frequencies, master curves in the form of a sigmoidal function Equation (1) were drawn using the principle of time–temperature correspondence [40], as displayed in Figure 7a. The temperature shift of the complex modulus (reduced frequency) was obtained by using the Williams-Landel-Ferry (WLF) equation Equation (2).

$$log|E^*| = log(E_{min}) + [\log(E_{max}) - \log(E_{mix})]\cdot(1 - e^{-\left(\frac{10+\log(f_{fict})}{\beta}\right)^{\gamma}}) \quad (1)$$

$$log f_{fict} = log f - \frac{C_1\cdot\left(T - T_{ref}\right)}{C_2 + T - T_{ref}} \quad (2)$$

where $|E^*|$ = absolute value of complex modulus (MPa); E_{min} = limiting minimum modulus (MPa); E_{max} = limiting maximum modulus (MPa); β, γ = fitting parameters; f_{fict} = reduced frequency at the reference temperature (Hz); f = loading frequency at the test temperature (Hz); C_1, C_2 = empirical constants; T = test temperature (°C); and T_r = reference temperature (20 °C).

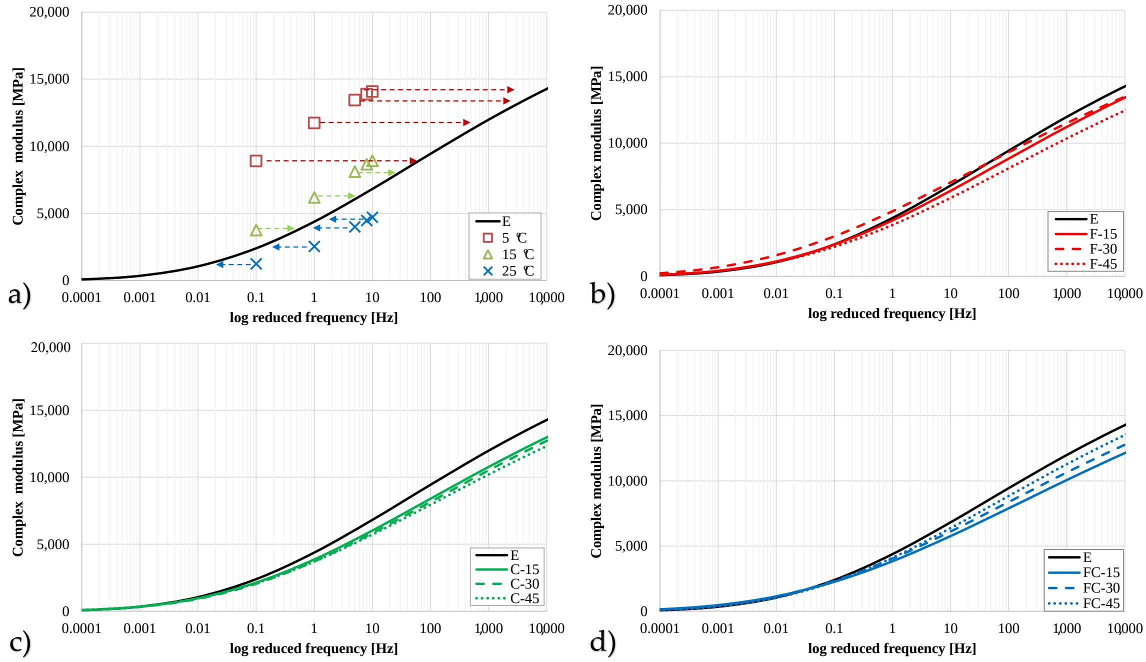

Figure 7. (**a**) The principle of master curve construction and master curves of (**b**) F mixtures, (**c**) C mixtures, and (**d**) FC mixtures.

The Hirsch model was applied to calculate the maximum modulus, assuming that the bitumen modulus in the glassy state is equal to 1 GPa.

The absolute values of the complex modulus at 20 °C and 10 Hz for the different asphalt mixtures are shown in Table 4.

Table 4. Absolute values of the complex modulus at a temperature of T = 20 °C and at a frequency of f = 10 Hz for different asphalt mixtures.

Mixture	E	F-15	F-30	F-45	C-15	C-30	C-45	FC-15	FC-30	FC-45
|E*| (MPa)	6731	6343	6980	5803	5913	5734	5633	5688	6027	6291

The results in Table 4 reveal that mixtures with RCA have approximately 15–20% lower stiffness than the control mixture, primarily due to higher OBC. The only exception is mixture F-30, which had a slightly higher stiffness than the control mixture due to similar air void content and OBC.

The master curves of all asphalt mixtures, drawn for a reference temperature of 20 °C, are displayed in Figure 7. Considering the three sets of the mixtures separately, it can be seen that the addition of fine RCA does not have a distinct impact on mixture stiffness (Figure 7b), particularly in the domain of testing results (between 0.1 and 10 Hz). Figure 7c indicates that the addition of coarse RCA slightly decreases stiffness of asphalt mixtures, confirming results from previous studies [20,21]. Finally, Figure 7d shows that a higher content of both fine and coarse RCA leads to increased stiffness despite the fact that they have higher OBC, opposing the research results from other studies [18,22,23]. This is a consequence of more favorable grain shape and better interlocking between aggregate particles, especially evident in mixtures with more than 15% RCA.

3.2. Fatigue Resistance

In order to evaluate the fatigue resistance of asphalt mixtures, the results from fatigue tests were fitted and presented in the form of a power (fatigue) function:

$$\lg\left(N_{i,j,k}\right) = A_o + A_1 \cdot \lg(\varepsilon_i) \quad (3)$$

where i = the specimen number; j = the chosen failure criteria (a 50% decrease in the initial complex modulus); k = the set of test condition (20 °C and 10 Hz); ε_i = initial strain amplitude measured at the 100th load cycle (μm/m); A_1 = slope of the fatigue line; A_0 = fitting parameter.

Figure 8a displays the resulting fatigue function for control mixture, with increased strain amplitude leading to a shorter fatigue life. Figure 8b–d present sets of fatigue curves of F, C and FC mixtures, respectively. Considering the established fatigue functions, the evaluation and ranking of asphalt mixtures regarding fatigue performance are based on the strain amplitude value (ε_6), whereby a fatigue life of 1,000,000 load cycles ($N_{f/50} = 10^6$) was obtained. The linear regression coefficients, fitting parameters, and calculated strain values for ε_6 are given in Table 5.

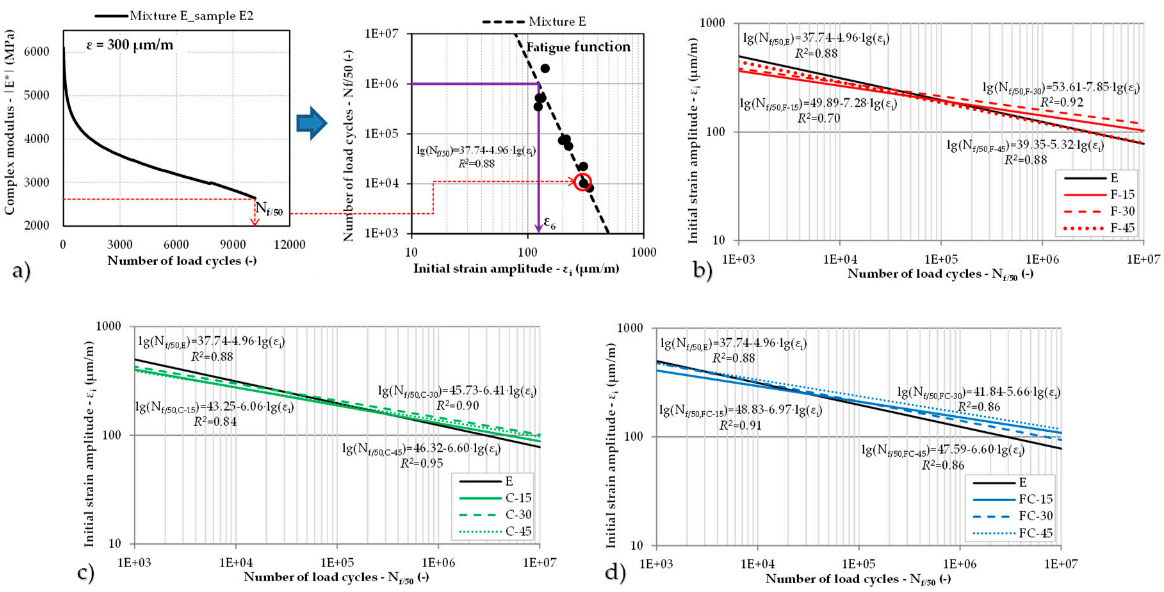

Figure 8. (**a**) Complex modulus evolution in the 4PBB fatigue test at a strain amplitude of 300 μm/m and corresponding fatigue law and fatigue curves of (**b**) F mixtures, (**c**) C mixtures, and (**d**) FC mixtures.

Table 5. Regression coefficients of fatigue lines.

Mix	E	F-15	F-30	F-45	C-15	C-30	C-45	FC-15	FC-30	FC-45
A_1	−4.96	−7.28	−7.85	−5.32	−6.06	−6.41	−6.60	−6.97	−5.66	−6.60
A_0	37.74	49.89	53.61	39.35	43.25	45.73	46.32	48.83	41.84	47.59
R^2	0.883	0.703	0.916	0.883	0.839	0.902	0.949	0.911	0.859	0.858
ε_6 ($\mu m/m$) ($N_{f/50} = 10^6$)	124.0	141.7	158.9	121.3	129.0	145.8	137.4	151.8	141.4	167.2

The strain values ε_6 demonstrate that mixtures with RCA typically have superior fatigue performance compared with the control mixture, which is a consequence of increased bitumen content. Similar conclusions were reported by Pasandín and Pérez [30] and Nwakaire et al. [24]. This kind of performance is especially evident in FC mixtures, where ε_6 values were 12–26% higher than for the control mixture. Additionally, the mixture with the same OBC as the control mixture (C-15) had approximately the same fatigue resistance as the control mixture, whereas mixtures with slightly higher OBC (F-15, F-30, C-30, and C-45) had 15% higher ε_6 values.

3.3. Resistance to Low-Temperature Cracking

The observed evolution of the cryogenic tensile stress in response to the temperature in the TSRST is displayed for the control asphalt mixture in Figure 9a. Temperature decrease leads to an increase in cryogenic stress until the specimen fails. The average values of the maximum cryogenic stress (σ_{max}) and the corresponding temperature (T_{crack}) at specimen failure for the asphalt mixtures are represented in Table 6 and displayed in Figure 9b (F mixtures), Figure 9c (C mixtures) and Figure 9d (FC mixtures).

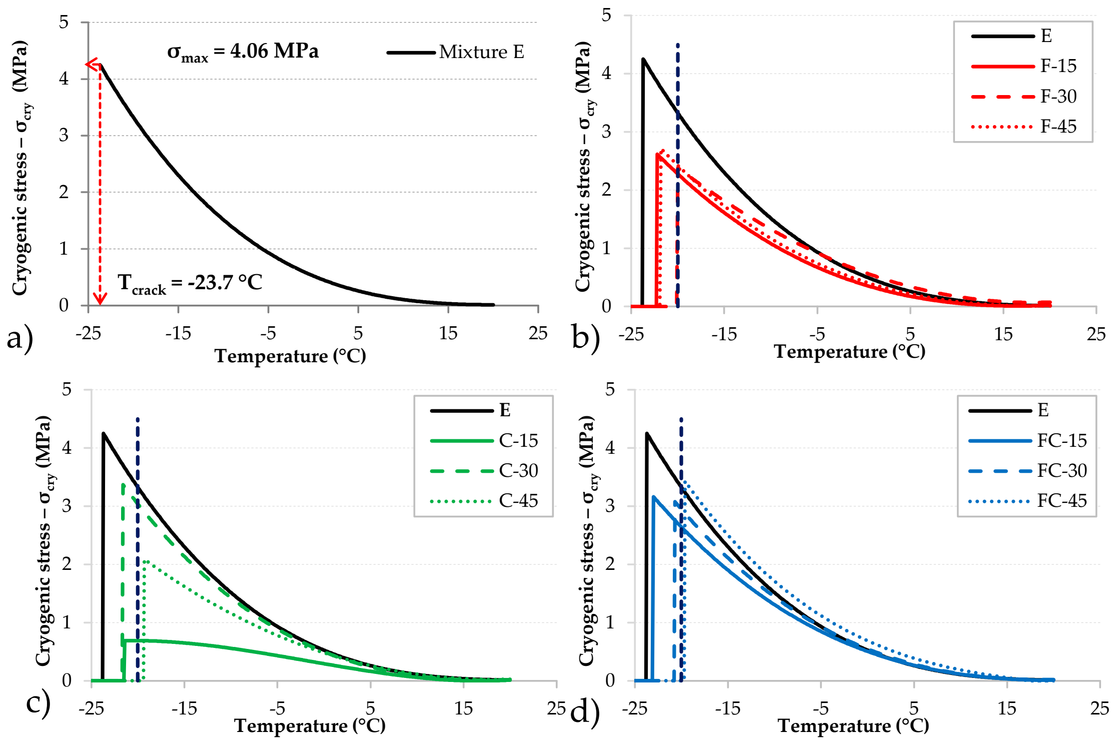

Figure 9. (**a**) Evolution of the cryogenic stress in response to temperature in the TSRST; cryogenic stresses of (**b**) F mixtures, (**c**) C mixtures, and (**d**) FC mixtures.

Table 6. Fracture temperatures and tensile strengths obtained from TSRSTs.

Parameter	E	F-15	F-30	F-45	C-15	C-30	C-45	FC-15	FC-30	FC-45
σ_{max} (MPa)	4.06	2.48	2.38	2.47	0.90	3.26	2.07	3.00	2.94	3.40
T_{crack} (°C)	− 23.7	−22.2	−20.0	−20.8	−21.5	−21.7	−19.4	−23.3	−20.8	−19.7

It can be concluded that the resistance of asphalt mixtures to low-temperature cracking decreases with increasing RCA content, as was observed in previous studies [10,33,34] using different testing methods. Although the RCA used in this study was of very good quality, it contained certain amounts of mortar and filler that may be identified as weaknesses due to their effect on the low-temperature resistance. However, the negative impact of the RCA addition was compensated for with higher OBC. Testing results showed that the failure temperatures of mixtures with RCA increased up to 4.3 °C in comparison with the control mixture.

Asphalt mixtures that fail at temperatures lower than −20 °C are considered to have satisfactory low-temperature performance for the climatic conditions prevailing in Central Europe. Except for mixtures F-45 (T_{crack} = −19.4 °C) and FC-45 (T_{crack} = −19.7 °C), all remaining RCA mixtures satisfy this criterion. It should be noted that mixtures F-45 and FC-45 have values practically at the criterion limit, and all mixtures are intended for use in base courses; hence, they are not directly exposed to thermal stress from temperature decrease. The highest cryogenic stresses were measured for the control mixture, highlighting its smaller deformability compared with the RCA mixtures, again due to lower OBC.

On the contrary, significantly lower cryogenic stresses were measured for the C-15 mixture, mainly because of the slight segregation of testing samples, without compromising the failure temperature.

4. Conclusions

This study examined the mechanical properties (stiffness, fatigue, and low-temperature cracking resistance) of road asphalt mixtures with partial substitution (15%, 30%, or 45%) of fine natural aggregate, coarse natural aggregate, and both fine and coarse natural aggregate by recycled concrete aggregate (RCA). Based on the results obtained from standardized testing protocols, the following conclusions can be drawn:

- As a result of the high porosity and surface area of RCA, asphalt mixtures made with more than 30% RCA required significantly more bitumen than the control mixture (0.5–1%). However, mixtures with less than 30% RCA required up to 0.2% bitumen more than the control mixture.
- Regardless of the particle size distribution of the used RCA, or the quantity of RCA applied, the complex modulus values of asphalt mixtures containing RCA, with the exception of F-30, were 15–20% lower than those of the control mixture, which is most likely related to the increased OBC and air void content.
- Most RCA mixtures (except for F-45), showed better fatigue resistance than the control mixture, primarily as a consequence of higher OBC (ε_6 was up to 26% higher).
- The low-temperature cracking resistance of asphalt mixtures decreased with increasing RCA content. The failure temperatures of mixtures with RCA were up to 4.3 °C higher in comparison to the control mixture. Based on these findings, an RCA content of 45% is viewed as the upper limit of applicability regarding low-temperature properties.

In accordance with the conclusions from a previous study that the addition of RCA does not have a significant impact on permanent deformation [16], the research results obtained in this study indicate that road asphalt mixtures composed of up to 45% RCA can be applied without altering the asphalt mixture's performance properties. Therefore, asphalt mixtures with up to 45% RCA can be viewed as a viable and sustainable resource option for road (re)construction. However, it should be noted that the RCA used in this study was obtained from relatively high-quality concrete (compressive strength class C35/45), with low water absorption and LA coefficient values. For these reasons, a reduction in asphalt mixture performance may be expected with a lower quality of RCA.

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