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## Relation between construction company size and the use of recycled materials

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### Abstract

For a circular economy approach in the construction sector, it is important to understand the value of using recycled materials in buildings and other constructions, reducing the extraction of natural resources, as well as the generation of construction and demolition waste. The role of construction companies is relevant in the sense that they are one of the main actors for this change. However, the differences within the sector, namely the size of the construction companies, can make it hard to implement, so it is essential to understand the factors influencing it. To this end, a structured questionnaire survey was submitted to Portuguese construction companies, dividing the sample of 652 answers into three groups (micro, small, and medium/large companies). Data treatment was carried out to determine whether there are significant statistical differences between groups regarding the use of recycled materials. Their use is carried out by most of the companies, in all groups, with the factors in favor related to the internal practices of the companies, and the against factors associated with market availability. For recycled aggregates, in particular, there is a weak self-evaluation of knowledge about these materials. Furthermore, there is a risk perception in terms of confidence in its use. These conclusions are important for the definition of differentiating strategies to promote and improve the use of recycled materials by construction companies.

### Keywords

Construction sector; Construction companies; Construction and demolition waste (CDW); Recycled materials; Recycled aggregates



## 1. Introduction

Using more sustainable materials is an important contribution of the construction sector to implement the circular economy principles (Tam *et al.*, 2018b; Le & Bui, 2020; López Ruiz *et al.*, 2020). This is relevant in terms of political and technical strategies leading to the minimization of environmental impacts regarding natural resources extraction (European Commission, 2011; European Commission, 2012), the mitigation of CO<sub>2</sub> emissions (Huang *et al.*, 2018), as well as the reduction of construction and demolition waste (CDW) generation, in this case through the reuse of materials, but also promoting recycling (European Commission, 2015; European Commission, 2016; European Commission, 2020). However, the use of recycled materials, understood as materials that fully or partially incorporate recycled waste (*e.g.*, recycled aggregates resulting from CDW, urban furniture made from plastic waste, plasterboard incorporating cardboard from paper and cardboard waste) involves specific legal and procedural obligations. Knowledge in this subject has been produced in recent years and has the potential to be even more explored. The results have shown that the use of recycled materials in the construction sector, with a great focus on recycled aggregates, can be carried out without raising great constraints, as long as meeting the final products technical requirements (Duran *et al.*, 2006; Contreras *et al.*, 2016; Pacheco *et al.*, 2017; Tam *et al.*, 2018b; Silva *et al.*, 2019; Wu *et al.*, 2019; Le & Bui, 2020).

In Portugal, although lagging behind other European countries (European Commission, 2017), there have been initiatives to integrate the concerns about CDW management and the use of recycled materials in legal and procedural guiding documents. However, the construction sector stakeholders recognize constraints to overcome, and there is a widespread consensus that the role of regions, municipalities, and construction companies, especially the practices of micro and small companies, must assume a primary worry in the construction sector vision and strategies (Ramos *et al.*, 2014; Ramos *et al.*, 2020). These observations have been corroborated by other authors concerning construction companies, in general, namely about: the importance of the technical knowledge covering (Li *et al.*, 2015; Bakshan *et al.*, 2017; Li *et al.*, 2018; Chen *et al.*, 2019), the companies' size and the practices' application in construction sites (Begum *et al.*, 2009), the relevance of cooperative relationships among stakeholders (Ajayi *et al.*; 2016; Tam *et al.*, 2018a; Mak *et al.*, 2019), as well as CDW illegal dumping reality (Solís-Guzmán *et al.*, 2009; Chen *et al.*, 2019; Lu, 2019). The last case is a problem in terms of potential loss of materials capable of being transformed into recycled components to be used in buildings and other constructions.

These constraints are essential to understand, in this case through the Portuguese reality, the factors influencing the incorporation of recycled materials, with a more detailed focus on the use of recycled aggregates. This is crucial to the extent of perceiving whether the strategies in progress should continue or be redirected towards different realities. Since this assessment is missing, this article aims to contribute to this subject, focusing the research on the size of construction companies.

## 2. Literature review

### 2.1. Construction and demolition waste generation and its physical composition

Considering all the waste generated in one year in the European Union, CDW represents around a third, in weight (Eurostat, 2018). The usual is that in datasets from countries with more complete and robust data registration systems on waste, and due to the CDW characteristics, the inert mineral fraction (*i.e.*, concrete, bricks, and masonry) appears in a greater proportion. Metals, on the other hand, usually appear in disproportionate quantities in less developed registration systems, where metals from other sectors of economic activity (*e.g.*, dismantling of vehicles at the end of their life) are wrongly coded in chapter 17 of the European List of Waste (Commission Decision 2014/955/EU, of 18 December, amending Decision 2000/532/EC on the list of waste), corresponding only to CDW (European Commission, 2017).

CDW generation indicators are presented in two ways, either by intervention area or *per capita*. The use of these indicators generates discussion, in Portugal, among the actors intervening in the CDW value chain, as they are not homogeneous. On the one hand, this is because they are based on a few case studies, but also since they rely on statistics where the absence of consistent data is notorious. For instance, datasets are based on declared CDW, ignoring CDW illegal dumping occurrences (De Melo *et al.*, 2011). Some indicators were disaggregated, with work based on monitoring construction interventions, with a focus on buildings, resulting in indicators for the urban reality of Portugal (Lisbon), by type of intervention (demolition, rehabilitation, and new construction) and for two types of use (housing and commercial) (Coelho & De Brito, 2011a).

On the other side, CDW physical composition differs depending on the construction materials that are used (Coelho & De Brito, 2011b), as well as on the type of construction activity intervention. The authors calculated the CDW average physical composition for Portugal, obtaining the following values: concrete, bricks, and masonry (73.6%); mixtures bituminous (13.5%); other CDW (7.4%); wood (3.2%); metals (2.2%), and plastic (0.1%). Other studies about the Portuguese CDW declared

show the prevalence of concrete, bricks, and masonry along with the CDW physical composition (Martinho & Ramos, 2015), corroborating the prevalence of the mineral component. The Portuguese Environment Agency also presented the declared values obtained through the registration system on waste for 2018, where concrete, bricks, and masonry mixtures represent around 76% of the CDW available for recovery (APA, 2018). These results show the great potential that CDW has for recovery, essentially through recycling.

Within this reality, the European Union, through the Waste Framework Directive (2008/98/EC on waste, amended by Directive EU 2018/851) stated the preparing for reuse, recycling, and other material recovery, including backfilling operations using waste to substitute other materials, of non-hazardous CDW, excluding naturally occurring material, shall be increased to a minimum of 70% by weight, until 2020. And to help to achieve that goal, currently Portugal also has a specific aim of incorporating in public construction works 10% of recycled materials or materials incorporating recycled components. Since the target is very low, the operational viability is easily proven. This is the case of a theoretical exercise, made regarding pre-selected subway construction works developed within Lisbon Metropolitan Area (Portugal), above all reflecting the possible use of recycled aggregates (Carneiro *et al.*, 2017).

The potential of recyclability resulting from the physical composition of CDW is a major factor where lies the importance of the construction sector for the circularity principles (EY-AM&A, 2018) and, for that reason, the analysis will continue with a greater focus on the recycled aggregates component.

## **2.2. From construction and demolition waste to recycled materials constraints**

Through studies that have been conducted within Portuguese municipalities (De Melo *et al.*; 2011; Ramos *et al.*, 2014; Ramos *et al.*, 2020), CDW illegal dumping is often identified. This reality reveals a problem in terms of losing waste with potential for recovery, namely through its transformation into recycled aggregates to be used in buildings and other constructions. The majority of Portuguese municipalities are aware of CDW illegal dumping reality but, in many cases, they assume they are unable to act due to lack of human resources to carry out oversight actions (Martinho *et al.*, 2013). Portuguese waste management operators also identify CDW illegal dumping as one of the main causes for CDW not reaching their waste management facilities (European Commission, 2017).

Although scarce, other studies identify CDW illegal dumping as a difficult problem to combat (Solís-Guzmán *et al.*, 2009) or analyze the causes for its occurrence. For example, Chen *et al.* (2019)

conclude that merely increasing the value of penalties does not greatly influence the disappearance of CDW illegal dumpsites, with oversight actions taking on a fundamental role. In Hong Kong, Lu (2019) used a methodology based on big data analysis, referring to CDW transport data, to assess through behavioral indicators the driving forces for CDW illegal dumping. It is stated that those who practice illegal dumping are mainly freelancers, who are usually less patient to wait in the lines of entry into the CDW treatment facilities, relating these occurrences to the behavioral issue, specifically at the individual level.

On the other hand, it is necessary to assess the CDW recovery facilities' territorial coverage. In Portugal, specifically for the Metropolitan Area of Lisbon, De Melo *et al.* (2011) indicates that the infrastructures for the CDW treatment are located at a distance of approximately 23 km from the geocentre of Lisbon. There are also records about CDW illegal dumpsites, as mentioned above. Thus, it is necessary to understand whether the distances are adjusted, or if other factors are influencing, such as communication and information and awareness, oversight, and control of procedures.

Regarding economic instruments, fixing CDW landfilling costs, as well as the associated environmental fees, is not an easy task, and it can even make CDW diverge towards illegal dumping. In this context, Wang *et al.* (2019) propose to consider life cycle analysis to optimize the environmental fee to be paid, mainly because there is wide variation in prices in China, where different zones charge prices without direct government oversight actions. These results show the need to harmonize criteria among regions, so it can be possible to tackle the problems in the same context.

Also for Portugal, the economic feasibility of using recycled aggregates, in specific, has been studied, as well as the CDW treatment infrastructures (Coelho & De Brito, 2013), including the influence that economic instruments may have in the delivery of CDW to licensed waste management facilities, since a large part of this waste continues to diverge to illegal dumpsites. The environmental cost is also not internalized into landfilling operations, nor into natural materials costs, penalizing the use of recycled aggregates.

### **2.3. The incorporation of recycled aggregates resulting from construction and demolition waste**

Although the use of aggregates is high in the construction sector worldwide, as pointed out by Tam *et al.* (2018b), the use of recycled aggregates may differ from country to country, due to the construction traditions, the legislation requirements, and the perception and acceptance level of the

construction sector stakeholders, but also including the clients' perception. Since CDW is generated by the construction sector activity in large amounts, the use of recycled aggregates is a great solution in terms of a circular approach to the sector's activity.

In Europe, the average for recycled aggregates incorporation on construction sites, compared to the use of total aggregates, is low (around 9.4%), with the countries above the average being those that have mature legislation and a long history about CDW management (European Commission, 2017). For instance, in Switzerland, Knoeri, Binder & Althaus (2011) demonstrated the importance that the interaction between stakeholders has in the choice of incorporating recycled aggregates, even though they continue to prefer conventional construction materials. The authors also determined that the decisions that prevail are not the ones that appear in the initial project specification, but the legal specifications and the experience in similar works, with the recommendations of other stakeholders also playing an important role.

Although depending on their characteristics, Tam *et al.* (2018b) concluded that recycled aggregates resulting from CDW can be applied in a wide range of civil engineering works, but most is being used in lower end applications, even if it is also being incorporated in structural concrete. Through a literature review conducted in 24 countries of Oceania, Asia, Europe, Africa, and America continents, the authors concluded there is a commitment to the use of recycled aggregate, if considering for instance legislation requirements (standards and normative documents) and the reduction of natural resources depletion. In this context, recycled materials have been used in concrete, concrete pavements, roadway construction, and other civil engineering projects. Complementing this analysis, Le & Bui (2020) accomplished a state-of-the-art about the application of recycled aggregate concrete, considering the recycling techniques of old-concrete-aggregates, the mix proportioning, the mechanical properties, the durability, the structural behavior, and the fire resistance, concluding about its viability: the possible substitution ratio for coarse aggregates can reach 100% in many cases, while for fine aggregates, it is more reasonable to limit the substitution ratio at 30% to 50%. In Switzerland, recycled aggregates have been used in civil engineering work in a percentage of around 30%, although in structural engineering this amount does not reach 10% (Knoeri, Binder & Althaus, 2011).

Silva *et al.* (2019) concluded about the technical viability for the use of recycled aggregates, through the analysis of several case studies, including the use in unbound, hydraulically-bound, and bitumen-bound applications, as well as in (non-)structural concrete in road and building construction.

However, the authors highlighted the lack of confidence in the use among designers and construction companies. The authors also mentioned the use of recycled aggregates in countries like Denmark, Netherlands, and Germany, where, apart from the scarce existence of natural aggregates, the existing environmental policies promoting the use of recycled materials are important to encourage confidence in its use. On the other hand, countries not committed to CDW separation and inadequate recycling procedures have led to a general lack of confidence amongst stakeholders.

The certification process has a high impact in terms of the acceptance for the use of recycled aggregates, although most of the recycling plants are producing non-certificate products (Tam *et al.*, 2018b). Also, the authors considered necessary the commitment of government authorities supporting policies related to the use of recycled aggregates, taking into consideration: the cost of recycled versus natural aggregates, the lack of a well-developed collection and processing facilities, the scale of the market, and the proper use considering the final product in terms of a cost-efficiency analysis.

Research opportunities are still missing in what regards CDW recyclability and criteria for wasted materials and recycled products, in terms of material science and engineering perspective, but also regarding reducing CDW considering the project phase, in terms of architecture, engineering, construction, and operation of buildings (Wu *et al.*, 2019). Cruz, Gaspar & de Brito (2019) propose the application to the construction sector of the concept of “sustainable sustainability”, including the design phase, trying to extend overtime the designs of the environmental, social, and economic pillars. And there is a lot of potential for innovation, as the case studied by González *et al.* (2021), using bioproducts and applying them to the surface of concrete with recycled aggregates. The purpose is to create a protective layer, being this solution a promising treatment to protect the surfaces and increase durability.

CDW recovery in waste recycling facilities is a process being conducted essentially since World War II (Tam *et al.*, 2018b; Silva *et al.*, 2019). But in the latest years, this subject gained importance through the implementation of circular economy principles. Nevertheless, recycled aggregates resulting from CDW are not being applied in developing economies, mainly because of regulatory frameworks and lack of knowledge and confidence. Their incorporation in buildings and other constructions still offers some resistance, although the studies by Pacheco *et al.* (2017), Contreras *et al.* (2016), Tam *et al.* (2018b), Silva *et al.* (2019), and Le & Bui (2020), are an important contribution to raising knowledge

and awareness to the confidence levels in the use of recycled aggregates in pre-determined conditions.

But it is essential to better understand the main factors that might contribute to the use in the construction sector of recycled materials, in general, and recycled aggregates, in particular. It is necessary to undertake deep knowledge about the factors influencing the perception of construction companies on the use of these materials. In this context, this research aims to present an evaluation of the main determining factors influencing it, trying to understand the criteria to adapt or change the policies applicable to the construction sector activity. This assessment will be made considering the reality of the construction company size.

### **3. Method**

#### **3.1. The questionnaire**

An online structured questionnaire was planned and submitted to Portuguese construction companies with two specific groups of questions. The first group was related to recycled materials, in general (with the questions and results presented in subchapter 4.1). The second group was related to recycled aggregates resulting from CDW, as a specific example of recycled materials (with questions and results stated in subchapter 4.2). The questions tried to answer the following variables:

- About the recycled materials, in general: the perception of the importance attributed to the advantages of using recycled materials, to assess the degree of consensus about the use of this type of materials in the construction sector; the use of recycled materials in construction works, to evaluate the factors that may interfere with it; the acquisition origin of the materials; as well as the predominant types, in terms of the proportion related to the use of recycled aggregates in the total of recycled materials;
- In terms of recycled aggregates resulting from CDW: to assess the degree of knowledge that Portuguese construction companies have regarding the value chain of this type of recycled materials; and the main determining factors contributing for using recycled aggregates, namely environmental, risk perception, execution, planning, but also information and awareness.

The platform LimeSurvey was used to submit the questionnaire in September of 2017, allowing to receive answers until November of the same year. It is important to note that the current regulatory

framework and practices referring to CDW management remain similar to that of 2017. The results obtained were statistically treated using IBM SPSS Statistics.

### 3.2. Population, sample size, and statistical treatment of hypotheses

To meet the main goal of this research, the size of the construction companies was selected as a group variable, using the Portuguese official classification in nine construction permit classes defined for construction companies, considering the number of employees and their turnover.

In 2017, 22,445 Portuguese construction companies were registered by a Portuguese public organization related to the construction sector, the *Instituto dos Mercados Públicos, do Imobiliário e da Construção* (IMPIC) (Institute of Public Markets, Real Estate, and Construction). Nevertheless, it was only possible to contact 11,626 companies using an online database available through IMPIC (2017).

The questionnaire was answered by 652 companies, with the distribution by construction permit classes rearranged in the three groups defined for this study (Table 1) (Ramos & Martinho, 2021): group A - micro construction companies (construction permits from classes 1 to 3); group B - small construction companies (construction permits from classes 4 to 6); and group C - medium/large construction companies (construction permits from classes 7 to 9).

**Table 1.** Number of Portuguese construction companies contacted and number that answered the questionnaire.

Groups	Construction permit classes	Construction companies contacted				Answers to the questionnaire	
		Total		Valid contacts		N.º	%, in relation to valid contacts
		N.º	%, in relation to the existing construction companies	N.º	%, in relation to construction companies contacted		
<b>A</b> (Micro companies)	1, 2 and 3	10,908	84.8	9,870	84.9	466	4.7
<b>B</b> (Small companies)	4, 5 and 6	1,707	13.3	1,532	13.2	144	9.4
<b>C</b> (Medium/large companies)	7, 8 and 9	242	1.9	244	1.9	42	18.8

Statistically significant differences between the groups were established as the hypothesis to be tested regarding the following variables: i) perception about the importance of the use of recycled materials, ii) use of recycled materials, iii) acquisition origin of recycled materials, iv) predominant

types of recycled materials used, v) knowledge about recycled aggregates, and vi) factors contributing for using recycled aggregates.

To evaluate statistically significant differences between the groups, the one-way ANOVA was used for sample means, and the Pearson's chi-square test ( $\chi^2$ ) for sample frequencies. For samples in which it is not possible to use the chi-square test, due to having counts below five corresponding to more than 20% of the total, the likelihood ratio (G2) was used for sampling frequencies. For these statistical tests, a value of  $\rho \leq 0.05$  was considered as the minimum acceptable significance level, corresponding to a 95% confidence level.

## **4. Results and discussion**

### **4.1. Recycled materials in general**

#### **4.1.1. Perception about the advantages of using recycled materials**

The respondents representing Portuguese construction companies answering the questionnaire were asked about the importance attributed to the advantages of using recycled materials, or materials incorporating recycled components, on construction works. For this assessment, a Likert scale was used, from 1 (totally unimportant) to 7 (extremely important). The average value increases from micro construction companies, from group A (5.34 average value), to small companies, from group B (5.49 average value), and again to medium/large companies, from group C (5.50 average value), although without statistically significant differences between the groups defined ( $F(2, 608) = 1.748$ ;  $\rho \leq 0.175$ ). The average value for all the construction companies (5.40, that is 1.40 above the midpoint of the scale) might be considered a good result concerning the importance attributed to the use of recycled materials in the construction sector. Answers corresponding to “not having an opinion about the subject” represent 6.3% of the total.

#### **4.1.2. Use of recycled materials on construction works**

The questionnaire asked whether Portuguese construction companies usually incorporate recycled materials, or materials containing recycled components, in the construction works performed, being the results described in Table 2. Although without statistically significant differences among groups ( $\chi^2(4) = 9.436$ ;  $\rho \leq 0.051$ ), 46.5% of the Portuguese construction companies incorporate these materials, with the medium/large companies (group C) executing it in a more consistent way (61.9%). Considering the technician who answered the questionnaire, the lack of knowledge about the company procedures decreases from micro to medium/large construction companies (group A to C,

respectively), with medium/large companies representing only 4.8%. These results also show the lack of knowledge among micro and small construction companies, that has been referred, in general, by other studies about CDW practices among constructions companies (Ajayi *et al.*, 2016; Bakshan *et al.*, 2017; Li *et al.*, 2018).

**Table 2.** Use of recycled materials, or materials containing recycled components, on construction works.

Does the company incorporate recycled materials, or materials containing recycled components, on construction works?	Number of answers (%), by construction companies' group			Total	Statistic test
	Group A	Group B	Group C		
	N = 466	N = 144	N = 42	N = 652	
Yes	44.4	48.6	61.9	46.5	$\chi^2 (4) = 9.436;$ $\rho \leq 0.051$
No	34.5	36.1	33.3	34.8	
Do not know	21.0	15.3	4.8	18.7	

For the 303 Portuguese construction companies (46.5% of the total) incorporating recycled materials in construction works, respondents were questioned about the reasons for companies acting this way, in this case allowing more than one answer for pre-selected options. The results are organized in Table 3 in descending order of the total number of answers. In general, it was observed that the most common answer is that it is a usual practice for the company to incorporate this type of material, and the less common in what regards the competitive prices in relation to other materials (60.7% versus 25.4%, respectively). It demonstrates the compromise to perform along with the current and past practices (corroborated by Knoeri, Binder & Althaus, 2011), as well as the question is the relation to costs, that has been highlighted by other authors when there are waste facilities and a positive cost-benefit balance (corroborated by Coelho & De Brito, 2013, and Tam *et al.*, 2018b). There are no statistically significant differences between the groups in these two cases ( $\chi^2 (2) = 4.843;$   $\rho \leq 0.089;$  and  $\chi^2 (2) = 0.450;$   $\rho \leq 0.799;$  respectively).

Two options achieved statistically significant difference among groups, one referring to the compliance with the contract specification ( $\chi^2 (2) = 11.564;$   $\rho \leq 0.003$ ), and the other relative to the quality of recycled materials when compared to other materials ( $\chi^2 (2) = 8.323;$   $\rho \leq 0.016$ ). Contract specifications are more relevant to medium/large construction companies, in line with what has been concluded by Silva *et al.* (2019), regarding the existence of environmental policies as a driving force to ensure the use of recycled aggregates. But maybe also because they assumed that is a usual practice for the company. In the case of the recycled materials quality guarantee, micro construction companies appear to be less convinced, not being clear if it is a matter of knowledge or a lack of

practice regarding the use of recycled materials. For this reason, this ambiguity should be explored in further studies.

**Table 3.** Reasons to use recycled materials, or materials containing recycled components, on construction works.

What are the main reasons to incorporate recycled materials, or materials containing recycled components, in construction works?	Number of answers (%), by construction companies' group			Total	Statistic test
	Group A	Group B	Group C		
	N = 207	N = 70	N = 26	N = 303	
Usual practice of the construction company	58.5	60.0	80.8	60.7	$\chi^2 (2) = 4.843$ ; $\rho \leq 0.089$
Comply with the contract specification	34.8	38.6	69.2	38.6	$\chi^2 (2) = 11.564$ ; $\rho \leq 0.003$
Recycled materials guarantee at least the same quality as non-recycled materials	24.2	37.1	46.2	29.0	$\chi^2 (2) = 8.323$ ; $\rho \leq 0.016$
Competitive prices compared to other materials	25.1	24.3	30.8	25.4	$\chi^2 (2) = 0.450$ ; $\rho \leq 0.799$

In a complementary way, the 227 companies (34.8% of the total) not incorporating recycled materials in construction works, were questioned about the reasons for this, also allowing more than one answer (Table 4). In this case, the lack of supply in the market for recycled materials is the more relevant topic for the construction companies (51.5% of the total), as also identified by Tam *et al.* (2018b). Nevertheless, it is a more relevant issue for micro construction companies, although it also appears to be important for medium/large construction companies. The differences are statistically significant between groups ( $\chi^2 (2) = 8.001$ ;  $\rho \leq 0.018$ ). This conclusion also corroborates the lack of this type of material in the European market (European Commission, 2017). On the other extreme, the reference that the topic is not specified in the contract specification seems to be more relevant to medium/large construction companies, than it is for micro and small companies, respectively, again with statistically significant differences between groups ( $G^2 (2) = 7.513$ ;  $\rho \leq 0.023$ ). In this case, it may also indicate that micro construction companies lack environmental issues detailed in the contract specification.

Although without statistically significant differences between the groups, and far less expressive than the first option mentioned, related to market supply, the following options are important for the construction companies: the legal framework conditions (18.9% of the total), which can express a feeling that there is not enough legal support on this matter, or that the compliance with the legal background can be difficult to achieve (supported by Tam *et al.*, 2018b, and Silva *et al.*, 2019), having

this topic to be more explored in other opportunities; and the uncompetitive prices of recycled materials (17.2% of the total), which can be justified by the fact that in Portugal raw materials are abundant, so recycled materials prices are not competitive (corroborated by Coelho & De Brito, 2013; and Tam *et al.*, 2018b).

But two more subjects need reflection: one concerning the lack of interest of the company regarding this matter (10.1% of the total); and a lack of confidence about using recycled materials (8.4% of the total) (also pointed out by Knoeri, Binder & Althaus, 2011; Tam *et al.*, 2018b; and Silva *et al.*, 2019). These two last results denote constraints that have to be resolved when trying to accomplish the circular economy principles in the construction sector.

**Table 4.** Reasons not to use recycled materials, or materials containing recycled components, in construction works.

What are the main reasons for not incorporating recycled materials, or materials containing recycled components, in construction works?	Number of answers (%), by construction companies' group			Total	Statistic test
	Group A	Group B	Group C		
	N = 161	N = 52	N = 14	N = 227	
Lack of supply in the market for recycled materials	57.1	34.6	50.0	51.5	$\chi^2 (2) = 8.001$ ; $\rho \leq 0.018$
Legal framework conditions	16.1	28.8	14.3	18.9	$\chi^2 (2) = 4.338$ $\rho \leq 0.114$
Uncompetitive price of recycled materials	14.3	21.2	35.7	17.2	$\chi^2 (2) = 4.905$ ; $\rho \leq 0.086$
Not applicable to the company's activity	11.8	9.6	21.4	11.9	$\chi^2 (2) = 1.473$ ; $\rho \leq 0.479$
Lack of interest by the company in this matter	12.4	5.8	0.0	10.1	$\chi^2 (2) = 3.593$ ; $\rho \leq 0.166$
Lack of confidence using recycled materials	6.8	13.5	7.1	8.4	$G^2 (2) = 2.063$ ; $\rho \leq 0.356$
Not specified in the contract specification	5.0	9.6	28.6	7.5	$G^2 (2) = 7.513$ ; $\rho \leq 0.023$

#### 4.1.3. Acquisition origin of recycled materials used

For the acquisition origin of the recycled materials used in Portuguese construction works, the questionnaire asked about the more frequent type of suppliers, between two types: national (Portuguese) or foreign. National suppliers represent 85.1% of the total answers, and only 2.0% are foreign suppliers, without statistically significant differences between the groups ( $G^2 (4) = 4.697$ ;  $\rho \leq 0.320$ ). Nevertheless, there is a considerable number of respondents from the construction

companies (12.9%) recognizing that they do not know the answer, being this consistent with the lack of knowledge reported by other authors about the practices adopted along the CDW value chain (e.g., Begum *et al.*, 2009; Ding *et al.*, 2016).

#### **4.1.4. Predominant types of recycled materials used**

About recycled materials, respondents from Portuguese construction companies were asked about the perception of the predominant types used in construction works. Although with no statistically significant differences between the groups ( $G^2(4) = 2.665$ ;  $p \leq 0.615$ ), 48.5% of the respondents recognized, in specific, the use of recycled aggregates resulting from CDW, and 48.2% the use of other recycled materials. In the last case, the questionnaire did not allow to specify which they are. These answers denote the perception about the use of a predominant type of recycled materials in the Portuguese construction sector, which are the recycled aggregates. It is also important to note that, in this case, only 3.3% of the total responded that they do not know the answer.

### **4.2. Recycled aggregates resulting from construction and demolition waste**

#### **4.2.1. Knowledge about recycled aggregates**

There is the perception that the predominant type of recycled materials used by Portuguese construction companies is the recycled aggregates resulting from CDW (subchapter 4.1.4). In this context, the respondents were asked to self-evaluate, in general, their knowledge in what regards different aspects of the value chain of this type of materials: the production, the different types existing and different uses, the certification process and oversight authorities, the costs, and the supplier chain. With this intention, a Likert scale was used, between 1 (does not know anything) and 7 (knows everything).

The results obtained (Table 5) are organized in descending order of results about the perception of knowledge, showing statistically significant differences between the groups for all the topics. The results are never superior to an average value of 3.48 (possible uses), below the midpoint of the scale. For all the answers, the Portuguese micro construction companies (group A) know less than the small companies (group B), and even less than the medium/large companies (group C). Although these results apply specifically to recycled aggregates, they demonstrate that the lack of knowledge is related to the construction company size. This conclusion is supported by Begum *et al.* (2009), although referring, in general, to CDW management practices in construction sites. These differences, depending on the construction company size, should be considered when defining

awareness and training programs on this subject, whether for buildings or other construction types in general.

Regarding the knowledge about recycled aggregates, the bottom topic refers to the responsibility about technical standards, preceded by oversight authorities (average values of 2.89 and 2.92, respectively). These results show a lack of interrelation to the authorities in the matter of regulatory framework and procedures, having to be taken into account when deciding strategies in relation to the involvement of the stakeholders, as pointed out by Bakshan *et al.* (2017), Tam *et al.* (2018b), and Silva *et al.* (2019).

**Table 5.** Knowledge self-evaluation about recycled aggregates.

Topic	Knowledge self-evaluation about recycled aggregates, in a Likert scale, from 1 (does not know anything) to 7 (knows everything), by construction companies' group			Total	Statistic test
	Group A	Group B	Group C		
	N = 466	N = 144	N = 42	N = 652	
Possible uses	3.35	3.70	4.24	3.48	F (2, 649) = 7.974; $\rho \leq 0.000$
Quality for its intended purpose	3.32	3.66	4.31	3.46	F (2, 649) = 8.677; $\rho \leq 0.000$
Cost	3.23	3.53	3.98	3.34	F (2, 649) = 4.876; $\rho \leq 0.008$
Different types existing	3.03	3.43	4.17	3.19	F (2, 649) = 12.298; $\rho \leq 0.000$
Certification for its intended purpose	3.00	3.49	4.17	3.18	F (2, 649) = 12.824; $\rho \leq 0.000$
Companies providing them	3.03	3.48	3.71	3.17	F (2, 649) = 6.634; $\rho \leq 0.001$
Production process	2.97	3.48	4.21	3.16	F (2, 649) = 15.605; $\rho \leq 0.000$
Oversight authorities	2.75	3.09	4.12	2.92	F (2, 649) = 13.905; $\rho \leq 0.000$
The entity responsible for technical standards	2.70	3.15	4.05	2.89	F (2, 649) = 14.795; $\rho \leq 0.000$

#### 4.2.2. Main factors contributing to the use of recycled aggregates

Aiming to better understand the behavior of Portuguese construction companies, the respondents were asked to evaluate their perception about the use of recycled aggregates compared to natural aggregates. With this objective, they were invited to complete a sentence, concerning the following

factors: environment, risk perception, planning, execution, and information/awareness. For this purpose, a Likert scale was applied, from 1 (totally disagree) to 7 (completely agree). The results are presented in Table 6.

In general terms, the environmental factor was better evaluated, considering the perception that the use of recycled aggregates can both contribute to avoiding the extraction of natural resources (average value of 6.25) but also for minimizing CDW generation (average value of 6.14). In the last case, there are statistically significant differences between the groups ( $F(2, 608) = 3.543$ ;  $p \leq 0.030$ ), where the micro companies (group A) recognize this subject less than the small companies (group B), and even less than the medium/large companies (group C). The environmental component related to the use of recycled aggregates, in specific, seems to be in line with the importance given to the use of recycled materials, in general (subchapter 4.1.1).

There is a risk perception, related to the guarantee of the safety issues of the products (average value of 4.99), but also to the client perception (average value of 4.11), with statistically significant differences among the groups in both cases ( $F(2, 573) = 6.874$ ;  $p \leq 0.001$ ; and  $F(2, 594) = 5.267$ ;  $p \leq 0.005$ ; respectively). In general, these conclusions are substantiated by Knoeri, Binder & Althaus (2011); Tam *et al.* (2018b); and Silva *et al.* (2019). Regarding these results, medium/large construction companies perceive the risks in a more solid way than micro companies. These two aspects should be reinforced in information and training campaigns, but also in the communications from authorities.

In terms of the execution of the construction work, the results show that the companies may comply with the use of recycled aggregates but is necessary to guarantee an economic advantage (average value of 4.59), so the scale of use of recycled materials is an important aspect to balance the costs, as supported by Coelho and De Brito (2013) and Tam *et al.* (2018b). Nevertheless, regarding the possibility of using the materials only in less demanding technical execution (average value of 3.56), medium/larger companies recognize it less, although without statistically significant differences between groups.

About construction works planning, there might be a perception that the regulatory framework is not appropriate or is difficult to comply with, and that the planning for construction works is missing (average values of 3.56 and 3.10, respectively) (supported by Li *et al.*, 2015). Finally, about the information and awareness factor, there is a recognition, in general terms, referring to the lack of knowledge (average value of 3.24), also previously validated by Begum *et al.* (2009).

**Table 6.** Perception about the factors influencing the use of recycled aggregates on construction works.

Main factors		Complete the sentence: Using recycled aggregates instead of natural aggregates ...	Perception about the factors influencing the use of recycled aggregates, in a Likert scale, from 1 (totally disagree) to 7 (completely agree), by construction companies' group			Total	Statistic test
			Group A	Group B	Group C		
Environment	Resources	... is a way to avoid the extraction of natural resources.	6.21 N = 437	6.25 N = 139	6.65 N = 40	6.25 N = 616	F (2, 613) = 2.478; $\rho \leq 0.085$
	Waste	... is a way to minimize the CDW generation.	6.09 N = 433	6.17 N = 138	6.63 N = 40	6.14 N = 611	F (2, 608) = 3.543; $\rho \leq 0.030$
Risk perception	Result	... guarantees safety issues and the quality of the final products.	4.98 N = 403	4.73 N = 135	6.00 N = 38	4.99 N = 576	F (2, 573) = 6.874; $\rho \leq 0.001$
	Client	... may be difficult to implement because of the clients' misleading risk perception.	3.99 N = 421	4.25 N = 136	4.95 N = 40	4.11 N = 597	F (2, 594) = 5.267; $\rho \leq 0.005$
Execution	Costs	... is possible but only if the costs compensate it.	4.60 N = 421	4.55 N = 137	4.72 N = 39	4.59 N = 597	F (2, 594) = 0.118; $\rho \leq 0.390$
	Technical component	... is possible for construction works if less demanding in terms of technical execution.	3.60 N = 399	3.66 N = 134	2.82 N = 39	3.56 N = 572	F (2, 569) = 3.005; $\rho \leq 0.050$
Planning	Legal framework compliance	... is possible because there is an appropriate legal framework.	3.54 N = 371	3.50 N = 125	4.03 N = 33	3.56 N = 529	F (2, 526) = 1.213; $\rho \leq 0.298$
	Execution	... is possible because there is planning for the construction works in the design phase.	3.10 N = 395	3.26 N = 130	2.55 N = 40	3.10 N = 565	F (2, 562) = 2.178; $\rho \leq 0.114$
Information and awareness		... is possible because there is enough technical knowledge about the subject.	3.19 N = 399	3.30 N = 132	3.50 N = 40	3.24 N = 571	F (2, 568) = 0.578; $\rho \leq 0.562$

## 5. Conclusions

In terms of circularity in the construction sector, including buildings and other constructions, it is important to understand the main determinant factors influencing the use of recycled materials, in general, and recycled aggregates, in specific. The main results, obtained through a questionnaire

submitted to Portuguese construction companies show the following, through the answers given by the respondents:

- The major reasons contributing for the practice of incorporating recycled materials include the compliance with internal procedures, as well as with the contract specification, although in this last case it is more relevant for medium/large companies than for micro and small ones;
- The lack of supply in the market for recycled materials is the main reason pointed out by the Portuguese companies for not executing it, being this subject more relevant for micro companies, but also for medium/large companies, denoting, in this case, a reality for the Portuguese construction sector itself;
- In specific to recycled aggregates, there is a weak self-evaluation of knowledge about the different aspects related, from the production, the different types existing and different uses and certification processes, the costs, the supplier chain, and the oversight authorities, showing the tendency, in all cases, that micro construction companies know less than other companies;
- The most important factor that justifies the use of recycled aggregates is the environmental factor (*i.e.*, saving resources and reducing CDW generation), which is in line with the importance attributed to the use of recycled materials, in general;
- The perceived risk of using recycled aggregates is a factor in which there are differences between the perception along with the size of construction companies, related to the guarantee of the safety issues, but also the client perception, being the medium/large construction companies more worried about those aspects than micro companies;
- For the information and awareness factor referring to recycled aggregates, there is the acknowledgment about the lack of technical knowledge.

In general, the results state the importance of using recycled materials in the construction sector. In specific, about recycled aggregates resulting from CDW, variables such as the degree of knowledge for different aspects of the value chain, but also the risk perception for its use, have to be considered in information and training campaigns. The results should also be reflected in the circularity strategies to apply in the construction sector, namely those concerning the constraints identified related to the size of construction companies.

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