MECHANICAL PROPERTIES OF HOT MIX ASPHALT MADE WITH RECYCLED AGGREGATES FROM RECLAIMED CONSTRUCTION AND DEMOLITION DEBRIS

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Abstract
This paper evaluates the mix design of asphalt mixtures made with recycled aggregates from construction and demolition debris. On the basis of several different tests, it was possible to characterise the mechanical behaviour of these mixtures. The mechanical parameters of the mixtures containing recycled aggregates are similar to those of mixtures made only with natural aggregates from quarries. However, the behaviour of asphalt mixtures containing recycled aggregates was poor in terms of diminished resistance from the loss of cohesion due to the action of water. Nevertheless, through the selection of better quality materials and the correction of this poor behaviour, it was found that possibilities do, in fact, exist to use recycled aggregates in asphalt mixtures. In order to do this, it will be necessary to expand upon the preliminary approach presented in this article.

Key words: Construction and demolition debris, recycled aggregate, asphalt mixtures.

1. INTRODUCTION

At the present time there is a widespread awareness of the need for sustainable development policies aimed at the correct management of the scarce resources stemming from the environment. Faced with this challenge, the construction industry has been at the forefront in the development of techniques to reuse the waste materials that it generates. The European Union (EU) promotes a recycling policy through a number of technical research projects with a view to put these materials to good use. In this sense the EU has envisaged a waste catalogue, known as the EWC (European Waste Catalogue), where construction and demolition debris (CDD) is reflected in code CER 170000. The CDD are generally known as "*rubble*". These materials are produced in large quantities, with their volume exceeding domestic waste. Their pollutant power is relatively low. In contrast, however, their visual impact is often high, owing to the sheer volume of space they occupy in addition to the lack of environmental control carried out on the lands earmarked for the deposit of these materials. Another negative environmental impact has to do with the squandering of raw materials. For this reason, the Spanish National Construction and Demolition Debris Plan was passed (PNRCD) [1] with one of the main objectives being to recycle 60% of the CDD in the year 2006. However, in Spain, this percentage is less than 5%, owing to a shortage of recycling plants. In Europe the average amount of material recycled is roughly 28%.

In keeping with this, it must be said that, in view of the huge quantity of aggregates that are used in making highway pavements, it would be fitting to consider the possible use of CDD in the different layers. Along these lines, at the present time a wide variety of technical literature is available on the characterisation of different types of structural concrete made with recycled aggregates from CDD [2,3]. Moreover, experiments have been conducted on the use of these materials as granular layers and layers treated with hydraulic bonding material in roads [4,5,6]. The authors of this article, however, are not aware of any previous technical studies that characterise these debris for use as asphalt mixtures in bituminous layers. In view of the above, the aim of this research is to expand the use of recycled aggregates beyond that of simple unbound granular or a cement-bound granular material used in highway pavements. This paper will focus on the study of the mechanical properties of hot asphalt mixtures containing recycled aggregates for use in road building.

2. EXPERIMENTAL SECTION

We investigated the feasibility of using two types of hot mix asphalts made from recycled aggregates (RA) applied in different proportions. In addition, the same types of asphalt mixtures made with natural aggregates (NA) from the quarry were used to compare the results. The mix designs were made according to the General Technical Specifications for Road and Bridge Construction, also known as PG-3 [7].

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2.1. Definition of the mixtures

A G-20 mixture was studied as a roadbase; while an S-20 mixture was used as a binder course. G-20 is a coarse mixture with a continuous particle size distribution and a maximum size of 25 mm. It is composed of almost three-fourths coarse aggregate with a content of filler and bitumen of roughly 4%. The S-20 mixture is semi-dense with a continuous particle size distribution and a maximum grain size of 25 mm. It is made up of approximately two-thirds coarse aggregate with a content of filler and bitumen of roughly 5%. Table 1 presents the particle size distribution and the grading envelopes of the two hot asphalt mixtures.

Table 1. Particle size distribution and grading envelopes

Mixture		Sieve sizes UNE-EN-933-2 (mm.)										
		Coarse aggregate						*Fine aggregate*				*Filler*
		40	25	20	12.5	8	4	2	0.50	0.25	0.125	0.063
Semi-dense S-20	Grading envelope	---	100	80-95	64-79	50-66	35-50	24-38	11-21	7-15	5-10	3-7
	NA	---	100	95	78	63	40	30	15	12	8	5.5
	RA	---	100	95	78	63	40	30	15	12	8	6.5
Coarse G-20	Grading Envelope	---	100	75-95	55-75	40-60	25-42	18-32	7-18	4-12	3-8	2-5
	NA	---	100	95	75	60	37.75	28.5	13	10	7	4.25
	RA	---	100	95	75	60	37.75	28.5	13	10	7	4.75

The Spanish technical standards NLT [8] (Road Tests) from the Road Study Centre and the UNE-EN Standards [9] of the Spanish Association for Standardisation and Certification (AENOR) were used to characterise the basic materials.

Bitumen. A conventional bitumen with average properties was decided on. The specific selection was a bitumen with a penetration of 60/70 (NLT-124), and a softening point (NLT-125) with the ring and ball method equal to 48.5. Pleiffer's penetration index (NLT-181) is equal to -0.8. Density is 1.03 g/cm^3 (NLT-122). This bitumen can be used in many different traffic situations and climates. In zones with mild climates, it can be used as a wearing course, binder course and roadbase. It was confirmed that the bitumen complied with all PG-3 specifications.

Natural aggregate. These aggregates originated from a quarry in fractions of 0/6, 6/12 and 12/25. The rock from which these aggregates were taken is a fine-grained feldspar schist produced by a regional metamorphism, consisting of small grey lines with an abundance of microscopic quartz crystals interspersed between tightly folded planes of schistosity. Its main components are quartz (35%), sodium feldspar (30%), colourless or moscovite mica (20%) and chlorite (15%). This rock has a lustrous grey colour and good properties as an aggregate for binder courses and roadbases. Table 2 shows the main characteristics of the aggregates pertaining to gradings S-20 and G-20. As can be seen, it complies with the PG-3 specifications, since the elongation index in all the fractions tested is <20% (UNE-EN933-3); all the coarse aggregate particles are fractured (UNE-EN933-5); the sand equivalent is 70.1 and 75.4% (UNE-EN933-8); the Los Angeles abrasion coefficient is 19.4 and 22.1% (UNE-EN1097-2). The water absorption coefficient is 0.17 and 0.19% (UNE-EN-1097-6). The aggregate density in paraffin oil (NLT-167) is 2.69 g/cm^3.

Table 2. Characteristics of the aggregates

Test	**100% NA**		**100% RA**	**50% RA + 50 %NA**	
	S-20	**G-20**	**S-20**	**S-20**	**G-20**
Elongation index (%)	17.2	19.4	16.2	17.1	18.3
Fractured particles (%)	100	100	100	100	100
Sand equivalent (%)	75.4	70.1	87.2	85.4	88.1
Los Angeles Abrasion (%)	19.4	22.1	39.65	25.6	24.8
Water Absorption Coefficient (%)	0.17	0.19	6.1	4.59	4.82
Relative density in paraffin oil (g/cm^3)	2.69	2.69	2.58	2.66	2.66

Recycled Aggregate. Recycled aggregate has the grading required for fill in fraction 0/40. It has the following composition in weight: concrete (72%); stone (20%); ceramic (2%) and bitumen (6%). Its main characteristics can be seen in table 2. As explained in section 3.1, when 100% RA is used in grading S-20, the values of the elongation index, fractured particles and sand equivalent meet the PG-3 requirements. However, the Los Angeles abrasion coefficient is well over the specified values, with a result of 39.65%. It is also interesting to note the high value of the water absorption coefficient, equal to 6.1%, which is 36 times greater than the S-20 grading value with 100% NA. The density of aggregates in paraffin oil is 2.58 g/cm^3. Moreover, by using 50% NA + 50% RA in all the fractions, of both gradings S-20 as well as G-20, it was observed that the elongation index and sand equivalent values also comply with the established values. Logically, in this case, the Los Angeles coefficient resulted in lower values, although they still do not meet the specifications stipulated in PG-3 for roads with medium traffic. The water absorption coefficient values are still high –around 27 to 25 times greater than the values obtained with 100% NA. Lastly, when the two types of aggregates are combined, this causes an increase in the relative density in paraffin oil until a value equal to 2.66 g/cm^3 is reached

Filler. The filler used in all cases came from the process of crushing natural aggregate. This was done to make sure that the filler behaved similarly in both cases.

2.3. Mechanical Tests

Presented below are the tests selected for the mechanical characterisation of the mixtures. The Marshall tests, the effect of water on compressive strength tests and the wheel tracking test were conducted to determine the optimum mix design of mixtures to be used according to the traffic categories listed in PG-3, Table 3. As a supplement to these studies, fatigue tests were also carried out, which, while not mandatory in the road specifications, make it possible to gain greater insight into the behaviour of the bituminous mixture when fissures start to appear owing to the presence of dynamic stresses.

Table 3. Criteria for mandatory mix design in PG-3

Characteristic			Category of heavy traffic$^+$			
			T00 and T0	T1 and T2	T3 and shoulders	T4
Marshall	Stability (kN)		>15	>12.5	>10	8-12
	Flow value (mm.)		2-3	2-3.5		2.5-3.5
	Voids in total mix (%)	Binder course S-20	4-6	5-8	4-8	4-8*
		Roadbase G-20	5-8	6-9	5-9	---
	Voids in mineral aggregate (%)		>14			
Conserved strength index CI (%)			>75			
Deformation velocity DV (μm/min)		Binder course S-20	<20			
		Roadbase G-20	---			

*service roads
+T00($AADT_{cv}$≥4000); T0 (2000≤$AADT_{cv}$<4000); T1 (800≤$AADT_{cv}$<2000), T2 (200≤$AADT_{cv}$<800); T3 (50≤$AADT_{cv}$<200); T4 ($AADT_{cv}$<50); ($AADT_{cv}$= annual average daily commercial traffic)

Marshall. (NLT-159). Five series of three cylindrical specimens 101.6 mm in diameter by 63.5 mm in height were compacted. Each series was made with an identical grading but a different percentage of bitumen in relation to aggregate weight. The average value of the following parameters was calculated for each percentage of bitumen: Voids in mineral aggregate, Va (%); Voids in total mix, Vm (%); Bulk specific gravity, Bg (g/cm^3); Flow value, F (mm) and Stability, S (kN). The results of this test were used to define the optimum bitumen content (Bo) in the mixtures to comply with the criteria established in the PG-3, Table 3. The specimens fabricated for the rest of the tests were elaborated with the optimum asphalt content selected in this test.

Effect of water on compressive strength (NLT-161 y NLT-162). Ten cylindrical specimens with the following dimensions were made: 101.6 mm in diameter and 101.6 mm in height. Five specimens were immersed in water at a temperature of 60 ºC for 24 hours and the other five were not. They were later subjected to simple compression and the average value of the maximum stress reached in each group was determined. The Conserved Strength Index CI(%) was calculated by dividing the strength of the group that was immersed in water at 60 ºC by the strength of the group that was not submerged. On the basis of this test it is possible to characterise the loss of cohesion produced by the action of the water in the mixtures. According to the PG-3, the CI values in mixtures S-20 and G-20 must be higher than 75% (Table 3).

Wheel tracking test (NLT-173). Three samples with the following dimensions were made: 300 x 300 x 50 mm. In this test the sample was subjected to the alternating passage of a wheel under specific pressure and temperature conditions, and periodically measuring the deformation depth produced. The mean deformation velocity (DV) was measured at a time interval ranging between 105 and 120 minutes from the start. This test is only mandatory for wearing or binder courses (table 3).

Bending Fatigue test (NLT-350). Prismatic beams measuring 300 x 50 x 50 mm were fabricated and tested in flexotraction in a servohydraulic press under displacement control at a frequency of 10 Hz. The deformation values were measured by means of a dynamic extensometer placed in the lower part of the beam which is where the greatest tensile stresses are supported. On the basis of these tests, the following values were determined for each mixture: the fatigue law, the dynamic modulus and the phase angles.

The fatigue law was used to quantify the fatigue failure of the material produced by the damage accumulated in the presence of dynamic loads and which is manifested in the fissuration of the material. The fatigue law relates the number of load cycles until the fatigue of the material is reached (N), to the level of deformation (ε) produced by the dynamic stresses. ε and N are bound by the following expression:

$$\varepsilon = kN^B$$

where k and B are constants that describe the behaviour in relation to the material fatigue and they depend on the aggregates of the mixture, among other factors.
The dynamic modulus (DM) is a measurement of the stiffness of the mixture and is calculated as the quotient between the cyclical amplitude of the tension function (T_c) and the cyclical amplitude of the deformation function (ε_c) in cycle 200. It is expressed as follows:

$$DM=T_c/\varepsilon_c.$$

The phase difference angle (φ) gives us an idea of the predominance of the elastic or viscose character of the mixture under study. An angle difference of φ=0º would indicate that the material is elastic, while an angle difference of φ=90º would denote viscose material. It is calculated by means of the expression:

$$\varphi=(B_t - B_\varepsilon)180/\pi;$$

where B_t and B_ε are the phase angles of the tension and deformation functions.

3. RESULTS AND DISCUSSION

3.1. Results of the Marshall tests

The results obtained with the Marshall method showed that it was impossible to use only recycled aggregate in the mixture. For mixture S-20-RA, comprised of 100% recycled aggregate, it was observed that the mixtures had little cohesion, the coarsest aggregate was not surrounded correctly by the bitumen and the mix as a whole looked gritty. This behaviour may be attributed to the excessive porosity of the aggregate. As the specific surface of the aggregate increases, greater quantities of bitumen are required to achieve the appropriate cohesion. Mixes made with 5.90% bitumen exhibit high Va, S and F values, but all within the PG-3 specifications. The value for Vm, in contrast, was 11.7 (%) and therefore did not meet this mandatory criterion for the fabrication of hot mix asphalt to be used in the construction of road pavements. In mixtures elaborated with smaller contents of bitumen, the mix did not achieve consistency and finally segregated.

On the basis of the previous analyses, we decided to use a measurement of 50% recycled aggregate in the RA mixtures. In mixtures using NA, the amount of filler was chosen in terms of the weighted ratio filler-bitumen recommended in the PG-3; whereas in the mixtures using RA, it was necessary to increase the amount of filler to almost the maximum limit of the grading envelope. Figure 1 presents a graph of the results of the Marshall tests for both NA and RA mixtures. The following observations can be made:

1. The Va curves do not have pronounced slopes, as they are affected very little by the bitumen content. Mixtures using RA cause Va to increase between 3% and 5% with respect to mixtures that use NA. This is due to the fact that greater absorption of the bitumen by the recycled aggregates causes a decrease in the thickness of the film enveloping the aggregates and finally, reduces their ability to bind.

2. The Vm curves decrease with the content of bitumen until they reach a minimum value where they remain relatively constant. The percentage of bitumen used was not high enough to reach this minimum. The mixtures containing RA have 3.0% more Vm in mixture G-20 and 7.0 % more in mixture S-20.

According to these results, it is possible to predict that mixtures containing RA will have a poorer performance with the entry of water.

3. The flow curve increases with the bitumen content. It was similar in both cases.

4. Ascending and descending branches may be seen in stability in both mixtures S-20-NA and G-20-RA. Mixture G-20-NA only shows an ascending branch, while mixture S-20-RA exhibits only a descending branch.

5. The bulk specific gravities of mixtures containing RA are slightly lower than those in mixtures with NA. This is due to the fact that compaction is more difficult in mixtures with RA.

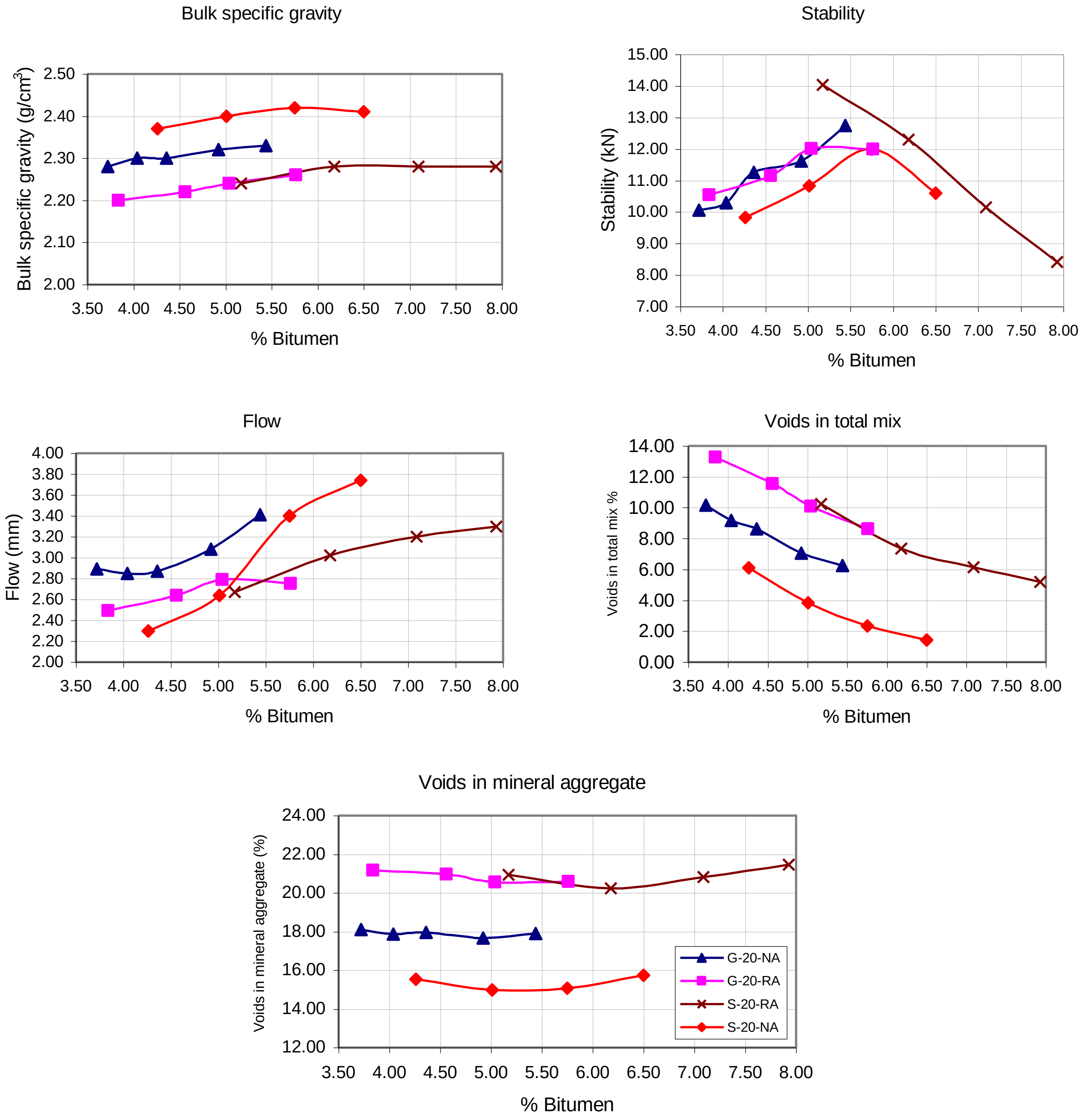

Figura 1. Marshall Test

On the basis of the results obtained from the Marshall test, the proportions of B_o were selected for each type of mixture in compliance with the required specifications of PG-3 for the different traffic categories (Table 3). In mixture S-20-NA the percentage of Bo used is equal to 5% of the total aggregate weight. With this proportion the mixture meets the requirements for traffic categories T3 and T4. In mixture G-20-NA the percentage of Bo used is equal to 4.25%, and therefore in compliance with all of the T3 and T4 specifications. Mixture S-20-RA has a Bo percentage of 5.90%, meeting the specifications from T1 up to T4. Lastly, mixture G-20-RA contains 4.75% Bo which resulted in a less satisfactory performance, since it was only able to meet the specifications for category T4. The results of the Marshall test for the selected proportions are given in Table 4.

3.2. Conserved strength index

The results of the conserved strength index CI (%) can be found in Table 4. For mixtures S-20-NA and G-20-NA the values obtained are slightly over the 75% mark given in Table 3. As regards mixtures containing RA, the conserved strength does not meet the specifications listed in Table 3. In particular, the values for G-20 RA were lower than those obtained using S-20-RA mixtures.
The value for voids in mixture S-20-RA is not excessively high (8%). Hence, the entry of water in the mixture and the subsequent loss of strength would be similar to that of other mixtures having the same amount of voids. This result may be explained by the fact that, owing to the nature of recycled aggregate, which contains clay and concrete, among other different materials, water may be retained inside the mixture, displacing the bitumen and consequently resulting in diminished strength. The extremely low values obtained for G-20-RA may be attributed to the high percentage of voids found in the mixture coupled with the clayey nature of CDD (similar to mixture S-20-RA).

3.3. Permanent deformation

The results of the mean DV of the test samples of the S-20 mixtures are shown in Table 4. In mixture S-20-NA, the DV velocity is equal to 19.29 μm/min.; and in mixture S-20-RA it is 15.07 μm/min. Both values are within the limit of 20 μm/min., (Table 3). The G-20 mixtures were not tested, since it is not required by the PG-3. Figure 2 represents the deformation-time curves of the two mixtures. It is possible to observe that mixture S-20-NA exhibits a high deformation at the beginning of the test, but then begins to stabilise as the test progresses. On the other hand, in mixture S-20-RA, at the beginning of the test, deformation is not as pronounced as in the case above. The stabilisation of DV occurs earlier in mixture S-20-NA than in S-20-RA. Towards the end of the test, deformation undergoes a slight increase in S-20-NA, while it decreases in S-20-AR. If this tendency continues, then in the long term S-20-NA would not be very resistant to plastic deformations. Mixture S-20-RA offers a more satisfactory resistance to plastic deformations.

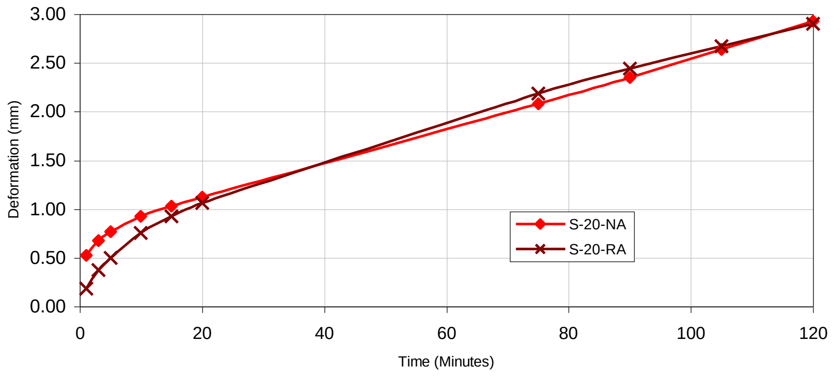

Figure 2. Wheel tracking test

3.4. Fatigue law

The experimental values of ε and N for the mixtures under study are represented on a logarithmic scale in figures 3a and 3b. These figures also include the laws of fatigue from the Experimental Centre of Public Works (Cedex) [10] and those used in Instruction 6.1-IC [11] for mixtures G-20 and S-20 to compare the results obtained and to determine whether or not the fatigue experienced by the mixtures subjected to load cycles is within the predicted limits.
Figure 3a shows that both mixture G-20-NA and G-20-RA behave similarly to fatigue. This is reflected by the fact that their slopes (*B*) and coefficients (*k*) are similar (Table 4). As regards the Cedex and Instruction curves, on the one hand, mixtures G-20-NA and G-20-RA are located above the Cedex law 2; while, on the other hand, they are consistently below the instruction law (with slightly more pronounced slopes).

In figure 3b it is possible to observe that mixture S-20-NA and mixture S-20-RA behave differently in terms of fatigue. Mixture S-20-RA has a much more pronounced slope (*B*) than mixture S-20-NA. The law of mixture S-20-RA falls within the interval designated by the CEDEX (with a more pronounced slope) while the law of mixture S-20-NA, in contrast, has a favourable result, falling outside said interval (with a much less pronounced slope). The Instruction law slope is more pronounced than that of the law corresponding to mixture S-20-NA. For the same deformation unit, the law of mixture S-20-NA predicts a higher number of cycles to reach fatigue failure than the laws of mixture S-20-RA and the instruction. Hence, it may deduced that mixtures S-20-NA behave in a more satisfactory manner than mixtures S-20-RA, although, the latter would also be acceptable.

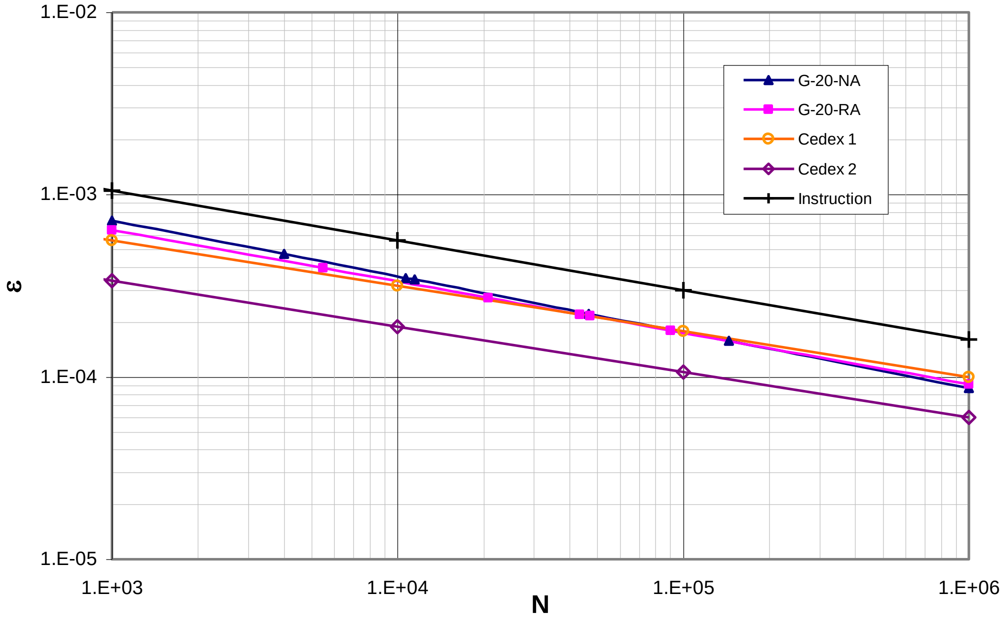

Figure 3a. Fatigue laws of the G-20 mixtures

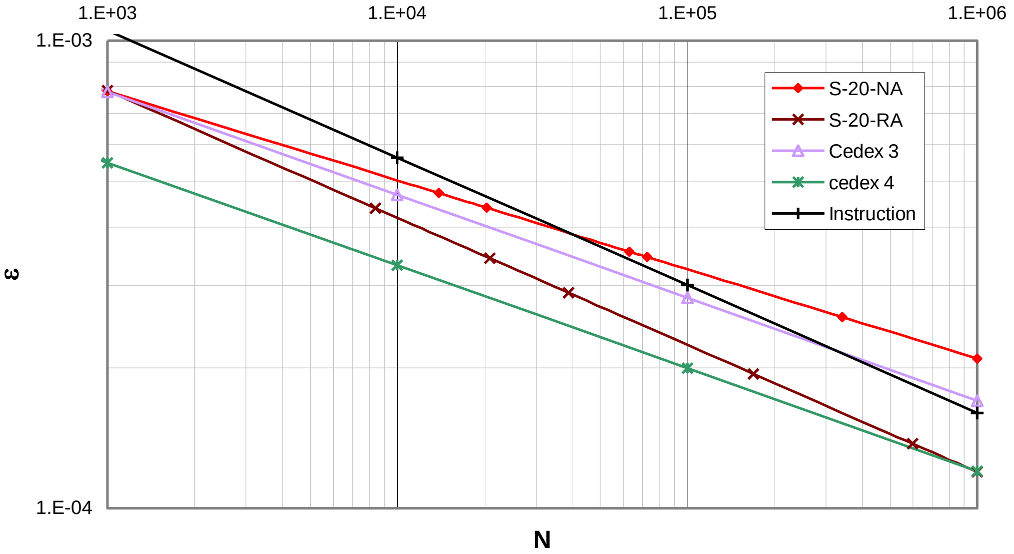

Figure 3b. Fatigue laws of the S-20 mixtures

Dynamic Modulus

The values of the dynamic modulus are presented in Table 4. The values of the dynamic modulus for S-20 mixtures containing bitumen 60/70 fall within the usual interval of 6000±1000 MPa [10]. In this sense, mixture S-20-NA is slightly lower than the usual modulus for these types of mixtures. Mixture S-20-RA, however, stays within this interval. Moreover, the interval of modulus values for the G-20 mixtures containing bitumen 60/70 is 5500±1000 MPa. In keeping with this, mixture G-20-NA falls below this interval and mixture G-20-RA stays within it. Mixtures of greater stiffness are obtained when RA is added. The stiffness values agree to a reasonable extent with the ability of the mixtures to withstand loads, as reflected in the stability values obtained in the Marshall tests (figure 1). These low modulus highlight a weak point in the mixtures made with NA. Owing to their lack of stiffness, with the passing of traffic, these mixtures would be subject to excessive deformation, since they are not able to absorb stress adequately. This could lead to premature fissuration of the mixture of the surface course as the base course lacks stiffness.

Phase difference angle

Table 4 shows the results of fit of the stress and deformation functions in cycle 200. These phase difference values are within normal levels and are very similar to those obtained by other authors [12]. The S-20-RA mixture is the most elastic (and it also has the largest modulus), while the S-20-NA mixture (with the smallest modulus of all) is the most viscose.

Table 4. Test results.

Mixture	Marshall Test						CI	DV	Fatigue law			DM	φ
	Bo (%)	Va (%)	Vm (%)	F (mm)	S (kN)	Bg (g/cm^3)	(%)	(μm/min)	*k*	*B*	R^2	(MPa)	
S-20-NA	5.00	15	4	2.6	10.8	2.4	76.99	19.29	0.0029	-0.1903	0.8575	3866	45.85
S-20-RA	5.90	20.2	8	2.9	12.6	2.28	63.72	15.07	0.0051	-0.2716	0.9697	5016	35.05
G-20-NA	4.25	18	8.9	2.8	11	2.3	79.34	----	0.0060	-0.3064	0.8620	4086	37.71
G-20-RA	4.75	20.9	11	2.7	11.5	2.22	50.26	----	0.0045	-0.2823	0.9502	4675	37.05

4. CONCLUSIONS

The main conclusions drawn from this research work are listed as follows:

1) It was possible to fabricate bituminous mixtures containing 50% aggregate weight in all the fractions. These mixtures are higher in bitumen content than the mixtures made only with natural aggregate and they also require a greater amount of filler. Moreover, only this composition was able to meet the specifications established by the PG-3 for the parameters obtained using the Marshall test on roads with low traffic. However, it was not possible to design the mixtures made only with recycled aggregate.

2) Mixtures made with natural aggregate react satisfactorily to the action of water and comply with the specifications of the effect of the water on compressive strength test, whereas mixtures made with 50% recycled aggregate exhibit an excessive loss of strength.

3) In general the S-20 mixtures show good resistance to plastic deformations, in compliance with the values stipulated in the PG-3 for roads with low traffic.

4) The fatigue laws obtained were similar to those reported by other authors. The values of the dynamic modulus are reasonable and found to be higher in mixtures containing 50% recycled aggregate.

5) In keeping with the above conclusions, it can be said that it is possible to use mixtures made with recycled aggregate in roads with low traffic. However, it is essential to continue researching different solutions that may be used to improve behaviour when water comes into play. Hence, listed below are a number of alternatives that may be considered to obtain more favourable results in the future:

- Select better quality recycled aggregates
- Decrease the proportion of recycled aggregate in the mixture
- Use of fillers such as lime and cement
- Use of harder or modified bitumens

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