Promoting the Circular Economy of Concrete Through Innovation in Asphalt Pavements

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Abstract. The circular economy is seeking to maximize the use of resources and reducing the consumption of raw materials as well as waste generation. In a circular economy, the producer takes responsibility, directly or indirectly, for the waste generated by the production process and for their products at the end of their life cycle. This concept is being integrated in most countries to achieve an environmental and economic balance. This paper presents a work in which this concept is used, where the waste generated in a concrete research project (waste aggregates) were drawn on asphalt mixtures. This project consisted of using the fine aggregates as a total or partial replacement of raw aggregates to manufacture asphalt mixtures. These fine aggregates are generated in the production process of high-quality recycled concrete aggregates. In this research, an IV-A 12 semi-dense gradation size and a CA-24 asphalt binder were used, where four different percentages of natural aggregate replacement were evaluated (0%, 25%, 75% and 100%). These asphalt mixtures were evaluated in their compliance of Chilean standards, as well as their performance in different properties such as cracking and water sensitivity. The results obtained show that the mixtures with total replacement of raw aggregates can be used, since they fulfill the Chilean standards. However, taking into account the water sensitivity results, the percentage of suitable replacement would be 50% for the same binder content. According to the cracking results, it is noted that increasing the replacement content of the aggregates in the mixture increases the fracture resistance compared to the conventional hot mix asphalt.

1. Introduction

Care for the environment has been gaining momentum for some time now, being formalized in global agreements like the Kyoto Protocol [1] and its ratification with the Paris Agreement [2], and Chile has signed both. Although these protocols mainly refer to mitigating greenhouse gases (GHG), these emissions and their relation to climate change are not the only effort, as waste generation is a pending issue. In Chile, the Minister of the Environment states that “Waste continues to be a significant problem and will worsen with continued economic growth” [3]. The average annual rate of waste generation in Chile for 2017 rose to 396 kg per inhabitant, so the Chilean government decided to enact the Waste Management Framework, Corporate Social Responsibility and Promotion of Recycling Law, built on the ‘polluter pays principle’ [4]. This Law is a clear incentive to strengthen the circular economy, where producers must take responsibility for their waste. The definition of the circular economy is broad; basically, the idea is to promote the responsible and cyclical use of resources, where the strategic axes are to reduce the raw material required for a process while reducing waste generation at the same time [5].
Of the waste generated in Chile in 2014 and 2015, concrete debris represented approximately 9%, equivalent to 905,102 tons in 2014 [3]. This material is potentially recyclable: after a crushing and selection process, it is transformed into recycled concrete aggregates (RCA). RCA is different from natural aggregates in that the old mortar layer adheres to the aggregates. When RCA are incorporated into a new concrete, two interfacial transition zones (ITZ) are created. The first, ITZ1, is the old adhered mortar, and the second, ITZ2, is the uncovered zone that produces direct contact with the aggregate at the core of the RCA and the new cement paste [6,7]. Studies conducted on the use of RCA have shown that they have greater water absorption than natural aggregates (8, 9), which is due to the old mortar adhered to the walls of the RCA, i.e., ITZ1 [10]. As ITZ1 is greater, the strength of the concrete decreases [11]. Consequently, the amount and quality of ITZ1 will be the main parameters that affect the mechanical behavior of the recycled concrete [12, 13]. It is in this context where the project “High-quality recycled aggregates from concrete debris” (CORFO: 15IPPID-45706) appears, the main aim of which is to design a production system that can crush the concrete debris, maximizing the detachment of the mortar adhered to the aggregates (ITZ1) without jeopardizing the particle integrity. During the process, mortar is generated as waste detached from the aggregates, which is the aim of this study, since in order to apply the concept of circular economy, the aim here is to address the waste from the production process, assessing the alternative of incorporating them in hot mix asphalt (HMA) as a partial and total replacement of the fine fraction.

Most studies on the incorporation of RCA in HMA indicate that the optimal binding content increases due to the high porosity and high specific surface of the mortar adhered to the aggregates [14–16]. Attempts to improve the mechanical performance of HMA with partial aggregate replacement with RCA have emerged from the application of treatments prior to recycled aggregates with various materials, such as precovering the recycled aggregates with cement paste, silicone and asphalt emulsion [17–19]. All these studies focus on the incorporation of RCA as a replacement for the coarse aggregate fraction in the asphalt mixtures; however, there is one study [2] that assesses the use of the fine fraction, < 0.6 mm as a replacement of the contribution filler to the mixture, concluding in that study that the mixtures with filler replacement from RCA improve their resistance to moisture damage, performance at high temperature and fatigue, their performance being slightly affected at a low temperature, but remaining within the limits specified by the current Chinese regulation. This is for similar optimal binding contents (5.1 and 5%, for mixtures with fillers from RCA and natural filler, respectively).

The present study will evaluate the effects of the partial and total replacement of the fine natural aggregate fraction with RCA in HMA. RCA will correspond to the waste from the production process of high-quality recycled aggregates, proposed in the CORFO: 15IPPID-45706 project, thereby contributing to the circular economy of the production process.

2. Materials

2.1. Asphalt Binder

The most conventional binder in Chile, CA-24, is used. The characterization must comply with the stipulation in section 8.301.1 of MC - V8 [21], which is in Table 1.

| Tests                                      | CA24          | Specification | Method   |
|--------------------------------------------|---------------|---------------|----------|
| Absolute viscosity at 60°C, (P)            | 3730          | Min 2400      | 8.302.15 |
| Penetration at 25°C, 100gr, 5 sec, (0.1mm)| 60            | Min. 40       | 8.302.3  |
| Ductility at 25°C (cm)                     | > 100         | Min. 100      | 8.302.8  |
| Spot test (% xylene)                       | < 30          | Max. 30%      | 8.302.7  |
| Solubility in Trichloroethylene (%)        | 99.8          | Min. 99       | 8.302.9  |
| Inflammation point (°C)                    | > 232         | Min. 232      | 8.302.16 |
| Softening point (°C)                       | 52            | To be reported| 8.302.18 |
Penetration index (PI)  -0.2 -2.0 to +1.0  8.302.11

Rolling thin-film oven test

| Test                              | Results | Specification | Method |
|----------------------------------|---------|---------------|--------|
| Loss on heating (%)              | 0.03    | Max. 0.8      | 8.302.33 |
| Absolute viscosity at 60°C (P)   | 8800    | To be reported | 8.302.15 |
| Ductility at 25°C (cm)           | >100    | Min. 100      | 8.302.8  |
| Durability index (DI)            | 2.4     | Max. 4        |        |

2.2. Natural Aggregates (NA)

These are crushed fluvial aggregates from of a local production plant located in Cajón, Region of La Araucanía, Chile. Their characterization was done according to the national regulation as stipulated in section 5.401.201 of the Highways Manual Volume 5 (MC- V5) [21]. The results are in Table 2.

Table 2. Characterization of natural aggregates according to Chilean regulations MC- V5 and V8 [21]

| Characterization of natural aggregates, coarse fraction according to Highways Manual 5.408.201.A |
| Tests                                                   | Results | Specification | Method |
| Los Angeles wear test                                    | 18.4    | Max. 25%       | 8.202.11 |
| Disintegration in sodium sulfate                         | 3.9     | Max. 12%       | 8.202.17 |
| Crushed particles                                        | 97.3    | Min. 90%       | 8.202.6  |
| Sintered particles                                       | 0.1     | Max. 10%       | 8.202.6  |
| Static adhesion method                                   | >95     | Min. 90%       | 8.202.29 |
| Dynamic adhesion method                                  | >95     | Min. 90%       | 8.202.31 |

| Characterization of natural aggregates, fine fraction according to Highways Manual 5.408.201.B |
| Tests                                                   | Results | Specification | Method |
| Plasticity Index                                        | NP      | NP            | 8.102.4  |
| Riedel & Weber adhesion                                 | 0-9     | Min. 0-5      | 8.302.30 |
| Disintegration in sodium sulfate                         | 5.3     | Max. 15%      | 8.202.17 |

| Characterization combined natural aggregates, Highways Manual 5.408.201.D |
| Tests                                                   | Results | Specification | Method |
| Soluble salts                                           | 0.5     | Max. 3%       | 8.202.14 |
| Sand equivalent                                         | 80.5    | Min. 50%      | 8.202.9  |

2.3. Recycled concrete aggregates (RCA)

Recycled aggregates from the production process of “high-quality recycled aggregates” are used (CORFO project 15IPPID-45706), from concrete waste from crushing compressed cement pipes. This material passes through a mechanical device designed especially as part of this project, where the removal of ITZ is maximized through rotation and shock between particles, reducing the damage of aggregates particles. The waste from the removal of ITZ including the material passing through the 2.5 mm sieve (ASTM N°8) are the RCA used in this study. Their characterization is in Table 3.

Table 3. Characterization of RCA according to Chilean regulations MC- V5 and V8 [21]

| Characterization of RCA, fine fraction according to Highways Manual 5.408.201.B |
| Tests                                                   | Results | Specification | Method |
| Plasticity                                             | NP      | NP            | 8.102.4  |
| Riedel & Weber adhesion                                 | 0-7     | Min. 0-5      | 8.302.30 |
| Disintegration in sodium sulfate                         | 6.5     | Max. 15%      | 8.202.17 |

| Characterization combined aggregates (Coarse Fraction 100% NA and Fine Fraction 100% RCA), Highways Manual 5.408.201.D |
| Tests                                                   | Results | Specification | Method |
| Soluble salts                                           | 0.5     | Max. 3%       | 8.202.14 |
| Sand equivalent                                         | 81.5    | Min. 50%      | 8.202.9  |

2.4. Granulometry

Semi-dense type IV A-12 particle size was used, which is in Figure 1, as it is the most used in Chile for intercity roads.
3. Methodology

The study is conducted in a sequential five-phase methodology. At the end of each phase, the results are analyzed to determine which procedures to adopt in the following phase: Figure 2. For each of the properties assessed, the average of three tested samples is given.

3.1. Phase I

This consists of the characterization of the materials, which includes NA and RCA, in their coarse, fine and combined fractions. This is presented in the Materials section of this work. The aim is to verify if the RCA and the combination of RCA and NA in the constitution of the particle size of the mixture fulfill the requirements stipulated in the Regulation, and based on the results obtained to determine the possible maximum limit of replacing the fine NA fraction with RCA.

3.2. Phase II

This corresponds to the design of the mixture according to the Marshall Design method described in point 8.302.47 of the MC-V8. This provided optimal asphalt binder content (AB), 5.4% referring to the weight of the aggregates.

3.3. Phase III

Four percentages of RCA replacement were assessed in the fine fraction: 100%, 75%, 50% and 25%, maintaining 5.4% of asphalt binder content, hereafter 100RCA-5.4, 75RCA-5.4, 50RCA-5.4 and 25RCA-5.4. Additionally, given that recycled aggregates have a lower density, a correction will be made to the concrete volume (CV), keeping the same amount of binder as the pattern mixture (5.4%). Hereafter, these mixtures will be called 100RCA-5.4CV, 75RCA-5.4CV, 50RCA-5.4CV and 25RCA-5.4CV. Finally, due to the greater absorption of RCA and the problems reviewed in the literature compared to subsequent failures due to moisture, mixtures with a greater percentage of binder will be evaluated (5.9%). These mixtures will be called 100RCA-5.9, 75RCA-5.9, 50RCA-5.9 and 25RCA-5.9. All the mixtures will be assessed with respect to the fulfillment of the Marshall method.
requirements for use as wearing courses in asphalt pavement structures according to what is stipulated in Tables 4 and 5, 5.408.203.A and 5.408.203.A, MC-V5 [21].

### Table 4. Requirements for asphalt mixtures, 5.408.203.A, MC-V5 [21]

| Type of asphalt mixture | Stability (N) | Fluency (0.25 mm) | Air Voids (%) |
|-------------------------|---------------|-------------------|---------------|
| Top Layer               | Min. | Max. | Min. | Max. |
| Binder                  | 9000 | 8    | 16   | 4.0  |
| Base Layer              | 8000 | 8    | 16   | 3.0  |
| Fine surface            | 6000 | 8    | 16   | 5.0  |

### Table 5. Minimum percentages of voids in the mineral aggregate (VMA), 5.408.203.B, MC-V5 [21]

| Nominal size (mm) | Minimum percentages of voids in the mineral aggregate (%) |
|-------------------|-----------------------------------------------------------|
| 25                | 13.0                                                      |
| 20                | 14.0                                                      |
| 12.5              | 15.0                                                      |
| 10                | 16.0                                                      |
| 5                 | 18.0                                                      |
| 2.5               | 21.0                                                      |
| 1.25              | 23.5                                                      |

3.4. Phase IV

At the end of Phase III, the evaluated mixtures that fulfill the Marshall criteria are expected to be defined. These mixtures will be studied in Phase IV with respect to their resistance to moisture damage and cracking, making it possible to determine the optimal replacement percentages of the fine fraction with RCA.

3.4.1. Susceptibility to water. This criterion is not a Chilean regulation. According to the literature review, the mixtures including RCA present deficient behaviors in terms of moisture damage; thus, this assessment criterion is included, and was determined using the indirect tensile strength ratio (ITSR), following the procedures stipulated in norms UNE-EN 12697-12 [22], UNE EN 12697-23 [23] and UNE EN 12697-30 [24]. The acceptance criteria regarding water sensitivity are:

- Mixture apt for wearing course: $\text{ITSR} \geq 85\%$
- Mixture apt for base and intermediate courses: $\text{ITSR} \geq 80\%$

These are established in the General Technical Specifications for Road and Bridge Works, part 5.4.2, Section 542.5.1.4 [25]. The testing conditions are a compaction using the Marshall method of 50 blows per side, to address mixtures with a maximum size below 22 mm (UNE EN 12697-30) [24], and the conditioning of test pieces at 25°C (range allowed by norm UNE-EN 12697-12 $5^\circ$-$25^\circ$). This temperature is chosen for being the most unfavorable condition.
3.4.2. Evaluation of cracking resistance through the Fenix® test. The Fénix® test is an unconventional test developed in the Roads Laboratory at the Universidad Politécnica de Cataluña. It consists of subjecting a cylindrical test piece to direct tensile stress until a previously induced crack spreads. The Fénix® test pieces are fixed by two steel plates. Then they are conditioned at the testing temperature. For this study, a testing temperature of 10°C was selected because the annual average temperature in the Region of La Araucanía is 11.5°C. The plates are fixed to the pistons on the test press by ball joints, which then move vertically at a constant speed of 1 mm/min (Figure 3). At the same time, the load and displacement values are recorded until the load has decreased to 0.1 kN, at which point the test is complete. With the collected data, a load-displacement curve is constructed (Figure 3) that provides the mechanical parameters that characterize the cracking resistance of the asphalt mixtures [26]. The main parameters of the Fénix® test analyzed in this study are:

- Maximum tensile load (Fmax): this is the highest value reached for the test piece in terms of the tensile stress to which it is subjected [26].
- Displacement at 50% Fmax (Δ50%) is defined as the displacement recorded when the load drops to half the value of its maximum load [26]. This parameter indicates the capacity of the mixture to tolerate deformations: the higher this value, the more malleable the mixtures and thus the more deformable.

**Figure 2.** Research methodology
4. Results analysis

4.1. Results of Phase I

The NA and RCA assessed in this study fulfill the requirements for use as material components of an asphalt mixture for pavement in a wearing course; therefore, there would be no regulatory restrictions to prevent the use of a 100% replacement of the fine aggregate fraction in the mixture with RCA. Table 2 and Table 3 show that RCA are more susceptible to the actions of sulfates because they have mortar in their walls, with a slightly higher disintegration percentage (1.2%) than NA. Nevertheless, RCA present a much lower disintegration percentage (6.5%) than the maximum allowed by the present regulation (15%). With respect to their behavior in terms of binder-aggregate adhesion, the results were also favorable for the RCA, but with values in the order of 2 points below the NA. This reduction in adhesion is likely due to a combination of factors. On the one hand, the mortar adheres to the outside of the aggregate (ITZ₁), and on the other, the mortar largely replaces the filler, which implies that the fine fraction is composed mainly of an aggregate of greater absorption and requires a greater amount of binder to maintain the adhesion conditions exhibited in the pattern mixture. The densities and the absorption percentage of the different aggregates were also calculated, which are presented in Table 6, where the RCA shows greater water absorption than the NA, approximately 3.4% more, which would cause an increase in the binder content required for the manufacture of a HMA.

On the other hand, it is noted that RCA have lower densities than NA, in the order of 306 kg/m³, which is due to the RCA containing mortar adhered to their walls and to the greater porosity they present, which causes them to have greater water absorption and lower densities. These results are consistent with studies conducted by different authors [14, 27], where absorption percentages for the RCA were in the range of 3.3 to 13%.

Table 6. Densities and absorption % of fine aggregate fraction

| Aggregates | Density kg/m³ | SD | Absorption | SD |
|------------|---------------|----|------------|----|
| NA         | 2629          | 9.13 | 0.98% | 0.25% |
| RCA        | 2323          | 8.46 | 4.33% | 0.12% |

4.2. Results of Phase II

The aim of this phase was to design the pattern mixture. The values of the parameters required by the regulation and the values of these parameters for the pattern mixture (5.4%) appear in Table 7. According to the results, it may be concluded that the HMA with a AB content of 5.4% fulfills all the requirements set out in the national regulation.

Table 7. Results parameters of Marshall Design for the pattern mixture

| Parameter         | Result | Regulatory requirement |
|-------------------|--------|------------------------|
| Density kg/m³     | 2360   |                        |
| Stability (KN)    | 12.3   | > 9                    |
| Holes in the mixture (%) | 4.4   | 4 – 6                  |
| Fluency (0.25mm)  | 9.6    | 8 – 16                 |
| VMA (%)           | 15.5   | > 15                   |
4.3. Results of Phase III

The aim of this phase was to design the pattern mixture. In this study it was verified that as the replacement percentage increases, the density (G) falls slightly, and reductions are observed between 4% and 1% for the mixtures 100RCA – 5.4 and 25RCA – 5.9, respectively. This is because RCA present a lower density than NA and represent around 30% of the total aggregate mixture. These results agree with the studies by Cupo-Pagano et al. [28], who describe the densities varying from 2300 kg/m³ to 2200 kg/m³ as the replacement of RCA is increased. It was also noted that there is an inversely proportional relation between the density reduction and the percentage of air voids in the mixture (Av), which agrees with what is to be expected in a denser mixture. This may also be due to the RCA replacement percentage decreasing: the Av decreases because NA are less absorbent than RCA, causing there to be a greater amount of effective binder, which closes the mixtures. Nonetheless, all the mixtures evaluated in this study fulfill the requirements established by the national regulation (Av between 4 and 6%), which differs from the results obtained by Cupo-Pagano et al. [28], whose study determined that the maximum percentage of fine aggregate replacement is 30%, since for a 50% RCA replacement the voids exceeded the regulatory requirements, which in their case could be due to the mortar content adhered to the walls of the RA and a lower binder content in the preparation of the mixtures (4% vs. 5.4% in the present project), causing greater binder absorption by the aggregates and due to the resulting larger Av content.

With respect to the evolution of strength, using the stability and deformation capacity of the mixtures and analyzing the fluency, the trend indicates that at a higher RCA replacement percentage in the mixtures there is an increase in the stability compared to the pattern mixture, with increases between 27% and 5% being observed for 100RCA-5.4CV and 25RCA-5.9, respectively. This may be because the fine RCA have greater angularity, which would contribute greater rigidity due to the greater internal friction that they experience when subjected to a load [29]. Consequently, the RCA replacement percentages fulfill the regulation, which stipulates that the stability must be greater than 9 kN. This agrees with the studies conducted by Wong et al. [30], where the stability of the samples with RCA increases 33%, 42% and 31% with RCA<0.075 mm, with RCA<3.15mm without treatment and RCA<3.15 with calcined aggregates, respectively.

In terms of the deformation capacity of the mixtures, an inversely proportional relation is observed with respect to the RCA replacement percentage. As the RCA replacement percentage falls, the deformation capacity of the mixtures increases, with reductions between 25% and 0.2% for 25RCA-5.4 and 100RCA-5.4, respectively. This may be because RCA have greater absorption and greater internal friction, which causes the samples to be less ductile. In any case, it was confirmed that all the mixtures with RCA replacement in the fine fraction fulfill the fluency limits established by the regulation, between 8 and 16 tenths of an inch. Finally, with respect to the values obtained for the VMA, all the mixtures fulfill this criterion, and it is verified that only the 25RCA-5.4 mixture is within the specification limit (VMA=14.9%). The previous results indicate that all the mixtures studied fulfill the criteria defined by the Chilean regulation for use as mixtures for asphalt wearing courses; however, according to the literature review, recycled aggregates do not behave well in humid conditions, which is why it is considered necessary to assess these mixtures in terms of their water resistance.

4.4. Results of Phase IV

4.4.1 Susceptibility to water

The results demonstrate that when the RCA content increases, water resistance decreases, and it is noted that the pattern mixture included between 25% and 9% for 100RCA-5.4 and 75RCA-5.4CV, since as the RCA replacement is increased, the mixtures present a higher percentage of water absorption (55% and 39% greater than the pattern sample, respectively) generating, for the mixtures with RCA, greater contact with water, enhancing the moisture damage. This effect can be counteracted by increasing the binder content to 5.9%, which produces a greater coverage of the aggregates and as a result a lower percentage of absorbed water (16% greater than the control sample). However, as a counterpart, this increase in the binder content generates an increase in production costs, which should
be evaluated in terms of their incidence in the final cost of the mixture (cost reduction in aggregates/increase in binder costs). Another option that reduces the production costs and has a favorable result is to use the 75RCA-5.4CV (ITSR = 86%) mixtures, since when the amount of aggregate (correction by volume) is balanced, the binder can counteract the high absorption of the RA and better cover the aggregates. Finally, if the desire is to maintain the same conditions as the control sample, it is only possible to use 50RCA-5.4 (ITSR = 85%). Indeed, according to this criterion, the RCA replacement contents that fulfilled the requirement were 50RCA-5.4, 75RCA-5.4CV and 100RCA-5.9.

This is consistent with the results reported by Mills-Beale and You [31], in whose study, for a replacement percentage of 50%, the value obtained was the same that in this study: ITSR 85%.

4.4.2 Cracking resistance
With respect to cracking resistance, the results indicate that as the RCA percentage increases, the cracking resistance of the test pieces also increases, with increases in the Fmax values between 39% and 30% for 100RCA-5.9 and 75RCA-5.4CV compared to the pattern mixture. This increase in resistance is accompanied by a reduction in the deformation capacity of the mixtures (Δmdp 41% and 21% lower than the pattern mixture, for 100RCA-5.9 and 75RCA-5.4CV, respectively), there being an inversely proportional relation between Fmax and Δmdp. This may be because when a greater amount of RCA, which have greater internal friction, is incorporated into the mixture, the resistance of the mixtures increases due to interlocking. When relating the results obtained to discussed the stability and fluency discussed in Phase III, the trend in resistance (Fmax) presented by the mixtures at 10°C is similar to that observed at 60°C (Stability), i.e., the greater the RCA replacement percentage, the greater the Fmax(10°C) and stability(60°C). However, when observing the deformation capacity of the mixtures (Δmdp), it is noted that at 10°C this decreases compared to the pattern mixture, with the difference being greater as the replacement percentage increases, unlike what occurs with the fluency at 60°C, which is greater for the mixtures with RCA than the pattern mixture, this difference increasing as the percentage of aggregate replacement decreases. This may be because when the RCA replacement percentage decreases, the proportion of binder that covers the aggregates increases, and at a high temperature, the binder is in a viscous state and acts as a lubricant, allowing for greater deformation of the mixtures with a lower recycled aggregate percentage.

5. Conclusions
Based on the experimental results it can be concluded that:

- In the characterization of the aggregates, both the NA and RCA used in this study fulfill the requirements for use as material components in an asphalt pavement mixture in wearing courses; therefore, there would be no regulatory restrictions that prevent the use of a 100% replacement of the fine NA fraction in the mixture with RCA.

- With respect to the design of the pattern mixture using the Marshall method, it is established that the optimal binder content for the type of NA used in the present study is 5.4% in relation to the total weight of the sample, which complies with all the parameters established in the national regulation.

- With respect to the design of the mixtures with RCA using the Marshall method, according to the criteria established in the national regulation, a 100% replacement of RCA in the fine fraction can be used, maintaining the binder dosage, because this mixture fulfills what is specified in the Chilean regulation regarding the percentage of voids in the mixture (4.5%), percentage of voids in the mineral aggregate (15.6%), stability (15.5 kN) and fluency (8.1%).

- Regarding susceptibility to water, for the execution of this test, not having a national regulation, the General Technical Specifications for Road and Bridge Works (PG 3) is used, written by the Spanish Ministry of Public Works and the Economy, which stipulates that for the wearing course, the indirect tensile strength ratio (ITSR) must be greater than or equal to 85%. Therefore,
according to this criterion, the RCA replacement contents that fulfilled this requirement were: 50RCA-5.4, 75RCA-5.4CV and 100RCA-5.9.

- Regarding the behavior due to cracking damage, which was done for the mixtures that fulfilled the criteria of resistance to moisture damage, it was shown that as the content of RCA replacement increases, the resistance (Fmax) increases and the deformation capacity (Δmdp) decreases, a result of the properties that the RCA present (greater internal friction and lower density, which produces a larger proportion of fine aggregates).
- Finally, according to the aim of this study and under all the parameters that the mixtures had to fulfill, three options were obtained: 50RCA-5.4, 75RCA-5.4CV and 100RCA-5.9. It is necessary to perform an economic analysis that involves the environmental impact to see which of these options would be the most preferable.
- Given that the mixtures recommended in this study fulfill the criteria of resistance to moisture damage, it is suggested that a test track be built in an area subjected to high precipitation levels to verify the performance of these mixtures under this condition on a real scale.

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