Pol. J. Environ. Stud. Vol. 24, No. 4 (2015), 1757-1763

Original Research

Critical Analysis of the Sustainable Consumption of Bitumen in Asphalt Concrete Mixtures Made with Recycled Concrete Aggregates from Construction and Demolition Debris

Ignacio Pérez[1]*, Ana Rodríguez Pasandín[1], Nuria Calvo[2], Jacobo Feás[3]

[1]School of Civil Engineering, Campus de Elviña, University of A Coruña, 15071 A Coruña, Spain
[2]Faculty of Economics and Business, Campus de Elviña, University of A Coruña, 15071 A Coruña, Spain
[3]Faculty of Business Administration and Management, University of Santiago de Compostela, Alfonso X "O Sabio", S/N. 27002 Lugo, Spain

Received: 10 December 2013
Accepted: 16 September 2014

Abstract

The frequent construction and demolition of buildings and civil works causes excessive waste of energy and natural resources. It is generally accepted that asphalt concrete (AC) mixtures made with recycled concrete aggregate (RCA) promotes sustainable construction. However, our analysis identifies an environmental downside: increased consumption of bitumen from these mixtures and therefore increased consumption of fossil fuels. Technical solutions to limit RCA content in mixtures, control their impurities, control the fraction in which it is used, and the application of pretreatments are emerging as potential tools to limit the consumption of bitumen by AC made with RCA. From the management point of view, we also propose as policy a revision of the technical specifications to adapt the technical standards to the particularities of RCA. This paper makes a contribution in joining both engineering and economic approaches in order to make proposals for construction management only using recycled materials economically feasible.

Keywords: sustainable management, recycled concrete aggregate, bitumen, environment impact assessment, strategic management

Introduction

The construction sector (both buildings and civil works) consumes a huge amount of energy [1] and endangers natural resources [2], which highlights its importance as a strong candidate when using waste as raw materials. This is particularly important in road building. Since the road network is characterized by its large size and because they are scattered over the entire surface, roads offer great potential for the use of waste. Especially considering that the industry road building is the largest consumer of aggregates at the European level [3].

Recycling is a key activity for sustainable construction. As world economies are heavily dependent on natural resources, both production and sustainable consumption

*e-mail: iperez@udc.es

of these are critical to achieving long-term and worldwide economic well-being. One way to do this is to reduce the dependence of such resources by reusing waste in order to prolong the life cycle of natural resources continuously.

The government of the most developed countries has strengthened from the '90s different options for management of construction and demolition waste (C&D), and its reuse in construction projects. Among the different options for managing this type of waste, recycling is the preferred option. However, there are many barriers and difficulties to applying recycling options [4].

Fractions of this type of waste that are objects of special attention as a material to be recycled are those formed by concrete, bricks, tiles, stones, ceramics, or asphalt, which represent 70–80% of total C&D, and they are primarily used to produce recycled aggregate.

The properties of the recycled aggregates depend on the characteristics of the materials from which they proceed, as well as selective demolition and crushing procedure, screening, and removal of impurities. Therefore, to make recommendations on their use, the first that arises is the need for classification. Below are the following types of recycled aggregates according to their composition [5]:

– Recycled concrete aggregates (RCA) are mainly obtained from C&D concrete. Jimenez et al., based on a study of three types of RCA, reached the conclusion that they are very pure because more than 96% of the particles are made of concrete [6]. The remaining components may be considered impurities (ceramic, asphalt, plaster, etc.).
– Recycled masonry aggregates (RMA) contain at least 90% brick and sand-lime brick, mixed or not with concrete.
– Mixed recycled aggregates (MRA) consist of mixtures of C&D, primarily concrete and ceramic.
– Construction and demolition recycled aggregates (CDRA) are recycled aggregates from construction and demolition debris that cannot be included in the categories listed above.

Also, the technical literature includes other recycled aggregates, such as recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) [7].

The use of recycled aggregate in the construction field is increasingly common in a variety of fields. In the case of RCA, there are experiences – in Spain and worldwide – of its successful use as a granular layer and cement-treated layer in roads [8, 9]. However, to date only a limited number of studies has been conducted on the use of RCA in bituminous mixtures [10, 11], but most of them show the great potential of using these materials in construction projects.

Preliminary analysis identifies a number of environmental benefits from the use of RCA in manufacturing asphalt concrete (AC) [3, 11, 12]:

– Reduce environmental impact of the extraction of natural aggregates such as noise, dust, vibration, visual, and landscape conditions.
– Mitigate the depletion of natural resources and, therefore, contribute to sustainable development in the medium term.
– Prevent the proliferation of abandoned quarries and reduce their environmental and landscape impact.
– Avoid strong socio-environmental impact caused by the dumping of RCAs and the waste of space that could be used otherwise.
– Avoid rejection of raw materials that if properly treated can be recycled.
– Avoid pollution of soils and aquifers that can arise when C&D are not separated properly in origin, or deposited in uncontrolled landfills. Many countries are witnessing this kind of uncontrolled dumping. For example, in Kuwait 33% of the waste produced is illegally discharged [13]. In Spain, despite efforts to eradicate this type of discharge, the National Integrated Waste Plan (PNIR) estimates that from the total C&D produced, 50% has been uncontrolled discharge [14].

Once detected the problem needs to be analyzed. This paper therefore seeks as an objective the technical-economic analysis of the use of RCAs in the manufacture of bituminous mixtures, and the proposal of measures to allow a greater use of this material in road construction.

After this introduction, the paper is structured as follows: first describing the environmental problem that limits the use of RCA in AC, given the increased demand of binders for this type of aggregate, and presents a causal analysis that relates, from a conceptual point of view, the consumption of aggregates with their environmental cost. Next we describe the experimental design based on research conducted in the laboratory of the School of Civil Engineering of the University of A Coruña (Spain). Finally, we present the results of the research and proposed solutions, some of them raised as a starting point for new research.

Description of the Environmental Problem: the Demand for Bitumen in AC Made with RCA

To facilitate the understanding of the environmental problem object of our study, we identified a number of relevant variables and we have related them through two loops with dynamic behavior, following the methodology of causal analysis of system dynamics [15]. This analysis is a starting point that allows us to intuitively understand how the stimulus for the use of construction waste need not necessarily contribute to reducing environmental impact.

To this end, we have identified the following variables:

– Pressure to encourage sustainable construction: determine the economic value of incentives offered by the government to encourage the consumption of construction waste.
– RCA consumption: the volume of recycled aggregates used in road construction.
– Natural aggregate consumption: the volume of natural aggregates used in road construction.

– Environmental impact: assesses the overall environmental impact in road construction.
– Bitumen demand: determines the required quantity of bitumen in road construction.
– Fossil fuel consumption: indicates the volume of fossil fuels (petroleum) required in the construction of roads.

The relationships between variables, according to the standards of the methodology chosen, reflect direct relationships (positive sign) or reverse (negative) set to dynamic variations of the elements related.

From a conceptual point of view, we can say that the use of waste as construction material components is part of the concept of sustainable construction [16], since it allows performing more efficient management of resources and thus reduces the environmental impact of the management and treatment of waste.

In addition, by recycling in construction and the consumption of recycled aggregates a number of benefits can be achieved such as, for example, reducing the need for energy and natural resources (natural aggregates) and optimizing the use of landfills.

The above increases social pressure from the government, which will provide incentives to sustainable construction that seeks the increased consumption of RCA in civil engineering construction. In the stimulation loop described below (Fig. 1), this reflects a dynamic behavior. Increased incentives for sustainable building (pressure to encourage sustainable construction) will increase the consumption of residues as components of the mixture in road construction (RCA consumption), reducing the consumption of natural aggregates (natural aggregates consumption). The reduction in consumption of these aggregates reduces total environmental cost (direct). And this will also reduce the volume of government incentives to this end, having fulfilled the goal.

The simplified analysis of this fact could lead us to say that a policy of incentives of temporary use of RCAs in road construction will help reduce the environmental cost would solve a major problem for the administration.

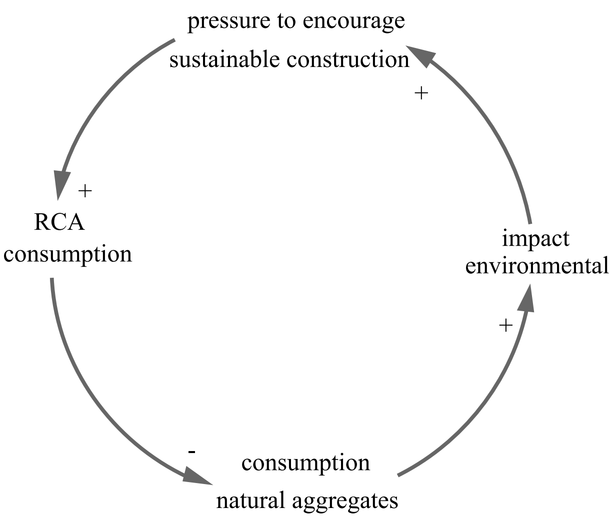

Fig. 1. Loop to encourage the consumption of RCA.

However, this reality is more complex than it seems, and this requires a more comprehensive technical analysis. The use of RCA in AC is an environmental problem that cannot be ignored, which is the increased demand for binders (bitumen) of such aggregates [11, 17] compared to that of natural ones. As shown in Fig. 2, the AC, manufactured in part with RCA from waste from construction and demolition (C&D), show optimum contents of binders higher than conventional mixtures [12, 18-25] i.e., those with a 0% RCA. This is most pronounced when the replacement of natural aggregate is performed by RCA in the fine fraction [23]. Furthermore, as shown in Fig. 2, the consumption increases with increasing binder content in the RCA mixture.

From an environmental perspective, it has to be taken into account that the asphalt bitumen or penetration bitumen is a petroleum product and, therefore, a higher consumption of bitumen means more oil consumption. Thus, as reflected in Fig. 3, an increase in consumption demand of RCA increases the bitumen blends (direct connection), and this would increase the consumption of fossil fuels, leading to greater environmental impact against the target set initially in all policy incentives to recycle and reuse these materials.

The conceptual analysis performed allows us to have an idea of the complexity of the problem and the difficulty of tracking detailed economic and environmental impact of the use of various materials, components, and procedures and their alternatives [26].

In order to go further with the analysis of the relationship between some of the variables involved, an experimental design aimed to estimate parameters of consumption of bitumen in AC mixtures made with RCA is presented in this paper.

Experimental Design

Research carried out in the Laboratory of Highway at the School of Civil Engineering of the University of A Coruña (UDC) suggest do not exceed 30% of RCA in manufacturing bituminous mixture type AC 22 base G. Fig. 4 shows the granulometric curve selected for this bituminous mixture. The production of AC base layer used two types of aggregate: natural aggregate and RCA. As natural aggregate has been used cornubianite. The RCA comes from construction and demolition waste from residential buildings of various origins and was supplied by a recycling plant of construction and demolition waste from Madrid, Spain. The asphalt mix was manufactured with RCA percentages of 0%, 5%, 10%, 20%, and 30% in fraction 8/16 mm and 4/8 mm (the latter only for 30% of RCA). In all cases this has been used as filler and gray Portland cement as binder penetration bitumen B50/70 from Venezuela. The optimum binder content was carried out for each of the selected percentages by performing RCA Marshall test [27] on cylindrical samples of 101.6 mm diameter and 63.5 mm height compacted with 75 blows per face with Marshall mace.

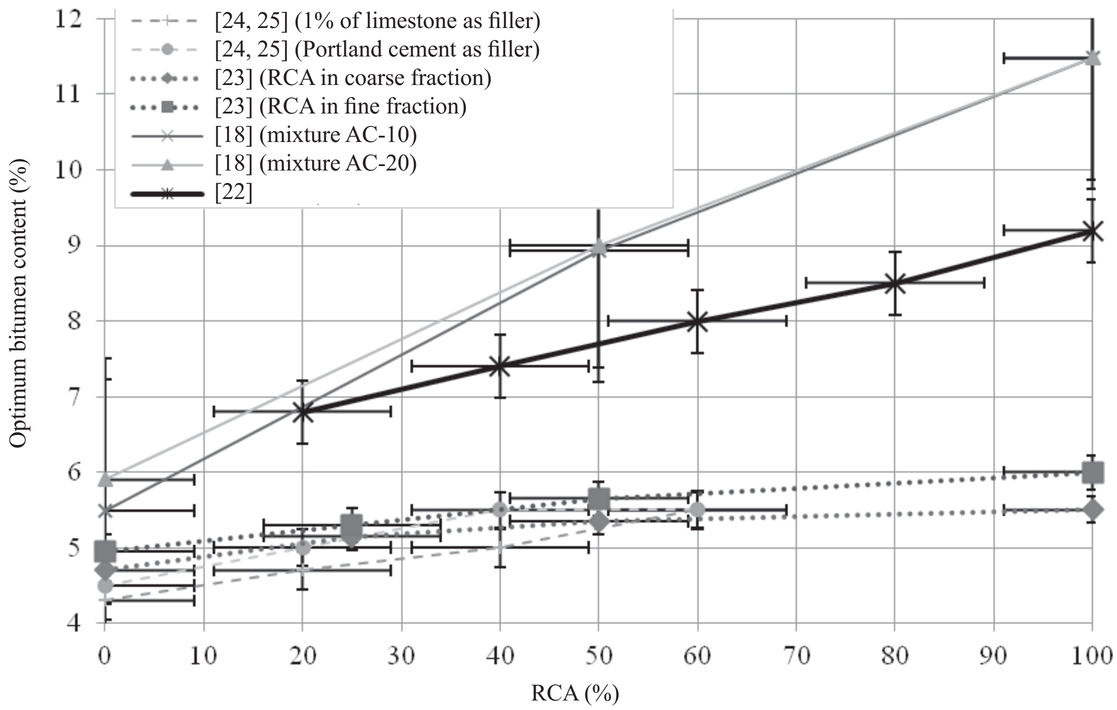

Fig. 2. Variation of optimum binder content based on the percentage of RCA.

This limit of 30% is given for two main reasons:

- The possible reduction in mechanical properties of the mixtures made with higher percentages.
- Grading instability posed by RCA. It has been shown that RCA fragments during mixing operations and compaction of asphalt mixtures that intervene, making this type of mixture present granulometric instability. This phenomenon also occurs in conventional mixtures to a lesser extent. It should be noted that other researchers [28, 29] have also noted the change in the size distribution of the AC made with RCA after mixing and compacting them, attributing this to the weak cement mortar attached. Fig. 4 shows the variation in the grading of AC 22 asphalt mix made with a base G 4% B50/70 and RCA percentages of 0%, 5%, 10%, 20%, and 30% in fractions 8/16 mm and/or 4/8 mm. After recovery of the aggregate [27] it can be seen that mixing with 30% of RCA goes slightly out of the spindle considered by Spanish specifications after mixing and compacting, and how it differs from the initially selected granulometry.

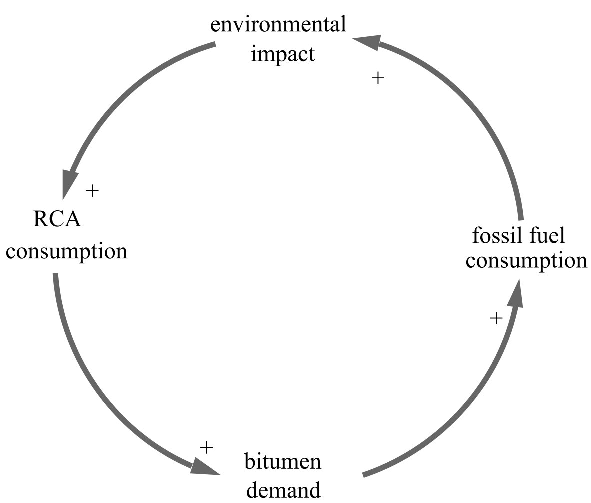

Fig. 3. Loop of disincentive to RCA consumption.

Accepting the limit of 30% of RCA in the manufacture of AC, and taking into account the data of Fig. 2, it can be seen that increasing the binder content between a mixture and a mixture with conventional RCA will reach a maximum of 2% (mixtures AC 10 and AC 20). The limit of the mixing set to 30% requires further study, since the properties of mixtures made with RCA will depend both on the type of RCA used in their manufacture and the properties of natural aggregate. Of particular importance is its affinity with the binder and its resistance to fragmentation.

The experiment was carried out with a dosage of such mixtures by using the Marshall method, according to standard NLT [27]. The results are attached in Fig. 5. As can be seen in this case, increasing the optimal bitumen content (Bo) between 0% and 30% RCA would be much lower (only 0.3%).

As shown, there are strong differences between the consumption of binder shown in Fig. 2 and those shown in Fig. 5. These differences in the increase of optimum bitumen content proposed by other researchers might be for several reasons: a) the type of RCA employed in the manufacture of mixtures, b) the fractions used in the RCA, and c) particular technical specifications of each country.

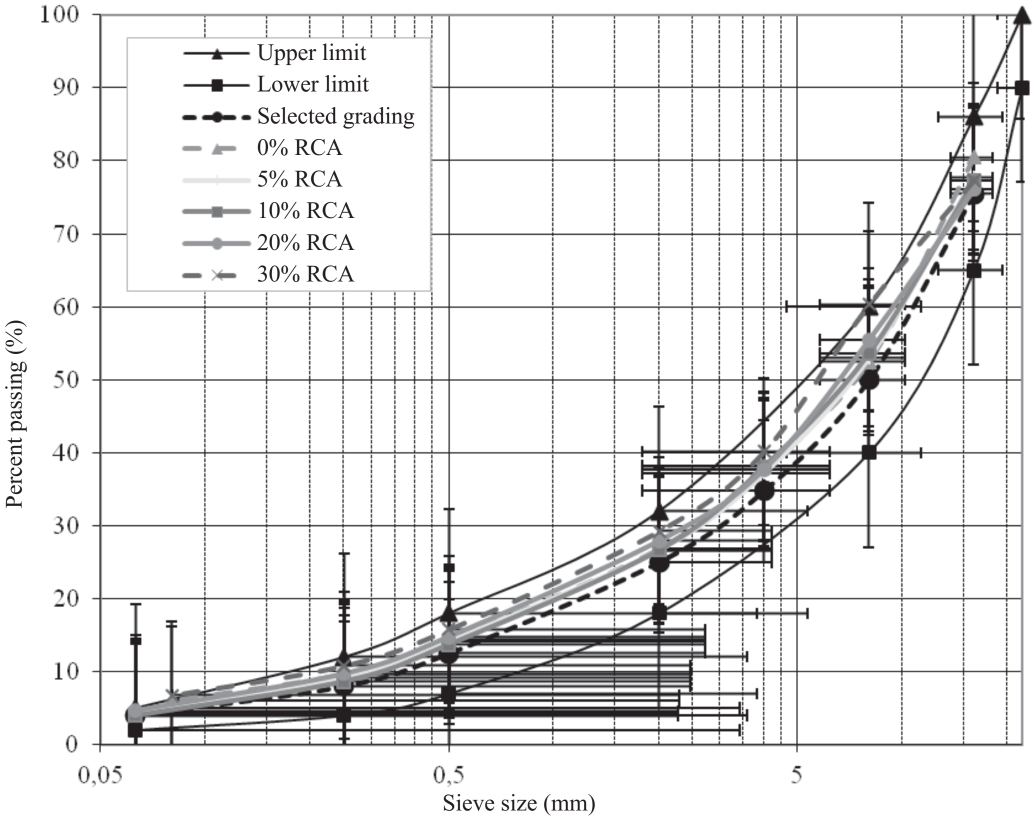

Fig. 4. Select granulometry and granulometry from bituminous mixes produced with RCA after mixing and compacting (obtained from recovered aggregates).

The following sections examine the reasons and indicate possible ways to reduce their effect on optimum binder content:

a) The type of RCA employed in the manufacture of mixtures

Difference: As for the type of RCA employed, it is noteworthy that Jimenez et al. [6] based on a study of three types of RCA from construction and demolition (C&D), concluded that they are fairly homogeneous, because over 96% of the particles are made of concrete (71-76% are natural aggregates with adhered mortar, and 20-25% are natural aggregates without adhered mortar). The remaining components may be considered as impurities. Thus there would be between 1.6% and 3.5% of ceramic material, between 0% and 0.3% asphalt, between 0% and 0.1% gypsum, and insignificant amounts of wood, glass, plastic, metal, natural soil, and light particles. Some of the impurities present in the RCA can cause an increased demand for binder materials because facing the making of AC they have lower quality than the concrete, except asphalt.

Proposal: to limit the consumption of bitumen, a prior removal of impurities would be required, in particular removal of ceramic material and the gypsum.

b) Fractions used in the RCA

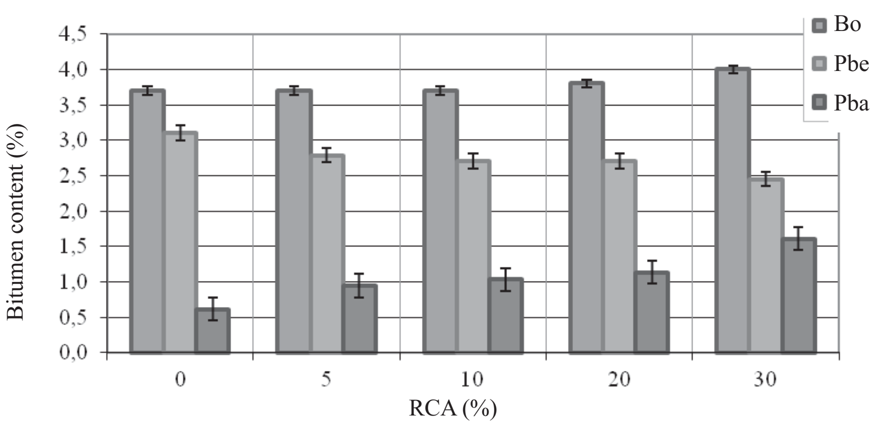

Fig. 5. Optimum binder content, effective binder content, and binder content absorbed by the percentage of RCA.

Difference: in order to see the influence in the consumption of bitumen of the fractions in which RCA is used, it should be noted that the RCA from C&D differs mainly from conventional aggregates having mortar attached to its surface [8, 13].

The attached mortar is primarily responsible for the binder increased absorption of RCA than a conventional aggregate [22]. Since the fine fraction has a higher mortar content than the coarse [8, 13], it also has a higher absorption than the coarse fraction. In this sense Bushal et al. [22], proposes that, for economic reasons, the RCA substitution should take place in the coarse fraction, to avoid greater optimum binder content.

Proposal: from the research, it is recommended that, for mixtures of maximum aggregate size of 22 mm, the substitution should be made in fractions of 8/16 mm and 4/8 mm. Using RCA in thicker fractions would introduce excessive heterogeneities in the mixture.

Therefore, to reduce the consumption of bitumen of AC made with RCA, the use of RCA should be limited to the coarse fractions, while keeping in mind that too thick fractions (greater than 16 mm) might introduce excessive heterogeneities to the mixture.

c) Technical specifications of each country

Difference: Finally it has been seen that the technical specifications may also influence the amount of binder. As is well known, in each country the technical specifications of the AC can be very different. In Spain the General Technical Specification for Road and Bridge Works, PG-3 [30] requires a minimum binder content of 3.5%, while for example the Florida Department of Transportation (FDOT) requires a minimum 5% effective binder content [31]. The effective binder content (Pbe) is the percentage of binder is not absorbed by the aggregate. Although most aggregates have certain absorptions of binder, in the case of RCA, absorption (Pba) adopts a high value. In this regard, it is interesting that some researchers [28, 32] indicate that the effective binder content of bituminous mixes made with RCA is lower than conventional mixtures, due to the high absorption of binder by RCA. As seen, the main responsibility of this feature is the absorbent nature of the cement mortar on the surface of the RCA, so that the larger the RCA content greater the absorption of binder [22]. As shown in Fig. 5, the tests performed in this study confirmed these results: with increasing percentage of RCA, Pba and Bo increase while Pbe decreases slightly.

Proposal: to ensure sustainable consumption of bitumen in bituminous mixes made with RCA it would be appropriate to review the rules of each state or country and adapt the specifications to the peculiarities of the RCA. Specifically, given the absorbent nature of the RCA it seems inappropriate to specify a minimum amount of effective binder.

Finally, the results of this research allow advances in new technical solutions aimed at reducing consumption of bitumen by the AC made with RCA. The embodiment of any "coating" of RCA with lime or bitumen emulsion to partially seal the pores of the aggregate could reduce absorption binder. This research is currently open in the University of A Coruña (Spain), and we hope it will be the starting point for further analysis.

Conclusions

From the experiment we can conclude that the AC made from RCA consumes a greater amount of bitumen and therefore a greater amount of oil. Thus, it calls into question the ultimate goal of sustainable construction going against the principles of reducing consumption of natural resources and thus their impact on the environment. It would be necessary to determine whether the reuse of RCA could environmentally compensate an increased consumption of bitumen as binder.

More research is needed to make the AC made with RCA an effective sustainable building material with a binder content similar to that used in conventional mixtures. To contribute to the reduction of the binder content of such mixtures, the following measures can be taken:

- Limit RCA content of the mixture. 30% seems to be the most appropriate value. Higher limits may be inadmissible due to unstable particle size having such mixtures.
- Adapting the specifications and technical standards to the particularities of the RCA. In particular, since the RCA has a greater absorption than conventional bitumen aggregates, it seems not appropriate to set a lower limit of absorbed binder content.
- Remove RCA impurities before its use in the manufacture of AC, particularly gypsum and ceramic materials. These materials, besides being highly absorbent, have a lower quality that may result in higher consumption of bitumen.
- Limit the use of RCA to coarse fractions, since the finer fractions contain a greater percentage of highly absorbent mortar. In any case it is not convenient to use fractions over 16 mm because they may introduce excessive heterogeneities in the mix.
- Perform an RCA pretreatment to partially seal the pores and thus reduce the absorption of binder. Conducting a "coating" of the RCA with lime or bitumen emulsion are research topics currently followed at the UDC.

On the other hand, if the use of RCA in the manufacture of AC is generalized, local waste could be used closer to the production of asphalt, thus saving on transport costs, particularly of fossil fuels.

The analysis presented in this paper is a new addition to the environmental impact assessment of sustainable construction from a technical-economic perspective, which seeks to improve the understanding among the stakeholders (administrations, producers and consumers of aggregates, society) in order to assess the complex systemic implications of their actions. Academically, this research opens new alternatives of analysis in a research topic that currently is very active.

Acknowledgements

The authors wish to acknowledge the Spanish Ministry of Education and Science for sponsoring this research through Project BIA2010-17751.

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