

A COST-EFFECTIVE RECYCLED AGGREGATES CLASSIFICATION PROCEDURE FOR CONSTRUCTION AND DEMOLITION WASTE EVALUATION

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Abstract

Current procedures for characterization of recycled aggregates from construction and demolition waste can be time-consuming and costly, and hinder a greater breadth of re-use application. A multi-level Aggregate Potential (Physical) (AP(P)) scale is presented as a *simple and cost-effective* procedure for this characterization. To validate the AP(P), a group of mixed recycled aggregate samples were tested for composition, density, fines content, water absorption and freeze-thaw resistance. The results identify different quality ratings with potential uses, and simple treatments for higher value purposes. This procedure is purported to improve recycled aggregate manufacturing and secondary material markets, therefore contributing to a more circular economy.

Keywords

Aggregates, recycled aggregates, construction and demolition waste, circular economy, up-cycling, aggregate classification, recycling

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1. INTRODUCTION

Construction and demolition (C&D) waste is *the* most significant waste stream across the EU, accounting for over 800 million tonnes per year [1]. The UK alone produced 66.2 million tonnes of non-hazardous C&D waste in 2016, which accounted for around 30% of total waste produced in the country [2]. As such, the EU's Waste Framework Directive set the target for all European member states to achieve a minimum of 70% recycling or reuse rate of non-hazardous C&D waste by 2020 [3]. Whilst the UK achieved a 91.0% recovery rate in 2016, exceeding the target set by the EU, statistics show that recovery is heavily reliant on backfill (DIR 2018/851 [4] defines backfilling as 'any recovery operation where suitable non-hazardous waste is used for purposes of reclamation in excavated areas or for engineering purposes in landscaping'): more than 75% of C&D waste in the UK was recovered as backfilling in 2011 [3]. This low-value application is due to the inconsistent quality of the source; dependent on multiple facets, such as differing construction and demolition processes, levels of segregation, age, degradation, etc. This leads to a lack of confidence in the quality of these secondary materials and contributes to the stigma that C&D recycled aggregates are low-value by default. Notably, and for example, Xu et al. [5] reports that '…it is well-understood that the incorporation of recycled concrete aggregates in a concrete mix can lead to some impacts on the mechanical properties of the concrete due to the inferior characteristics.' Additionally, there is also the associated uncertainty circumventing the potential health risk for workers using these recycled materials. This, in turn, reduces and restricts the demand for C&D waste recycled materials and inhibits the development of waste management and recycling infrastructures in the EU [6].

Typically, non-hazardous C&D waste streams converge from different construction sites, with variable volumes and characteristics. Classification and characterization of primary aggregates is relatively easy as the source is constant and only periodical tests are needed. Whereas, with recycled aggregates with variable and uncertain sources, is, therefore, very expensive and inefficient to follow the same procedure. Mixed waste is usually crushed as all-in-one recycled aggregate and used as a low-value product. Thus, the aim of this research is to present a *simple* classification method for recycled aggregates from C&D mixed waste that can aid the selection of appropriate re-use applications according to their quality. To achieve this, existing literature was reviewed to identify suitable standard tests and requirements for physical properties of C&D waste, of which, a simplified method for classification according to basic physical properties was developed to improve such evaluation. To initially validate, a group of ten recycled aggregate samples was tested and this procedure was applied in order to determine their quality with respect to potential low- and high-value uses of aggregates. Recommendations can subsequently be made by selecting simple treatments to improve the quality of these recycled aggregates and upgrade their potential use. This method, integrated in a bigger manufacturing process development, can enhance the way C&D mixed recycled aggregates are classified and applied in the construction industry. Doing so, it would support the reduction in the ongoing exploitation of natural resources for primary aggregates and improve the opportunities for business, with more solutions to this waste in the market and at a higher value.

2. BACKGROUND

In 2014, 137 million tonnes of crushed rock aggregate (more commonly termed primary or natural aggregate) was extracted and sold in England and Wales [7], which was subsequently used in a variety of applications, such as: concrete manufacturing, road construction, railway ballast or drainage [8]. In doing so, natural aggregates have to meet specification standards of the relevant application quality requirement. These specification thresholds are no different for recycled aggregates [from C&D waste] and therefore appropriate quality testing needs to be in place if C&D replacement is to be viable.

C&D waste generally consists of several waste types, such as: concrete, ceramics/ bricks, soils, and contaminants such as gypsum/ plaster, glass, wood, bituminous material, metals or plastics. C&D waste properties vary according to the proportion of these waste types, and valorization can be compromised if these contaminants exceed 1% of the total mass [9]. Due to the inconsistency and variable performance of the source material, research has been carried out that has developed classification systems for recycled aggregates. This allows material to be categorized by its suitability for certain uses compared to primary aggregates.

Existing research generally focuses on the properties of recycled aggregates in application areas, such as, for example, in concrete columns; but sparse research exists to support how to cost-effectively evaluate C&D waste *for* use in application domains; for example: see Xu et al [10] for analysis in the application of FRP-confined columns (fiber-reinforced polymer); Silva et al [11] for analysis on the compressive strength of concrete; Wang et al [12] for evaluation in concrete columns under cyclic loadings; Xu et al [13] for evaluation of compressive behavior in concrete columns; Ferreira et al [14] on pre-saturation of concrete properties; Chen et al [15] for application in concrete-filled steel tubes; Folino and Xargay [16] for mechanical behavior under uniaxial and triaxial compression; and Xu et al [5] for parametric sensitivity analysis.

An extensive review of studies governing the assessment process of aggregates (Table 1) demonstrates that there is no standard and consistent procedure; existing procedures vary in the properties tested (which are typically grouped in terms of physical, mechanical and chemical properties) and the resultant classification scale (which varies in terms of A-C and A-G). Of note, the greater the number of procedures required, the more costly and time consuming to undertake. Thus, the principal underlying requirement is to determine the type of procedures required to meet threshold standards that can effectively evaluate quality – in a *simple* manner that is not resource intensive (both in terms of time and cost). Hence, the purpose of this research.

TABLE 1. COMPARISON OF RECYCLED AGGREGATES ASSESSMENT PROCEDURES AND CLASSIFICATIONS

Researcher	Aggregate properties			Classification	Commentary
	Physical	Mechanical	Chemical		

	Water absorption	Density	Drying shrinkage	Grain size	Flakiness index	Weak particles	Dry & wet strength	Los Angeles abrasión value	Aggregate impact value	Chloride content	Sulphate content		
Tam and Tam [17]	✓	✓	✗	✓	✓	✗	✗	✗	✓	✓	✓	Class A-G	Based on international standards
Paine and Dhir [18]	✓	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗	Class A-C	Focuses on performance characteristics rather than composition or source
Kotrayothar [19]	✓	✗	✗	✗	✓	✓	✓	✗	✗	✓	✓	Class A-C	Described a classification scale but failed to demonstrate in practice. Argued need for reducing the number of tests
Silva *et al.* [11]	✓	✓	✗	✗	✗	✗	✗	✓	✗	✗	✗	Class A-D	A performance-based system based on work of Paine & Dhir [18]
Rodriguez-Robles *et al.* [20]	✓	✓	✗	✓	✓	✗	✗	✓	✗	✗	✗	Class A-D	Based on Silva *et al.* [11], however, it has been criticized because of greater number of tests involved

3. METHOD

This research forms part of a larger project that addresses C&D mixed waste up-cycling in concrete products as shown in Figure 1. The proposed method described in this paper corresponds to the development and validation of the Aggregate Potential (Physical) (AP(P)) score. It includes two different stages: stage 1 is focused on developing a simple procedure to evaluate the quality of C&D mixed recycled aggregates from construction and demolition (C&D) waste; stage 2 puts emphasis on sampling and testing of C&D waste mixed recycled aggregates and validation of this AP(P) score.

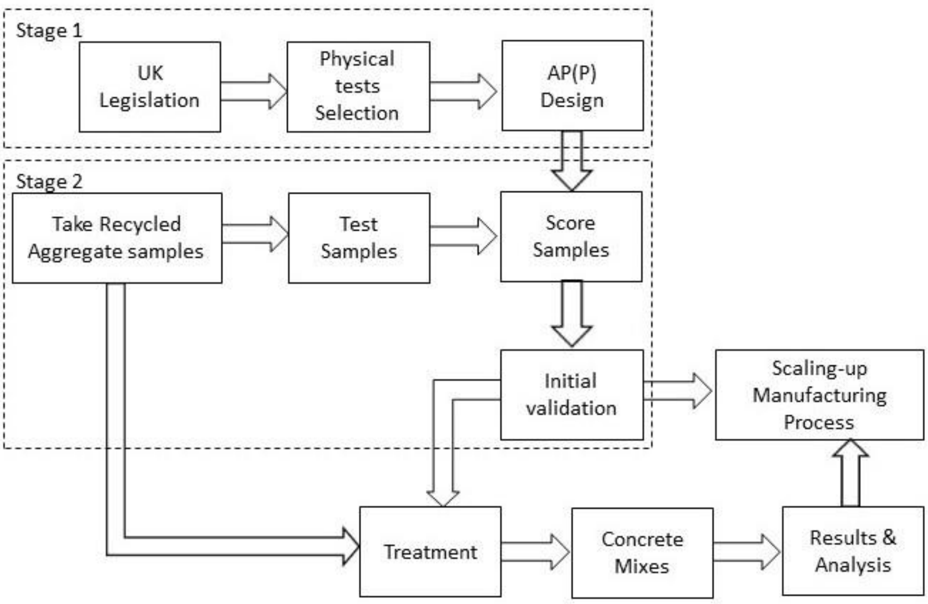


FIGURE 1. METHODOLOGY (STAGES 1 & 2) FOR C&D MIXED WASTE UP-CYCLING IN CONCRETE PRODUCTS

3.1 Stage one - Design of the AP(P) scale

The definition of the AP(P) scale involved three steps: a thorough desktop review of the legislation applied in the UK for natural and recycled aggregates for different uses; the selection of most appropriate physical tests that could represent best the aggregate characterization; and finally, the creation of the AP(P) score was achieved for comparison of C&D waste samples. Research was guided by the experience of project team members in C&D waste, material science, engineering and construction, which contributed to its development.

A review of the legislation of natural and recycled aggregates in the UK, and of existing evaluation methods as applied in C&D waste was firstly undertaken. Thus, it was concluded that the basic physical properties of recycled aggregates were centric in determining aggregate classification in a cost-effective manner that would yield the same or similar classification results as existing studies. Physical properties encompass the majority of issues governing aggregate evaluation, focusing on evaluating grain size, porosity structure and internal cracking. Additionally, potential operational resource constraints (time, cost, capacity etc.) were also considered. The principal reasons for the selection of physical tests to build the AP(P) were:

- Recycled aggregates have a higher quantity of fines, a significant part of which is present on the coarse aggregate surface [21]. These fines, together with the increase in porosity, causes an increase of water absorption and a higher demand of water which, for example, increases the w/c ratio in concrete and impacts on mechanical strength. Particle adherence with cement may also be affected.
- It is recognized that mechanical properties of recycled aggregates are affected by the interfacial transition zone and internal cracks produced during the aggregate crushing processes [21] [22] [23]. Freeze-thaw resistance can identify the affection of this internal cracking in the material.
- Porosity also impacts on mechanical properties of the aggregate [24]. Old cement has a porous nature, and it can be adhered or loose to aggregates surface [21]. Density can be an indicator of porosity in aggregates.
- Chemical attack can be improved as long as accessible porosity increases and with specific porosity structure. This is the case, for example, with external sulphate or chloride attack [25]. The higher porosity of recycled aggregates indicates potential further affection on chemical properties [26]. Water absorption can indicate accessible porosity and potential surface affection in aggregates, whereas freeze-thaw resistance also depends on the porosity structure.

The number of physical tests selected was optimized and the multi-level Aggregate Potential (Physical) (AP(P)) scale was, therefore, based solely on four physical properties, namely: fine content (for fine and coarse aggregates), density, water absorption and freeze/thaw resistance.

Our AP(P) proposes the introduction of a freeze/thaw resistance test, which was omitted by previous assessment procedures (see Table 1). It is acknowledged that it requires different freeze-thaw cycles to complete the test and that this is time consuming, but it is regarded as a viable physical test to be developed without the need of any complex equipment, and it competently identifies the porosity structure and micro-crack level of aggregates. It straddles physical, mechanical and chemical properties boundaries and is considered a durability testing indicator for weather erosion and exterior chemical attack as well as mechanical properties affection due to potential cracking and increase of porosity [27] [28].

The proposed AP(P) adopts a scale reference approach to enable comparison and to establish limits according to standards and intervals of compliance, formed using British Standards for allowable ranges and guidelines. In short, it outlines the allowable performance limits against specific application-uses.

These performance limits can be adapted to differing regulations or can be bespoke depending on other requirements from the market, specific customers or the manufacturing process. In this case, the following British standards applicable to structural concrete and road pavements were used in order to determine limits:

- BS EN 12620:2002+A1:2008 [9]
- BS 8500‐ 2:2015+A2:2019 [29]
- BS EN 206:2013+A1:2016 [30]
- BS EN 1097-6:2013 [31]
- BS EN 1992-3:2006 [32]
- BS EN 13242:2002+A1:2007 [33]
- BS EN 13285:2018 [34]
- Specification for Highway Works Series 500 [35]
- Specification for Highway Works Series 600 [36]
- Specification for Highway Works Series 800 [37]

The results were compared to industrial standards and categorized as: Very Good, Good, Acceptable, Poor, or Very Poor – purposely, the classification was adapted equally to these five categories for all tests included for simplification in application, and differed from the usual A to C, A to D or A to G classifications, as per Table 1, to avoid any confusion between the demarcations. The category limits are given in Table 2.

TABLE 2. CATEGORY LIMITS ACCORDING TO BS STANDANDARDS

	Fine content (BS EN 12620 [9])		Density (BS EN 206 [30])	Freeze-Thaw (BS EN 12620 [9])	Water Absorption (BS EN 1992-3 [32])
	Coarse	Sand			
Very Poor	>6%	>22%	<2.48	>7%	>6%
Poor	4%-6%	<22%	2.48-2.52	4%-7%	5%-6%
Acceptable	3%-4%	<16%	2.52-2.56	2%-4%	4%-5%
Good	2%-3%	<10%	2.56-2.60	1%-2%	3%-4%
Very Good	<2%	<3%	>2.60	<1%	<3%

Based on the limits identified, a sample would gain 4 points for Very Good, 3 points for Good, 2 points for Acceptable, 1 point for Poor and 0 points for Very poor. The AP(P) score was calculated by summing the number of points gained. In the case of fine content, only one of these results (coarse or sand) will be considered in this calculation as these aggregates are commonly classified separately when produced. The lower the AP(P) score, the less suitable the sample is for higher value applications. In that case, processing or treatment would be needed to bring it into acceptable physical limits.

The limits were also used to construct suitability tables to identify how a material can be classified according to application with reference to the British standards. As an example, in Table 3, sample X had two Poor (2 x 1 point) and two Very Poor (2 x 0 points) scores leading to a grade of 4 overall. On the other hand, sample Y had one Good (1 x 3 points), one Acceptable (2 points), one Poor (1 point) and one Very Poor (0 points) leading to a score of 9 overall. It achieved a better score, and therefore the AP(P) grade is different.

TABLE 3. EXAMPLE OF THE AP(P) SCORE

Sample	Coarse Range	Density Range	Freeze-Thaw Grade	Absorption Grade	AP Grade

X	V Poor	Poor	Poor	V Poor	2
Y	Poor	Good	Acceptable	V Poor	6

It was assumed that for each sample, any property that is rated as Good or Very Good was within a range that met the definition of appropriate for use, as recycled aggregates for concrete mixes with different levels of application (structural or non-structural). If, however, the sample had any property that was rated as Acceptable, Poor or Very Poor, then it would not be adequate for concrete. It would need some type of adjustment through a physical process in order to bring it into the usable range for that purpose. In some cases, it may not be possible to improve the aggregate characteristics, so mixing it with primary aggregates in some proportion would help to adapt it.

The given AP(P) score can also be expressed as an alphabetical classification A-E grade as shown in Table 4. It can be observed that a material which fell into the higher range of AP(P) scores was higher classified, meaning that it was appropriate for higher value applications while lower AP(P) scores were more suited to lower ones.

TABLE 4. CLASSIFICATION SCALE BASED ON AP(P) SCORE

Examples of application	AP(P) Scale Range	Classification
Structural Concrete	15 to 16	A
Non-Structural Concrete	12 to 14	B
Subbase	8 to 11	C
Capping	5 to 7	D
Pipe Bedding	1 to 4	E

3.2 Stage two - Application to recycled aggregates

In the second stage, ten C&D mixed waste recycled aggregates were sampled and tested, classified and compared using the AP(P) score. In addition, two primary/natural aggregate samples were also evaluated as a means for comparison and evaluation of the AP(P).

All ten C&D waste samples were obtained from a waste management facility of the company partner based in Swansea, UK. The C&D mixed waste was collected from various demolition sites across South Wales, the original source was unknown. The samples were taken after the jaw crushing and screening processes of the materials in the plant. As aggregates were previously classified during the screening process, the maximum aggregate size ranged from 20mm – 40mm. The samples were taken to the laboratory, dried and separated into coarse and fine aggregates using a 4mm sieve. All coarse aggregates were then sieved and only the sample passing 16mm was considered for later testing so as to provide a uniform grading size. As planned, the tests developed were as follows:

- Density, according to BS EN 1097-6:2013 [31]
- Fine content (for fine and coarse aggregates), according to BS EN 12620:2002+A1:2008 [9]
- Freeze-thaw under salty conditions, according to BS EN 1367-6:2008 [38]
- Water absorption, according to BS EN 1097-6:2013 [31]

The freeze/thaw test was developed under specific exposure conditions for maritime construction, considering a higher level of degradation in a high-salt environment.

A material composition test for coarse aggregates (by visual inspection) was also developed, calculating the different masses of each component and proportions in the sample according to the equations in BS EN 933-11:2009 [39].

Two primary aggregate samples were also tested following the same procedure so as to compare the resulting AP(P) scores with the recycled aggregate samples.

The samples were scored and classified according to the AP(P) as designed. Potential applications were identified, and compliance compared to current legislation according to the tests developed. Additionally, a study was developed considering basic physical operations of treatment and theoretical results concluded. Treatment considered were fine washing and proportionally mixing with primary aggregates. Improvements were identified and samples re-scored, following a discussion of the results obtained.

4. RESULTS AND DISCUSSION

The results of the ten C&D mixed waste samples performed poorer in general compared to the two primary aggregates, as expected. This firstly highlighted that the C&D waste samples' quality was low and, secondly, the variability that C&D waste provided was evident in relation to these properties.

Aggregate Potential AP(P)

The use of the AP(P) scale aided the understanding of recycled aggregates' performance better than the existed procedures as listed in Table 1 and established different grades of performance. The overall AP(P) scores and A-E grades are shown in Table 5 for the ten recycled aggregate samples and the two primary aggregate ones, together with their constituent property scores.

TABLE 5. AGGREGATE POTENTIAL (PHYSICAL) (AP(P)) SCORE.

Sample	Fines Content (coarse)	Density Range	Freeze-Thaw Grade	Absorption Grade	AP(P) Grade	Class A-E
SA1	V Poor	Good	V Poor	V Poor	3	E
SA2	Poor	Good	V Poor	Poor	5	D
SA3	Poor	Poor	V Poor	V Poor	2	E
SA4	Poor	Acceptable	V Poor	Acceptable	5	D
SA5	Acceptable	Poor	V Poor	V Poor	3	E
SA6	Poor	Poor	V Poor	V Poor	2	E
SA7	Acceptable	V Poor	V Poor	Good	5	D
SA8	Acceptable	Acceptable	Poor	Poor	6	D
SA9	Acceptable	V Poor	V Poor	Poor	3	E
SA10	V Good	V Poor	V Poor	V Poor	4	E
PA1	Poor	V Good	V Good	Good	12	B
PA2	Acceptable	V Good	V Good	V Good	14	B

Based on the results given in the AP(P) score, C&D waste materials were further scored in Table 5 according to the alphabetical grade A-E shown in Table 4. All recycled aggregate samples fell into the lowest categories D and E. Despite that, differences between samples were evident due to the AP(P) results. The scale designed tried to adapt these differences at different levels: the lower the AP(P) score, the less likely the material is to perform correctly in higher value applications. This was also clearly identified as an area of concern for recycled aggregate samples at certain properties such as fines content and freeze-thaw resistance, which poor performance under these properties resulted in a reduced AP(P) score.

It is important to note that the performance limits for the AP(P) score were taken from current British regulations. Further, the application of recycled aggregates has been well researched (see section 2).

Restrictions established by standards are focused on the use of primary aggregates in most cases, rather than considering special characteristics that can be found in recycled aggregates. The comparison of recycled aggregates under this umbrella makes the performance limits very restrictive and complicates their application in the construction industry, which is one of the main problems nowadays this type of aggregates are facing to achieve higher-value uses. Despite that, the discussion of this paper is not about the application of current legislation to recycled aggregates, but about the design of the AP(P) score and application to industry.

Fine content is limited to fine and coarse aggregates in concrete mixes [9]. The tests showed moderate to high levels of fines content in coarse aggregates, which was common to all samples. C&D waste usually have increased proportions of fines due to the crushing process [21]. Additional fines contribution could be from excavation soils, introducing impurities of clay or lime on the aggregate surface. Notwithstanding, annex D of BS EN 12620 [9] states that the possibility of use for concrete is considered when there is equivalence of performance with other known satisfactory aggregate or evidence of previous satisfactory use. In this case, C&D waste could be considered as a specific group of aggregates with equivalent performance and the reduction of limits for fine content could be studied further whenever other contaminants are not present (e.g. clay or lime). Special considerations should be taken for other specific uses, such as self-compacting concrete, where sand and fine content is purposely increased.

Freeze-thaw resistance had a limit of >4% according to BS EN 1367-6:2008 [38] but the results obtained were very high and with large variation within each sample, from 6.67% (SA8) up to 12.18% (SA10). The interfacial transition zone is affected by the crushing process which causes a weaking of the material on the old aggregate surface and increases the level of microcracking [21] [22] [23]. Additionally, it is important to consider that alterations could have occurred during the material lifecycle, which may have eroded the original material (e.g. chemical attack, weathering, abrasion, overloading, etc.) resulting in the erosion of the aggregate and changing porosity structure and surface. This showed that these samples cannot be used for concrete mixes. Notably, the freeze-thaw resistance test is the most complex of all the four tests proposed by AP(P), and is subsequently more costly and time consuming to undertake (see section 3.1). Therefore, modifications could be introduced in this procedure so that this test could be avoided for low-value specific final purposes of the aggregate.

Absorption and density results for recycled aggregates are shown to be worse than those for the primary aggregates. This is due to multiple factors such as degradation of original aggregate material, increase of porosity with old cement in the interfacial transition zone, increase of fine content or changes in internal structure of aggregates. Despite that, water absorption seemed to be affected to a higher degree, which could be due to the fact that this degradation was mainly on the material external surface, rather than internally, and could indicate that the material composition was not notably affected [28]. The relationship with freeze-thaw testing results could show a hint of correlation with water absorption, but it could not be proven with the results obtained.

This categorization of physical properties made samples easier to analyze and classify due to the small number of tests required. The simple AP(P) score could be useful as a first stage of a more comprehensive analysis that would help to clearly define the performance of the material. Notwithstanding, one limitation in this study was the reduced number of C&D waste samples tested. A larger number of samples might have made it possible to identify correlations between C&D waste material properties and their composition.

Waste-type composition

The waste-type composition in the samples analyzed showed that excavation soil was consistently the most common prevalent element in the samples tested with an average result of 55.84%. The second and third most common waste type were concrete and ceramics, accounting for 24.55% and 11.51% on average respectively. The rest were considered as contaminants (such as wood, gypsum, bitumen and others), which percentages were high and could substantially affect the characteristics of the recycled aggregates [11].

TABLE 6. MATERIAL COMPOSITION OF C&D WASTE SAMPLES

Sample	Concrete	Aggregate (soil origin)	Ceramics	Wood	Gypsum	Bitumen	Other	Total
SA1	25.66%	58.27%	13.84%	0.04%	0.30%	1.85%	0.04%	100.00%
SA2	24.7%	63.4%	9.2%	0.1%	0.0%	2.7%	0.0%	100.00%
SA3	24.09%	51.27%	17.44%	0.00%	0.00%	7.21%	0.00%	100.00%
SA4	21.12%	59.14%	9.90%	0.00%	0.20%	9.59%	0.05%	100.00%
SA5	19.00%	64.60%	11.30%	0.40%	0.10%	4.45%	0.15%	100.00%
SA6	35.86%	42.61%	5.24%	0.76%	0.00%	15.48%	0.06%	100.00%
SA7	30.25%	51.55%	4.08%	0.52%	0.57%	13.03%	0.00%	100.00%
SA8	23.98%	49.53%	15.85%	0.00%	1.67%	8.96%	0.00%	100.00%
SA9	18.91%	57.77%	14.65%	0.05%	1.34%	6.88%	0.40%	100.00%
SA10	21.93%	60.28%	13.65%	0.15%	1.03%	0.34%	2.61%	100.00%
Mean	*24.55%*	*55.84%*	*11.51%*	*0.20%*	*0.53%*	*7.05%*	*0.33%*	
Standard Deviation	*4.93%*	*6.54%*	*4.20%*	*0.25%*	*0.58%*	*4.64%*	*0.77%*	
Maximum	*35.86%*	*64.60%*	*17.44%*	*0.76%*	*1.67%*	*15.48%*	*2.61%*	
Minimum	*18.91%*	*42.61%*	*4.08%*	*0.00%*	*0.00%*	*0.34%*	*0.00%*	

It can be observed in Table 6 that a large amount of excavation soil was identified in the recycled aggregate samples. This type of waste is commonly segregated and treated separately. Notwithstanding, this depends on volumes and waste management procedures on site: the smaller volumes of waste types, the less classification and separation. Materials, construction methods and storage have also a big impact on types of waste mixed, including pollutants. All these considerations are related to waste management techniques followed on construction sites, and should be discussed accordingly. Our research is focused on the final product obtained as a consequence of this waste management, and the samples tested showed actual composition of C&D mixed recycled aggregates. The discussion presented is, therefore, limited to application areas under these characteristics.

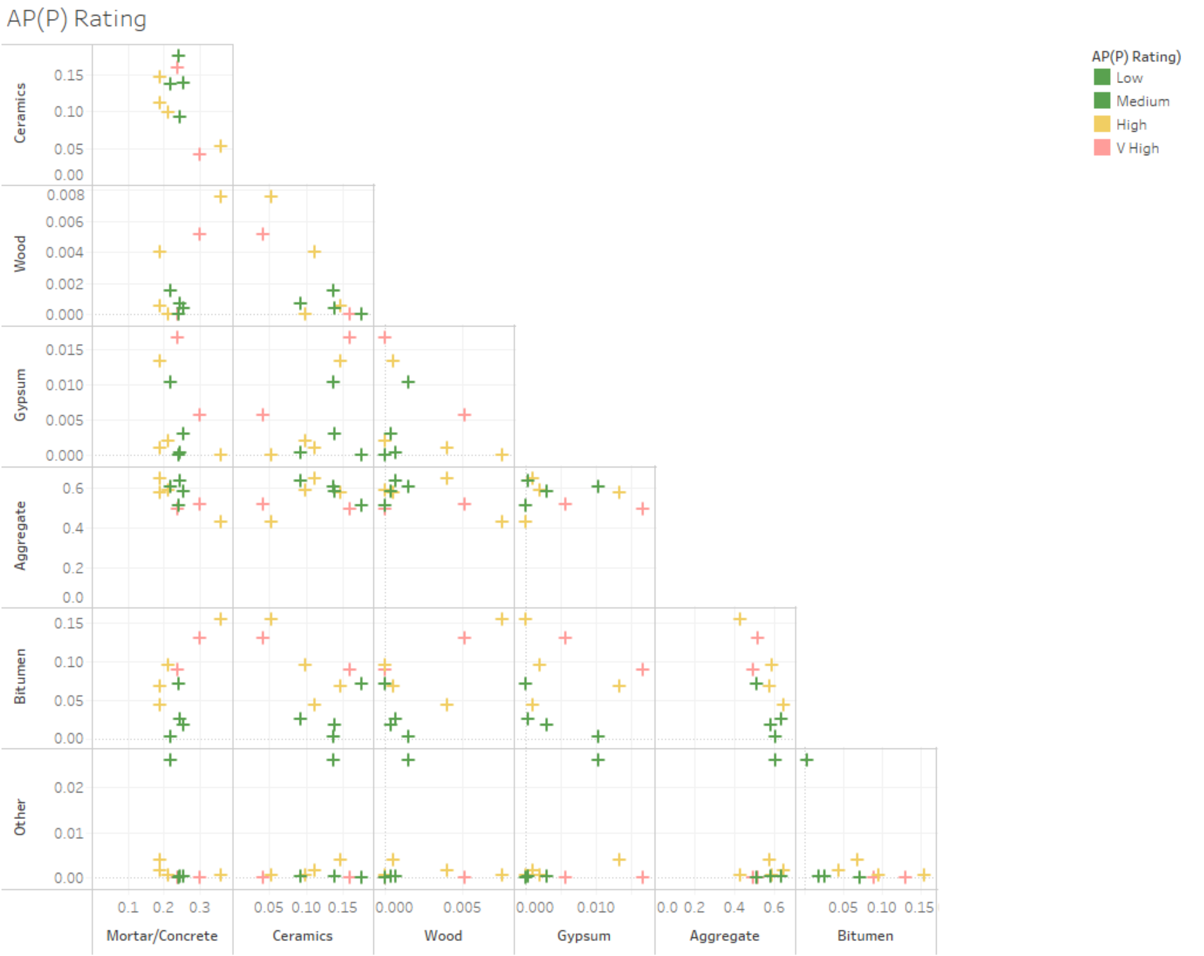
BS EN 12620:2002+A1:2008 [9] and BS 8500‐2:2015+A2:2019 [29] establish that, in order to be suitable for structural concrete, coarse recycled aggregate should meet the quantities of up to 10% mass for bituminous material and no more than 1% mass for a combination of wood, gypsum and other contaminants. Following this criterion, samples SA6, SA7, SA8, SA9 and SA10 would be excluded for this application.

Following these BS standards, the samples could be classified according to their composition:

- Regarding concrete waste type, all samples would be classified as Rc Declared (less than 50% concrete waste). However, considering the amount of unbound aggregates from excavation soil, they could be categorized as Rcu70 in all cases (more than 70% concrete and unbound aggregates).
- Regarding ceramic waste, SA2, SA4, SA6 and SA7 samples fell within the Rb10 classification (less than 10% ceramic waste) whereas the rest were classified as Rb30.
- Regarding bitumen content, SA1, SA2, SA5 and SA10 are classified as Ra_{5-} (less than 5% bitumen); SA3, SA4, sA8 and SA9 are Ra_{10-} (less than 10% bitumen); and the rest are not acceptable (more than 10% bitumen)

This is an initial indicative of quality in composition, where concrete waste and unbound aggregates are considered to provide good quality, and ceramic and bitumen waste content are considered as bad quality. Specifically, bitumen could work in a positive way if these aggregates are recycled in road pavement, but not in structural concrete. In that case, the limit is recommended to be not more than 1% [11]. Other components, such as wood and gypsum are considered as impurities and should be avoided. In the UK, only Rc90, Rcu90, Rb_{10-} and Ra_{5-} could be used in structural concrete, mixed with natural coarse aggregates (BS 8500-2:2015+A2:2019).

Trends about performance were sought according to the composition of these samples. A scatterplot matrix was created based on the 10 samples to identify any relationships or correlations between the composition based upon the four parameters that were defined for the AP(P) – density, fine (sand), water absorption and freeze-thaw (Figure 2). The results obtained highlight the high variability that was visible in C&D waste. Properties could be affected at different levels by different composition and, therefore, it was difficult to foresee the potential performance of samples.



Mortar/Concrete, Ceramics, Wood, Gypsum, Aggregate, Bitumen and Other vs. Ceramics, Wood, Gypsum, Aggregate, Bitumen and Other. Color shows details about AP(P) Rating).

FIGURE 2. SCATTERPLOT MATRIX FOR SAMPLE COMPOSITIONS AND AP(P) RATING

No clear correlations could be identified in Figure 2 based upon the composition of recycled aggregate. The results were shown to be dispersed, and no clear trends or relationships were clearly visible. This was similar to other results shown in Table 5, in which the high variability of the source material composition had an impact on the reliability of the material. Despite that, there was a slight hint that indicated some kind of trend with bitumen content, showing that a higher bitumen content reduces the overall AP(P) rating. However, it could not be stated clearly with the results obtained, with more samples needing to be tested to validate it correctly and to identify any causal relationships.

Suitability for different purposes

To complete the proof of concept, the properties analysed were verified for different applications considering the limits established according to the standards described. Tables 7, 8, 9 and 10 show the suitability of the ten C&D waste and primary aggregates samples for the applications previously considered, ranging from structural concrete to pipe bedding. In these tables, the samples are classified according to the test results and following the corresponding standards. Acceptance is identified in green, whereas rejection is in red.

TABLE 7. STRUCTURAL CONCRETE SUITABILITY (BS EN 12620:2002+A1:2008)

Sample	Composition	Fines Content (coarse)	Particle Density (kg/m^3)	Freeze-Thaw	Absorption
SA1	Rc 80, Rb 30-, Ra 5-, XRg 0,5-	F F Declared	2000 to 3000	F Declared	≥3%
SA2	Rc 80, Rb 10-, Ra 5-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA3	Rc 70, Rb 30-, Ra 10-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA4	Rc 80, Rb 10-, Ra 10-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA5	Rc 80, Rb 30-, Ra 5-, XRg 1-	F4	2000 to 3000	F Declared	≥3%
SA6	Rc 70, Rb 10-, Ra ND, XRg 1-	F Declared	2000 to 3000	F Declared	≥3%
SA7	Rc 80, Rb 10-, Ra ND, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA8	Rc 70, Rb 30-, Ra 10-, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA9	Rc 70, Rb 30-, Ra 10-, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA10	Rc 80, Rb 30-, Ra 1-, XRg ND	F4	2000 to 3000	F Declared	≥3%
PA1	N/A	F Declared	2000 to 3000	F1	≥3%
PA2	N/A	F4	2000 to 3000	F1	≤3%

TABLE 8. SUBBASE SUITABILITY (BS EN 13242:2002+A1:2007)

Sample	Composition	Fines Content (coarse)	Particle Density (kg/m^3)	Freeze-Thaw	Absorption
SA1	Rc 80, Rb 30-, Ra 5-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA2	Rc 80, Rb 10-, Ra 5-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA3	Rc 70, Rb 30-, Ra 10-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA4	Rc 80, Rb 10-, Ra 10-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA5	Rc 80, Rb 30-, Ra 5-, XRg 1-	F4	2000 to 3000	F Declared	≥3%
SA6	Rc 70, Rb 10-, Ra 20-, XRg 1-	F Declared	2000 to 3000	F Declared	≥3%
SA7	Rc 80, Rb 10-, Ra 20, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA8	Rc 70, Rb 30-, Ra 10-, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA9	Rc 70, Rb 30-, Ra 10-, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA10	Rc 80, Rb 30-, Ra 1-, XRg ND	F4	2000 to 3000	F Declared	≥3%
PA1	N/A	F Declared	2000 to 3000	F1	≥3%

PA2	N/A	F4	2000 to 3000	F1	≤3%

TABLE 9. CAPPING SUITABILITY (BS EN 13242:2002+A1:2007)

Sample	Composition	Fines Content (coarse)	Particle Density (kg/m³)	Freeze-Thaw	Absorption
SA1	Rc 80, Rb 30-, Ra 5-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA2	Rc 80, Rb 10-, Ra 5-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA3	Rc 70, Rb 30-, Ra 10-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA4	Rc 80, Rb 10-, Ra 10-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA5	Rc 80, Rb 30-, Ra 5-, XRg 1-	F4	2000 to 3000	F Declared	≥3%
SA6	Rc 70, Rb 10-, Ra 20-, XRg 1-	F Declared	2000 to 3000	F Declared	≥3%
SA7	Rc 80, Rb 10-, Ra 20, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA8	Rc 70, Rb 30-, Ra 10-, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA9	Rc 70, Rb 30-, Ra 10-, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA10	Rc 80, Rb 30-, Ra 1-, XRg ND	F4	2000 to 3000	F Declared	≥3%
PA1	N/A natural aggregate	F Declared	2000 to 3000	F1	≥3%
PA2	N/A natural aggregate	F4	2000 to 3000	F1	≤3%

TABLE 10. PIPE BEDDING SUITABILITY (BS EN 13242:2002+A1:2007)

Sample	Composition	Fines Content (coarse)	Particle Density (kg/m³)	Freeze-Thaw	Absorption
SA1	Rc 80, Rb 30-, Ra 5-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA2	Rc 80, Rb 10-, Ra 5-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA3	Rc 70, Rb 30-, Ra 10-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA4	Rc 80, Rb 10-, Ra 10-, XRg 0,5-	F Declared	2000 to 3000	F Declared	≥3%
SA5	Rc 80, Rb 30-, Ra 5-, XRg 1-	F4	2000 to 3000	F Declared	≥3%
SA6	Rc 70, Rb 10-, Ra 20-, XRg 1-	F Declared	2000 to 3000	F Declared	≥3%
SA7	Rc 80, Rb 10-, Ra 20, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA8	Rc 70, Rb 30-, Ra 10-, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA9	Rc 70, Rb 30-, Ra 10-, XRg 2-	F4	2000 to 3000	F Declared	≥3%
SA10	Rc 80, Rb 30-, Ra 1-, XRg ND	F4	2000 to 3000	F Declared	≥3%
PA1	N/A natural aggregate	F Declared	2000 to 3000	F1	≥3%
PA2	N/A natural aggregate	F4	2000 to 3000	F1	≤3%

It could be observed that, according to limitations established in these BS standards, the C&D waste samples tested were not suitable for any application in general. Regarding structural concrete (Table 7), sand fines content, freeze-thaw resistance and absorption were of concern, with some added issues regarding high proportions of bituminous material which caused it to fail classification. For other applications considered, the most prevalent issues were the fines content of both fine and coarse aggregates, but also compositions with higher percentages of gypsum and wood than required. This caused all samples to be unsuitable for use in any of the mentioned applications. While these were not positive results, they helped identify any areas of concern relating to the quality of the C&D waste material and showed what aspects needed to be improved so as to make the material more suitable for construction applications.

In order to improve the accuracy for the limitations needed in other applications, such as pipe bedding, there were only two main visible variables to consider from the AP(P) score: these were (both coarse and sand) fines content. This was due to a lack of clear standards stating any requirements needed for these applications. In defining a sample's suitability for such purposes, a reduced AP(P) score might be used that focusses on these two properties, providing a maximum of score 4 points with a required minimum of 2 points. It was clear that any material that performed to a Poor (D) or Very Poor (E) standard would require treatment to improve it to a usable quality (with an associated increase in AP(P) score). Treatment methods could improve recycled aggregate performance. That said, it is important to note, the purpose of this paper is to test and evaluate the proposed AP(P) scale, and not the viability of the C&D samples themselves.

Treatment

The AP(P) score was posited to be a signifier of the material's potential performance, and it was evident that all C&D waste samples tested need a degree of processing or treatment in order to perform similarly to natural aggregates, which showed scores of 12 and 14. Significant differences could be identified between samples. For example, SA8 (AP(P) score of 6) and SA3 (AP(P) score of 2) were clearly different in quality.

On the other hand, according to literature and previous experience, it was considered that recycled fine aggregates do not perform as well as coarse in concrete [40] [41]. Taking into account this consideration, coarse aggregates could be used for concrete mixes whereas the fine part could be allocated for other uses. Further considerations could be taken if coarse C&D waste recycled aggregates are to be washed and, as a result, fines content is reduced to acceptable limits for concrete mixes. Finally, mixing proportions with primary aggregates would also help improve the characteristics of the resulting final aggregates. In fact, this is the solution proposed in the use of recycled concrete aggregates for structural concrete, where a replacement of no more than 20% of primary aggregates is accepted specifically in some standards and countries [29] [42], as well as other considerations such as the increase of water in the concrete mix by 5% [41]. It is acknowledged, however, whilst mixing different aggregate types (namely, principal/natural with recycled) could be another viable option (always referring to non-hazardous waste), it could be construed as a general mixing of waste and been seen as a potential environmental threat. Therefore, this may not be a feasible option in some regulatory contexts.

A theoretical estimation of the AP(P) was calculated for these samples in different situations, considering previous physical operations to improve the aggregates characteristics: coarse aggregate washing, mixing with primary aggregates (considering PA2 aggregate sample) at 50% and 20% respectively, and the combination of both. The results are shown in Table 11.

TABLE 11. VARIATIONS OF AP(P) GRADE AND CLASSIFICATION ACCORDING TO DIFFERENT (THEORETICAL) TREATMENTS

	No treatment		Washing		mix 50%		Wash+mix50%		Mix 20%		Wash+mix20%	
Sample	AP(P) Grade	AP(P) Grade	AP(P) Grade	Class A -E	AP(P) Grade	Class A -E	AP(P) Grade	Class A -E	AP(P) Grade	Class A -E	AP(P) Grade	Class A -E
SA1	3	E	7	D	7	D	9	C	11	C	12	B
SA2	5	D	8	C	9	C	10	C	11	C	12	B
SA3	2	E	5	D	7	D	9	C	11	C	12	B
SA4	5	D	8	C	9	C	10	C	12	B	13	B

12	B	E	5	D	8	C	9	C	11	C	12	B
SA6	2	E	5	D	7	D	8	C	11	C	12	B
SA7	5	D	7	D	8	C	9	C	12	B	13	B
SA8	6	D	8	C	9	C	10	C	12	B	13	B
SA9	3	E	5	D	7	D	8	C	11	C	12	B
SA10	4	E	4	E	7	D	7	C	11	C	11	C

As it can be observed from Table 11, significant improvements are achieved in the AP(P) grade of each sample if differing treatments are applied. In the case of coarse recycled aggregate washing and mixing proportions up to 20%, the results obtained changed to Class B in almost all samples (the primary aggregate considered for this mix, PA2, was formally evaluated as class B; see Table 4). Higher scores could be obtained if it is mixed with Class A primary aggregates. These results make evident the potential use of recycled aggregates for higher value purposes and the impact in the consumption of primary aggregates, therefore reducing the exploitation of natural resources.

5. CONCLUSION

Scientific value of research:

- This research has demonstrated a *simple* procedure to effectively classify recycled aggregates from C&D mixed waste by its properties to delineate its potential application. The AP(P) proposes the application of four tests as a means to be a cost-effective evaluation approach, namely: density, fine content (for fine and coarse aggregates), water absorption and freeze/thaw resistance.
- Existing research focuses on *the* properties of recycled aggregates in application areas, such as, for example, in concrete columns, but sparse research exists to support how to cost-effectively evaluate C&D waste *for* use in application domains – there is currently no universal procedure or classification system for the evaluation of C&D aggregates.

Theoretical and practical implications:

- There are few specific procedures that consider the properties and limits for the use of recycled aggregates. Those that do exist are mainly focused on primary aggregates, which limits their usefulness when dealing with recycled aggregates.
- In doing so, the results from its application in this study showed that C&D waste is a product with a high level of variability compared to primary aggregates. The AP(P) helps to identify materials that performed well or poorly, and the properties that caused this. The scales established could suggest different potential applications for the recycled aggregates that would help classification and selection of better quality products for higher value purposes. This indicator could help waste managers identify potential uses in their own facilities without much complexity. Notwithstanding, it can never replace a full quality control analysis of the aggregates as required for such purposes, further tests will be required inevitably to confirm the use is appropriate.
- The use of the AP(P) score could support further improvements in the manufacturing process of C&D waste mixed recycled aggregates in waste treatment plants, where the combination with other technologies (sensoring, automation, big data, AI, etc.), could achieve higher-value applications and cost-effective solutions for this type of waste.
- Deviations can happen in the aggregate manufacturing process at different stages: transport, treatment (crushing), classification, stacking and transport to application. To achieve a standardized procedure, the proposed AP(P) should be applied after crushing, in the classification process. Stacking time can affect the properties analysed if these aggregates are not sheltered/protected accordingly. Therefore, new tests and re-classification should be considered for prolonged stacking time in these conditions.

Limitations:

- The C&D samples presented were all outside viable limits for any relevant application in their current form. Treatments were suggested that could be applied to improve this quality to a point where the material could be used for other up-cycling applications. The first treatment purported was ‘wash,’ thus reducing the fines content and any other potential impurities; the second approach, ‘mixing with natural aggregates’ would be suitable for improving materials with high absorption and low freeze-thaw resistance. The most suitable treatments to apply could be identified from the analysis of results with the AP(P) scale. The maximum proportion of recycled aggregate for structural concrete should be less than 20% of the total mass according to standards. This highlighted that there was still potential for the use of recycled aggregates provided that steps are taken for adequate treatment.
- Whilst it was not possible to find any clear correlations between material compositions and physical properties, a larger number of samples is necessary in order to investigate these relationships.
- Other factors that can affect the performance of recycled aggregates include: materials used and age of original construction, exposure to weather conditions, contact with different materials and contaminants (e.g. soils, fuels, seawater), etc, which were outside the scope of this research. The study of the waste traceability would help identify the potential types of waste, degradation and potential contaminants, as well as testing frequency and the determination of steps for deconstruction processes.
- The performance limits used for the AP(P) score are mostly applied to primary aggregates. This is a handicap for recycled aggregates and creates a comparative disadvantage. Further discussion about the existing regulatory framework should be developed to be able to increase the number of application options for these recycled aggregates.

Recommendations for further research:

- Further applications for C&D mixed waste aggregates could be explored. The use of fines for specific applications, such as self-compacting or lightweight concrete, could open other usage options for this mixed waste.
- Further exploration of treatment options for recycled aggregates would help improve their quality in other ways, such as the removal of adhered mortar, accelerated carbonation, polymer impregnation, pozzolanic slurry immersion, etc. Other parameters should, therefore, be considered for the selection of these treatments such as cost, availability of technology and resources, or environmental impact and circularity.
- Adoption of the AP(P) could be used to lead the development and adoption of cleaner production technologies to enhance environmental sustainability, including digital and automation.
- Further testing of the applicability and alignment of the AP(P) to recycled aggregate regulations in differing countries would widen its adoption to a global market.
- Explore the potential need for importance weighting of each AP(P) indicator. At present, each test is considered of equal importance/ value in the AP(P), but future research could determine if the AP(P) could be made *more* cost effective by the introduction of algorithms to support improved classification scoring.

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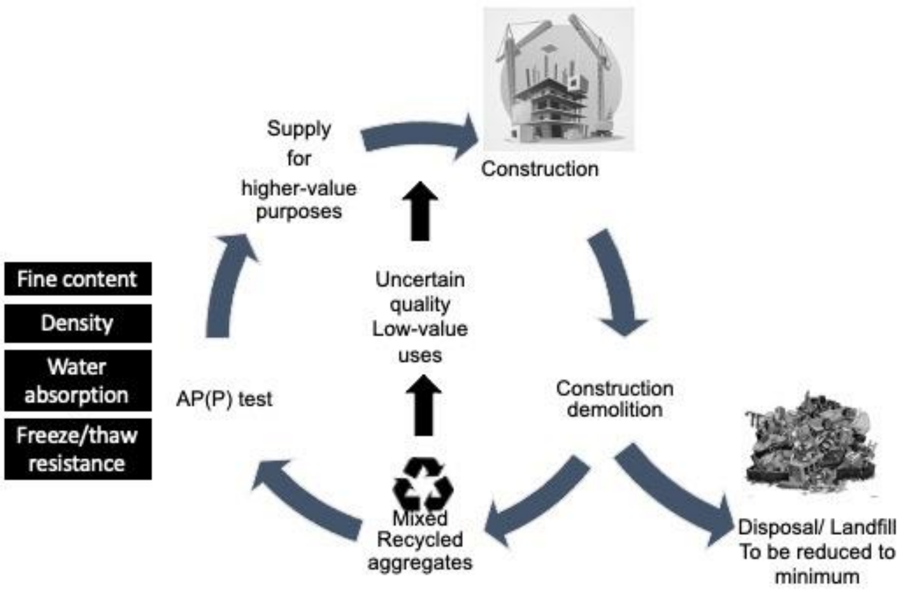
A COST-EFFECTIVE RECYCLED AGGREGATES CLASSIFICATION PROCEDURE FOR CONSTRUCTION AND DEMOLITION WASTE EVALUATION

Highlights

- A classification for mixed recycled aggregates is proposed to improve higher-value uses
- The Aggregate Potential (Physical) (AP(P)) is defined as an indicator of recycled aggregate quality
- Simple treatment procedures are checked with this AP(P) for potential improvements of quality
- A more cost-effective manufacturing process can be developed with this classification procedure.

Graphical Abstract



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