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1 **Adopting Recycled Aggregates as Sustainable Construction Materials: A**
2 **review of the Scientific Literature**

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20 **Abstract**

21 Adopting a holistic three-step literature review workflow, a total of 1,639 journal articles
22 were used in this study as the literature sample related to recycled aggregate (RA). This study
23 summarized the existing research topics focusing on RA, gaps of current research, suggestions
24 for promoting RA usage, and research directions for future work. A research framework was
25 also proposed linking the existing research themes into trends in RA research. This review

26 work serves as a foundation work to bridge the gap between scientific research and industry
27 practice, as well as to guide the directions in RA-related academic work using an
28 interdisciplinary approach.

29 **Keywords:** Circular economy; recycled aggregate; construction waste; sustainable concrete;
30 literature review

31 **1. Introduction**

32 Over the last decade the concept and development model of Circular Economy has been
33 gaining a growing attention [1]. It aims to provide an alternative to the traditional and dominant
34 model [2] featured at consuming resources and then disposing it. Circular Economy emerges
35 through three main actions, namely reduction, reuse, and recycle [3]. According to Ghisellini
36 et al. [1], waste management, as a recovery of resources and environmental impact prevention,
37 has become an important sub-sector of Circular Economy. Around 30% to 40% of the urban
38 solid wastes come from construction and demolition (C&D) activities [4]. The overwhelming
39 amount of C&D wastes generated in the forms of concrete, bricks, and tiles are causing
40 pressures on the limited urban landfill space [5]. On the other hand, limited natural resources,
41 such as virgin aggregates, call for the utilization of recycled alternatives to meet the
42 construction industry needs [6].

43 The increasing needs for sustainability in the construction industry and the movement of
44 Circular Economy is driving the research of recycling and reusing waste streams, such as
45 recycled aggregates (RAs) obtained by crushing C&D wastes. RA was identified [7] as one of
46 the main research topics in the domain of C&D waste management. It is a typical product after
47 the initial treatment of C&D wastes (e.g., old concrete). So far, limited research has been
48 performed to provide a holistic overview of the RA-related scholarly work. However, a review
49 of RA-based research is important for multiple stakeholders including engineers, policy makers,
50 and academics based on the facts that: (1) it is a concrete example of waste management

51 strategy in the micro level of Circular Economy as proposed by Ghisellini et al. [1]; (2) it is the
52 main form that C&D wastes are processed for reuse to reduce the demands on natural resources
53 and to release the landfill pressure; and (3) the utilization of RAs in the construction sector has
54 multiple effects to the cleaner production in terms of social, economic, technical, and
55 environmental aspects. The technical and environmental effects of adopting RAs have been
56 widely studied according to existing literature, such as how the cement composite products'
57 quality would be affected by reusing RAs [8], and the carbon emissions of adopting RAs [9].
58 The cost factors (e.g., labor and equipment inputs) of adopting RAs have also been considered
59 in reusing RAs as the alternative approach to consuming natural aggregates [10]. The social
60 aspect in the cleaner production includes education and training aiming to produce sustainable
61 outcomes, to raise public awareness, and to change the public attitudes as indicated by
62 Kjaerheim [11]. Social aspects involved in adopting RAs include the public awareness,
63 governmental policies, social value and cultural acceptance towards using RAs [12, 13].

64 Adopting a holistic literature review approach by incorporating text-mining method in the
65 RA literature sample followed by an in-depth discussion, this study aims to provide answers to
66 the following research questions: (1) what are the mainstream research topics or themes in the
67 RA domain? (2) what are the current research gaps and challenges of adopting RAs for a
68 cleaner production? (3) what recommendations could be made to promote the usage of RAs in
69 the construction industry? and (4) what could be the promising research directions for future
70 scholarly work?

71 Existing review-based studies [14, 15] have targeted on the applications of RA in concrete
72 production, especially the investigation of properties of recycled aggregate concrete (RAC)
73 containing RAs. Some of the existing review-based studies [16-18] have been focusing on RAs
74 using C&D wastes, such as old concrete. Silva et al. [19] provided the review of the fresh-state
75 performance of RAC; Guo et al. [20] targeted on the durability issue of RAC; Tam et al. [21]

76 extended the scope of RA into the general applications in concrete. Based on these prior studies,
77 researchers believe that some further work could be performed. For example, a more
78 comprehensive review for RAs in terms of its sources and applications could be provided. It is
79 worth noting that the source of RAs may not be limited to C&D wastes, but may also include
80 other industrial waste streams, for instance, agricultural and aquaculture by-products [22],
81 urban or industrial wastes such as oyster shell [23], bottom ash [24], and rubber [25].
82 Furthermore, the application of RAs may not be limited to concrete mix design and production
83 [26], but can also include other uses such as pavement base [27], roadway construction [6], and
84 other cement composites [28].

85 Besides the need for the review of RA in a wider scope in terms of its sources and
86 applications during the life cycle process, the text-mining-based scientometric approach could
87 also be adopted in assisting the literature review of RA-related studies. As stated by Song et al.
88 [29] and Hosseini et al. [30], several existing review-based studies were prone to subjectivity,
89 either due to limited literature sample or because of researchers' pre-selection of journal
90 sources in a given research domain. To address this issue of subjectivity or biasness in literature
91 search, more recent review-based studies [31, 32] introduced the scientometric analysis
92 approach by incorporating the text-mining method in analyzing the contents within a larger
93 sample of literature. By adopting the scientometric analysis, articles and keywords that are
94 influential in the given research domain could be summarized in a quantitative way. Aiming to
95 address the research gaps in RAs in terms of its scope and review method, this study aims to
96 achieve these following objectives: (1) establishing a comprehensive literature sample covering
97 a wider scope of RA-related studies; (2) identifying the mainstream keywords and influential
98 articles that are active in RA research; (3) adopting a further in-depth discussion for linking the
99 existing research themes in RA to future research directions; and (4) providing suggestions for
100 enhancing the RA usage. The novelty of this study lies in that: (1) it provides a more

101 comprehensive coverage of RA-related research topics from a potentially larger literature
102 sample; and (2) it moves forward from several existing studies applying scientometric review
103 [29, 33] by utilizing the text-mining outputs for further in-depth discussion, which would then
104 initiate a research framework guiding future scholarly work in RA-related studies as well as
105 propose recommendations for promoting RA usage in the construction sector.

106 The following sections of this study are structured as: Section 2 describes the review
107 methodology consisting of three steps; Section 3 presents the results of the scientometric
108 analysis conducted to the literature sample of RA; Section 4 extends the scientometric review
109 from the prior section into a further in-depth discussion; Section 5 concludes this review-based
110 study.

111 **2. Methodology**

112 This study was based on a three-step workflow to evaluate the research outputs in RAs.
113 Fig.1 describes the review steps adapted from Xu et al. [31], consisting of bibliometric search
114 of literature using *Scopus* as the database, scientometric analysis adopting *VOSViewer* as the
115 text-mining tool [34], and the follow-up qualitative discussion. The scientometric review
116 approach, as described by Hosseini et al. [30] and Song et al. [29], could address the biasedness
117 or subjectivity problems in previor studies in the construction sector (e.g., Tang et al. [35]).
118 However, some existing scientometric analysis-based review (e.g., Zhao et al. [36]) are also
119 limited to the self-explanatory discussions such as who are the most productive sholars in the
120 research domain. Aiming to address both limitations in these two literature review approaches,
121 this study provides a more comprehensive approach as shown in Fig.1 by combining the text-
122 mining method and the in-depth discussion.

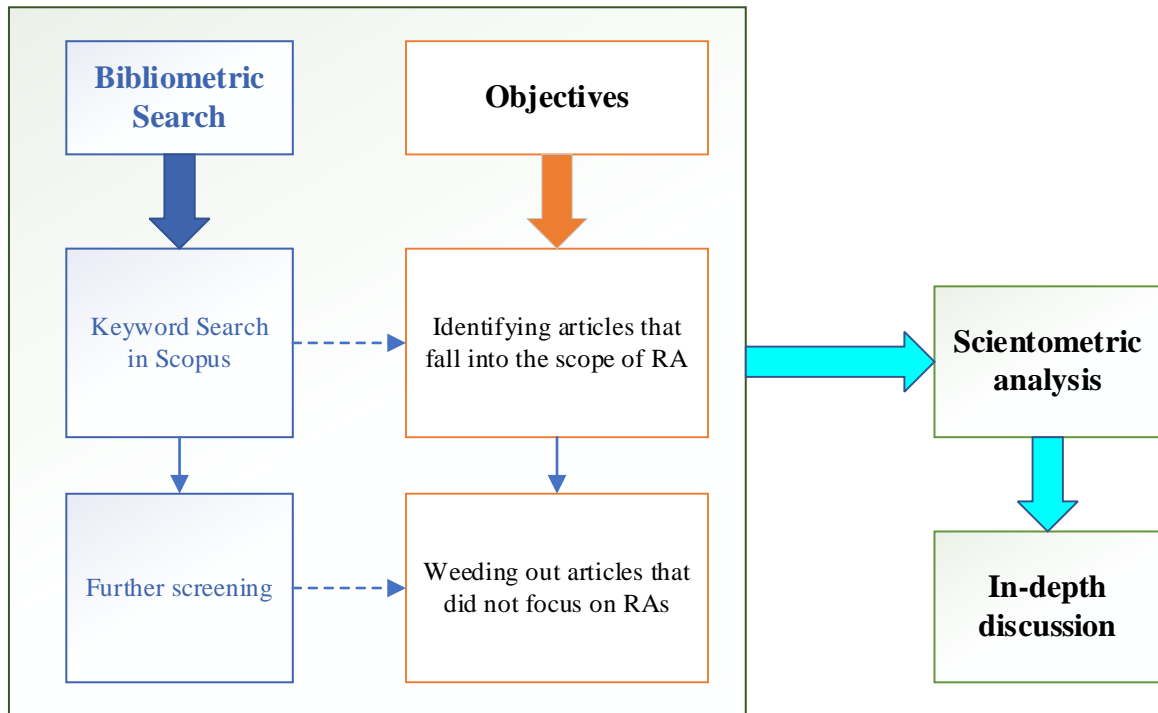


Fig.1. Description of three-step literature review of RA-related studies

2.1. Bibliometric search

The bibliometric search of RA-related research was conducted in *Scopus*, which was defined by Aghaei Chadegani et al. [37] with a wider coverage of articles and more recent publications compared to *Web of Science*. The keyword input and filtering of publications in *Scopus* is shown below:

TITLE-ABS-KEY ("recycled aggregate" OR "recycled aggregates") AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j"))

Only journal articles including review papers published in English were recruited for literature review in this study. As seen in Fig.1, extra sub-steps (i.e., further screening) were performed to screen out initially selected articles that did not target on RA research. These articles, which barely mention RA in their texts but not really focus on RA-based research,

138 would be removed from the initially identified literature sample. During the further screening
139 process, all the eight researchers in this study reviewed the title, abstract, and keywords of the
140 initial literature sample. Discussions were held among researchers to agree on the decision of
141 removing each of these articles.

142 *2.2. Scientometric analysis*

143 Based on the literature sample finalized from the prior step, all the articles were uploaded
144 to *VOSViewer* for scientometric analysis. *VOSViewer* was described by van Eck and Waltman
145 [38] as a tool that provided a distance-based visualizations of bibliometric networks, especially
146 for visualizing larger networks with text-mining functions. Some existing studies in other
147 research domains adopting *VOSViewer* can also be found, such as Song et al. [29] in project
148 management, and Xu et al.[31] in cement composites reinforced by graphene oxide. Similar to
149 the study of Jin et al. [7], *VOSViewer* was utilized in this study to: (1) load the RA-based
150 literature sample from *Scopus*; (2) compute, and evaluate the influence of mainstream
151 documents and RA-related research keywords; (3) summarize the main existing research
152 keywords in this domain.

153 *2.3. Qualitative discussion*

154 Following the scientometric review, a further in-depth qualitative discussion was
155 conducted to address the three main research questions related to: (1) the mainstream research
156 topics or themes within RA; (2) the limitations of existing research; (3) suggestions for
157 promoting RA usage in the construction sector; and (4) recommendations for future research
158 in RA. The discussion also aimed to propose a research framework that could link existing
159 research topics into future directions in RA-related scholarly work.

160 **3. Results of scientometric analysis**

161 The keyword inputs in *Scopus* initially generated a total of 1,652 journal articles published
162 between 1984 and 2018. These journal articles were initially screened by the research team of

163 this study to remove those which did not focus on RAs. Excluding those not targeting on RA
 164 research, the remaining 1,639 articles were agreed by the research team as the finalized sample
 165 for further literature review.

166 *3.1. Articles influential in recycled aggregates*

167 The total 1,639 articles selected for literature review are ranked according to the total
 168 citation . Table 1 provides the ranking of most influential articles evaluated by the total citation.

169 Table 1. Most influential articles measured by Total Citations in the RA domain

Reference	Article Title	Total Citation
Etxeberria et al. [39]	Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete	490
Xiao et al. [40]	Mechanical properties of recycled aggregate concrete under uniaxial loading	360
Evangelista and de Brito [41]	Mechanical behaviour of concrete made with fine recycled concrete aggregates	339
Sagoe-Crentsil et al. [42]	Performance of concrete made with commercially produced coarse recycled concrete aggregate	328
Poon et al. [43]	Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates	326
Katz [44]	Properties of concrete made with recycled aggregate from partially hydrated old concrete	314
Poon et al. [45]	Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete	299
de Juan and Gutiérrez [46]	Study on the influence of attached mortar content on the properties of recycled concrete aggregate	297
Tam et al. [47]	Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach	295
Ajdukiewicz and Kliszczewicz [48]	Influence of recycled aggregates on mechanical properties of HS/HPC	285

170
 171

172 Table 1 provides ten top ranked articles in terms of total citation. It could be inferred these
 173 articles in Table 1 tended to unanimously focus on mechanical properties of cement composites
 174 adopting RAs. Nevertheless, it can be found that some more recent studies have extended the

175 mechanical properties to durability of RAC [49-51] as well as computing and modeling
176 methods [52, 53]. More studies [54-56] applying data science methods (e.g., data mining in
177 sustainable concrete) can be found in recent years. Researchers have also started reviewing
178 literature of how RA affect properties of RAC [14, 16, 57].

179 *3.2.Keyword analysis*

180 Keyword analysis is an important work to depict the existing topics that have been focused
181 within a given topic [58], such as RA in this study. According to van Eck and Waltman [34],
182 the keyword network shows the knowledge, research themes, as well as their relationships and
183 intellectual organizations. Adopting *VOSViewer* as the text-mining tool, the research team
184 identified the most frequently studied “Author Keywords”. These keywords had a minimum
185 occurrence of 10. Initially 74 out of totally 3,052 keywords were identified. General keywords
186 such as “Recycled Aggregate” were removed from the keyword list. Other keywords with the
187 consistent semantic meanings were combined, for example, RAC and “recycled aggregate
188 concrete”, RCA and “recycled concrete aggregate”, etc. Several keywords were combined into
189 a single keyword representing the same category. For instance, the original keywords including
190 “Split Tensile Strength”, “Compressive Strength”, and “Mechanical Strength” were combined
191 into “Mechanical”. Ultimately a total of 38 keywords were selected for analysis.

192 Mechanical properties of RAC were the most frequently studied topic in RA-related
193 research. RAC is the second most frequently studied keyword. It should be noticed that the
194 third highest ranked keyword “Concrete” is different from RAC. RAC refers to the application
195 of RA in the concrete mix design. “Concrete”, on the other hand, could be either the source of
196 RA or the application of RA. In other words, concrete exists across the life cycle stages of RA.
197 It is found that LCA is another frequently studied topic in the RA domain. The highly occurring
198 keywords (e.g., “Mechanical” and RAC) may not be the ones with highest average citations. It
199 is inferred that HPC and LCA are the keywords with the highest influence to the research

200 community of RA with their high average citations, followed by “Microstructure”, “Durability”,
201 and “Shrinkage”.

202 The keywords were divided into eight clusters in *VOSViewer*. Keywords in the same
203 cluster are more likely to have mutual impacts of being cited by each other, for example,
204 “Mechanical”, “ITZ”, and “Microstructure”. Based on the visualization and quantitative
205 measurements of mainstream keywords in RA, these following themes of research keywords
206 can be summarized as below.

- 207 • Coarse RAs applied in concrete mix design and how they would affect the mechanical
208 properties and microstructure of new concrete: examples of existing studies in this theme
209 include but are not limited to Abreu et al. [59], Luo et al. [60], and Cantero et al. [61], etc;
- 210 • Fine RAs recycled and reused in cement composites (e.g., mortar): these studies also
211 emphasized how the recycled fine RAs affected the performance of cement composites.
212 Examples of studies adopting fine RAs in cement composite products can be found in Sosa
213 et al. [62], Martínez-Aires et al. [63], Kim et al. [64], and Ho et al. [65];
- 214 • LCA approach in studying the sustainability of adopting RAs from C&D wastes: these
215 studies may extend the engineering properties of recycled products (e.g., RAC) with a more
216 comprehensive analysis of the environmental, social, and economical aspects of recycling
217 wastes. Examples of these studies can be found in Marinković et al. [66], Rosado et al. [67],
218 Hossain et al. [68], and Gan et al.[12];
- 219 • The effects of RAs on the fresh concrete properties, such as rheological properties in SCC
220 [69, 70]: the workability [71, 72] of concrete containing RAs is a concern;
- 221 • The inter-relationship between creep/shrinkage [73] of RAC and the seismic performance
222 of reinforced concrete structures [74]: seismic resistance of reinforced concrete structural
223 members containing RAs has been gaining a momentum in the academic research in both
224 numerical simulation and experimental studies, such as Liu et al. [75], and Ma et al. [76];

- 225 • The inferior properties of RAs due to its higher water absorption compared to NAs: studies
226 [77, 78] have been focusing on improving the qualities of cement composites containing
227 RAs. The nature and quality of RAs, as identified by Abdulla [79], could have significant
228 impacts on RCA properties. Besides water absorption, the nature and quality of RAs also
229 include their density[80], composition [49], as well as the waste treatment method [81];
- 230 • Adoptions of RA in pervious concrete [82, 83], and the effects of RAs on the permeability
231 of RAC: to minimize the negative effects of the RA porosities, different sizes, sources,
232 admixtures, and supplementary cementitious materials (SCMs) [84, 85] were considered in
233 the mix design of pervious concrete;
- 234 • Durability of concrete containing RAs, including adopting RAs in HPC [86, 87]: the
235 durability properties of HPC that have been studied in literature included permeability,
236 resistance to carbonation, and resistance to chloride penetration [88, 89].

237 Besides these aforementioned RAC types, including pervious concrete, HPC, steel
238 reinforced concrete structure, SCC, it should also be noticed that fiber-reinforced polymer
239 (FRP) composite materials adopting RAs [90, 91] have also gained some increased attention
240 in the academic community adopting RAs.

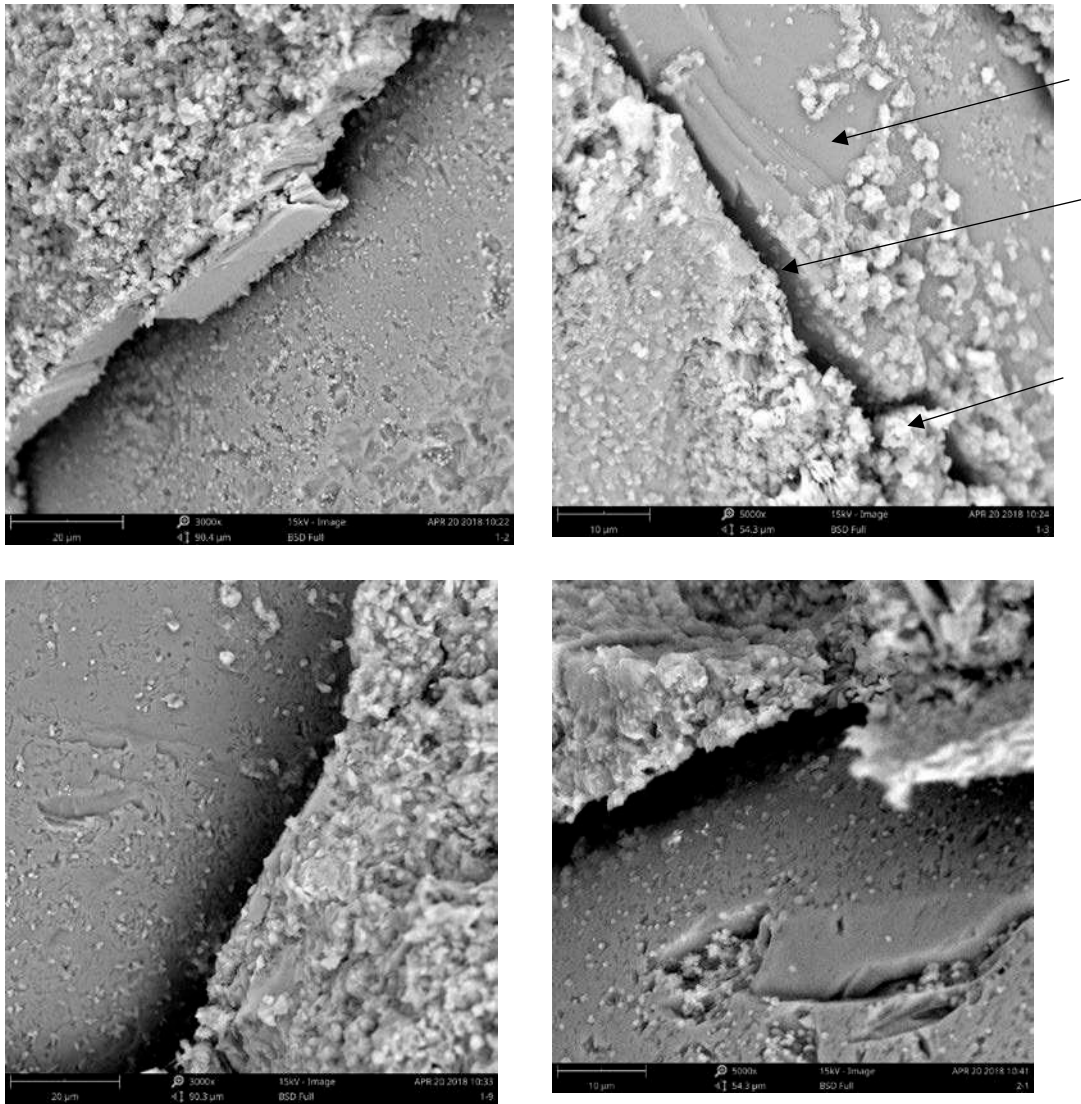
241 **4. In-depth discussions**

242 *4.1. Mainstream research topics in recycled aggregates*

243 Most studies from the literature sample focused on RAs from recycled C&D wastes,
244 especially old concrete. Existing studies using RAs for a cleaner production were also mostly
245 targeted on cement composites especially new concrete mixing and tests. Fig.2 demonstrates
246 the typical micro-structure of RAs from crushed concrete observed under scanning electron
247 microscope (SEM).

Aggregate
surface

Crack



248 Fig.2. Microstructure of RAs from crushed concrete

249 It is seen in Fig.2 that RAs from recycled concrete generally have rough surface, cracking,
 250 and attached mortar. These micro-structural features could cause significant impacts on the
 251 engineering properties of cement composites containing RAs, for example, the mechanical
 252 behavior and durability of RAC. Several important studies demonstrating the influences of RAs
 253 on cement composites are showcased in Table 2.

254 Table 2. Studies investigating the influences of RAs on cement composites' properties

Study	Type of RA	Mix design adopting RA	Cement composite properties tested	Applications of the cement composite containing RAs	Major findings

Alexandridou et al. [49]	RA from different Greek recycling plants	0% , 25%, and 75% of coarse natural aggregates (NA) replaced by RA respectively	Compressive strength, concrete absorption, sorptivity, and carbonation resistance of RAC	Concrete specimens for the laboratory tests	The compressive strength of RAC ranged from significantly lower (37% reduction) than that of ordinary concrete. Clay minerals had a more adverse effect to concrete's strength. Higher water absorption of coarse RA was their most negative physical characteristic. Coarse RA reduced the durability of hardened concrete.
Dimitriou et al. [50]	Coarse RAs from different sources of crushed concrete	NA replaced by 50% and 100% of RA	Compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, porosity, sorptivity, and permeability of RAC	Concrete specimens for the laboratory tests	Increasing the replacement ratio of RA to NA resulted in lower quality of RAC compared to normal concrete. Both mechanical and durability properties are negatively affected by the increase of the replacement ratio. But a simple treatment method to reduce the adhered mortar at RA surface could diminish the negative effects of RAs and create a better quality of RAC which could be competitive to normal concrete.
Ozbakkaloglu et al. [51]	Coarse RAs in two different sizes (i.e., 7 mm and 12 mm)	RAs used to replace NA at different replacement rates, including 0, 25%, 50%, and 100%	Compressive strength, elastic modulus, flexural strength, splitting tensile strength, workability, drying shrinkage, and water absorption of RAC	Specimens for testing, including cylinder specimens and prism specimens	An increase in the coarse aggregate size led to an increase in the 28-day elastic modulus and a decrease in the 28-day flexural and splitting tensile strengths. Coarser RA caused higher drying shrinkage and water absorption in concrete mix. RACs with up to 25% RA content exhibited slightly inferior mechanical and durability-related properties compared to the conventional concrete with the same compressive strength. But replacement of 100% NA would cause significant reductions in concrete properties.
Thomas et al. [92]	Fine and Coarse RAs from crushed test concrete specimens	20% of replacement of RA to the coarse NA, and 100% replacement to both fine and coarse NAs	Compressive and tensile strength, permeability, water penetration, chloride penetration	Mortar and concrete specimens for the laboratory tests	The sulphur within RA did not significantly affect the mechanical or physical performance of mortar or RAC. But using RA from crushed concrete, with or without sulphur, was viable for the manufacture of recycled structural concretes for applications without

					exposure to high temperatures. The use of the fine fraction in RAs caused a significant loss of properties.
Etxeberria et al. [39]	Coarse RA from crushed concrete	Four different RAC produced, made with 0%, 25%, 50% and 100% of RA respectively	Compressive and tensile strength, modulus of elasticity of RAC	Concrete specimens for laboratory tests	Concrete crushed by an impact crusher achieves a high percentage of RAs without adhered mortar. Adhered mortar in RA caused the weak point in the RAC microstructure. RAC made with 100% of coarse RA had significantly lower compression strength than conventional concrete, or required more cement in mix design to achieve higher strength.
Evangelista and de Brito [41]	Fine RA from crushed concrete	Five different replacement ratios of fine RA to fine NA were adopted, namely 10%, 20%, 30%, 50%, and 100%	Compressive strength, split tensile strength, modulus of elasticity and abrasion resistance of RAC	Structural concrete specimens for laboratory tests	It was viable to produce concrete made with fine RA for structural concrete. Up to 30% replacement of fine RA to fine NA did not seem affecting the compressive strength of RAC. Both tensile splitting and modulus of elasticity were reduced with the increase of the replacement ratio. The abrasion resistance seemed to increase with the replacement of fine NA with fine RA.
Tam et al. [47]	RAs collected from local recycling plants, with sizes at 10mm and 20mm respectively	0%, 10%, 15%, 20%, 25% and 30% of RA was used to replace NA	Compressive strength of RAC specimens at different curing ages by using the normal mixing approach and the two-stage mixing approach	RAC specimens for laboratory tests	The two-stage mixing approach gives way for the cement slurry to gel up the RA, providing a stronger interfacial transition zone by filling up the cracks and pores within RA. This two-stage mixing approach can provide an effective method for enhancing the compressive strength and other mechanical performance of RAC.
Xiao et al. [40]	Coarse RA from waste concrete brought from runway	Replacement percentages of RA to NA at 0%, 30%, 50%, 70% and 100% respectively	Compressive strength, the elastic modulus, the peak and the ultimate strains of RAC	RAC specimens for laboratory tests	RAC specimens failed in a shear mode. The stress-strain curves of RAC indicated an increase in the peak strain and a significant decrease in the ductility. The compressive strength, elastic modulus of RAC generally decreased as the replacement ratio of RA increased. The peak strain of RAC also increased with the increase of RA contents.

Poon et al. [43]	Coarse RAs from two different type of crushed concrete, namely normal-strength concrete (NC), and high-performance Concrete (HPC)	Full replacement of NA by RA from NC, and RA from HPC respectively	Microstructure and compressive strength of RAC	RAC specimens for laboratory tests	RAC prepared with the RA from HPC developed higher compressive strength than RAC prepared with RA from NC at all tested ages. In particular, the strength of RAC prepared with the RA from HPC was comparable to that of conventional concrete. The difference in strength development between the RAC with HPC and with NC aggregates was due to the differences in both the strength of the coarse aggregates and the microstructural properties of the interfacial transition zones.
Poon et al. [45]	Coarse RA from crushed and graded unwashed concrete from a single source, sized at 10mm and 20mm	Various replacement ratios of RA to NA, were adopted, namely 0%, 20%, 50%, and 100%; The moisture states of RAs were controlled at air-dried (AD), oven-dried (OD) and saturated surface-dried (SSD) states prior to use.	Slump and compressive strength of RAC	RAC specimens for laboratory tests	The moisture states of the RAs affected the change of slump of the fresh RAC. RA with OD led to a higher initial slump and quicker slump loss, while RAs with SSD and AD had normal initial slumps and slump losses. RAC from RA with AD exhibited the highest compressive strength. Aggregates in the AD state containing not more than 50% RA should be optimum for normal strength RAC production.

255

256

These influential studies showcased in Tables 1 and 2 could lead to further discussions

257

below.

258

4.1.1. Engineering properties of cement composite materials adopting RAs

259

It is generally believed by the public that RAs would decrease concrete strength or lower

260

other RAC properties. This could be due to their high porosity, internal cracking, high level of

261

sulphate and chloride contents, high level of impurity and high cement mortar adhered to RAs

262

[93]. This has been proved by many existing studies [47, 51, 94]. However, multiple studies

263 showed that a moderate percentage of replacement of RA to NA could achieve comparable or
264 even higher mechanical strength of concrete. This replacement percentage of RA to NA, as
265 recommended in previous studies, generally ranges from 25% to 50% [95, 96]. A further mix
266 design methodology was proposed by Pepe et al. [97] to predict the performance of RAC (e.g.,
267 compressive strength). Utilizing the positive effects of RAs for enhancing RAC properties was
268 discussed extensively by Xu et al. [98], who proposed an optimized replacement percentage of
269 RA to NA in concrete mix design, when the “internal curing” feature of RAs due to its
270 porosities could compensate the inferior qualities of RAs. In order to improve the engineering
271 properties and also to reduce carbon emissions, it is commonplace to adopt both RAs and SCMs
272 (i.e., supplementary cementitious materials) in concrete mix design. For example, fly ash could
273 enhance concrete workability when RA absorbs more moisture during concrete mixing [99].
274 These commonly adopted SCMs (e.g., fly ash) identified by Jin et al. [100] in commercial
275 concrete production have been widely adopted together with RAs in sustainable concrete mix.
276 Besides the addition of SCM and adding chemical admixture (e.g., superplasticizer) as
277 suggested in existing studies [101, 102] to reduce the negative effects due to the water
278 absorption of RAs, some pretreatment of RAs, such as removing impurities [103] and pre-
279 wetting of RAs [104], could also be applied to to reduce the effects from the inferior properties
280 of RAs.

281 *4.1.2. The effect of RA sources on properties of recycled products*

282 The effects of RA on concrete properties could be affected by multiple factors, such as its
283 water absorption rate and chemical composition [49]. Chakradhara Rao [105] studied the
284 effects of RAs coming from different parent concrete samples on RAC properties. It was found
285 that RAs from the parent concrete would reduce the new concrete’s compressive strength, but
286 RAs from parent concrete with higher strength could result in comparable strength in the new
287 concrete [105]. Kou and Poon [106] found that RAs from high-strength parent concrete (i.e.,

288 80-100 MPa) samples could be used to produce high performance concrete with higher strength,
289 lower drying shrinkage, and higher resistance to chloride ion penetration. The study from Kou
290 and Poon [106] provided the guide of selecting proper parent concrete source to produce RA.
291 However, how the higher strength of parent concrete would also produce higher quality of RA
292 leading to better performance of RAC was not explained in-depth in most relevant existing
293 studies [105, 106]. Despite that, it could be indicated from Lotfi et al. [107] that the quality of
294 the parent concrete would affect the RAs' microstructure, which further impact RAs'
295 engineering properties (e.g., water absorption, roughness, and abrasion resistance, etc). Jin et
296 al. [104] compared two different types of RAs (i.e., RAs from demolished concrete and from
297 recycled red bricks) in terms of their effects on concrete properties. It was found that the water
298 absorption and hardness of RAs could cause differences in mechanical properties of RACs [47].
299 It was indicated by Poon et al. [43] that the RA from different parent concrete samples could
300 affect the newly produced RAC's interfacial transition zones, which further affect the
301 engineering properties of RAC. It was further suggested by Pepe et al. [103] that "cleaning"
302 RAs to enhance their physical properties could reduce the performance gap between RAC and
303 ordinary concrete. The "autogenous cleaning" of RAs, as described by Pepe et al. [103],
304 referred to removal of surface impurities and reduction of particle heterogeneities.

305 *4.1.3. Different types of RACs containing RAs*

306 Ongoing research has been studying the feasibilities of adopting RAs in multiple types of
307 RACs, including pervious concrete [82], reinforced concrete[108], SCC [69], FRP composites
308 [109], and HPC [110]. Aslani et al. [111] optimized the mix design of high-performance SCC
309 adopting RAs by testing the fresh and hardened properties. It was found that the proposed mix
310 design could save cement amount up to 40% [111]. Yan et al. [112] adopted flax FRP tube
311 encased RAC to improve both the sustainability and the mechanical behavior of concrete
312 specimens. Mechanical properties were also checked by adopting RAs in structural concrete.

313 For example, Gonzalez-Corominas et al. [113] found that a high performance recycled
314 aggregate concrete could meet the structural requirements for prestressed concrete sleepers.

315 *4.1.4. Sustainability effects of adopting RAs*

316 Although most existing studies in RAs, as indicated in Table 3, have been focusing on the
317 engineering properties of cement composites (especially concrete) containing RAs, other
318 aspects of RA adoption such as economic factor [50] has also been concerned. Life cycle
319 assessment (LCA) methods [114] have been developed to assess the impacts of adopting RAs,
320 especially in comparing the environmental impacts between RAs and NAs based on available
321 database and established inventory[115]. The sustainability effects of adopting RAs could be
322 defined in a certain scope such as carbon dioxide (CO₂) emissions and energy consumption
323 [116]. It was evaluated by Ding et al. [116] that the longer transportation distance for delivering
324 NAs would make RAs an alternative option to lower environmental impact. Similarly,
325 Colangelo et al. [117] adopted the LCA approach assisted by a computer simulation to
326 demonstrate that RAs outperformed NAs in terms of environmental sustainability. It was
327 further indicated that different types of RAs had variable sustainability impacts [117]. The LCA
328 approach not only covers the cost and environmental effects by adopting RAs, but also affects
329 policy making [118].

330 *4.2. Research gaps in existing recycled aggregate studies*

331 *4.2.1. Sources of RAs*

332 A review of the RA literature sample in this study reveals that the majority of RAs adopted
333 for scholarly work come from C&D waste, especially demolished concrete [119]. Although
334 C&D wastes from other building materials such as bricks [120], tiles [121], and ceramics [122]
335 have also been studied as RA sources, significantly less research work has been performed to
336 obtain RAs from other locally available sources. For example, oyster shells from food wastes

337 in coastal cities could potentially be reused as RAs for new applications (e.g., building wall
338 claddings).

339 Even within existing studies which adopted RAs from demolished concrete, the
340 uncertainty on the source of the parent concrete could cause variability of RAs' engineering
341 properties (e.g., water absorption), which would further lead to uncertainties in the RAC
342 properties (e.g., mechanical strength and durability). Therefore, a comprehensive list of
343 parameters that influence the RAC properties need to be established. As indicated in some
344 existing studies [86, 123], these parameters could include the mix design of the parent concrete
345 which further affects its strength, crushing method of the old concrete, and pretreatment of RAs.
346 Most studies [105, 106] have been limited to the description of experimental findings of how
347 the property of parent concrete would affect the RAC qualities. So far, there is still insufficient
348 investigation from the material science perspective to explain how these parameters would
349 affect RAC properties.

350 *4.2.2. More engineering properties to be tested of cement composites containing RAs*

351 More studies adopting RAs so far have been more focusing on RAC's performance in
352 terms of traditionally defined properties such as mechanical properties [124] and durability
353 [125]. There have been limited applications of RAs in being studied for their effects on other
354 properties of RAC, such as environmental protection functions. For example, Xu et al. [98]
355 stated that although there have been some ongoing studies of developing photocatalytic
356 conventional concrete, not sufficient research had been performed to utilize the feature of RAs
357 in the mix design of photocatalytic RAC. The internal pores and rough surface of RAs could
358 become an advantage of RAC to capture photocatalysts (e.g., titanium dioxide or TiO₂) for air
359 purification purpose [122]. The applications of RAs in building or infrastructure sectors are
360 limited to non-structural members [126]. Developing RAs for a variety of engineering

361 applications could be explored. RAs could also be tried with different cementitious materials
362 in concrete mix design, e.g., graphene oxide composites, as suggested by Xu et al. [31].

363 The literature sample from this study also indicates that there has been limited research
364 investigating the performance of concrete structures containing RAs under fatigue or adverse
365 outdoor environment. Assisted by Design Expert and Center Composite Design (CCD)
366 software, Li et al. [127] found that fatigue and freeze-thaw cycles would influence the
367 compressive strength and substantially impact the performance of pavement recycled aggregate
368 concrete. Liu et al. [128] concluded that the RAs could enhance the fatigue life of rubber-
369 modified recycled aggregate concrete (RRAC). Somewhat in contrast, the research of Peng et
370 al. [129] showed that the fatigue life, residual strength, and residual stiffness of RAC all
371 decreased with an increase in RA replacement percentage. Thomas et al. [130] also suggested
372 that the use of RA reduced the ability of RAC to resist fatigue cycles. These existing studies of
373 RAC did not reach completely consistent findings. Before extending RAs' application in
374 practical engineering, the experimental and theoretical investigations need to continue in order
375 to reveal more insightful findings regarding RAC or other composite structures' fatigue
376 performance or their performance under adverse environment.

377 *4.2.3. Recycled products adopting RAs*

378 So far the majority of existing studies from this literature sample focused on RAC. Less
379 attention has been paid to other cement composites (e.g., ready-mixed mortar), or other
380 applications of RAs. The gap between scientific research and engineering practice can be found
381 by reviewing the literature sample. For example, most of the studies have been focusing on the
382 engineering properties of concrete containing RAs. However, the commonplace applications
383 of RAs (e.g., from old concrete), could be largely limited to roadway construction, pavement
384 sub-base, and backfilling according to several existing investigations [100, 131, 132]. The

385 uncertainty of RA sources would cause problems of deciding the reapplication of RAs, as
386 indicated by Oikonomou [133] and Meyer [134].

387 *4.2.4. Enhancing the reuse rates of RAs*

388 Crushed concrete for recycling and reuse could cause secondary wastes due to the fact that
389 not all the sizes of RAs could be reused. Koshiro and Ichise [135] attempted to address this
390 issue by adopting the entire waste reuse model through utilizing different sizes of RAs in
391 cement composites (e.g., clay tiles). However, there have been so far limited studies addressing
392 how RAs from different sources, sizes, and compositions could be efficiently utilized to
393 enhance their reuse rate. It is common to see only part of the RAs from demolished buildings
394 being reused in RAC production. There is a need to have standards, guidelines, or even
395 legislations to specify the applications of RAs according to their qualities or properties.
396 Technological applications to obtain this information of quality or property of RAs would
397 become necessary.

398 *4.2.5. A comprehensive indicator system of RA adoption*

399 There has been insufficient research on a holistic evaluation of the impacts of adopting
400 RAs. Existing studies may even come up with contradictory findings on the impacts. For
401 example, Tam [136] and Gull [10] held different views on the cost-effectiveness on reusing
402 RAs from C&D wastes. Factors contributing to the adoption between RAs and NAs include
403 but are not limited to labor costs, available equipment, energy inputs, local availability, and
404 reuse purpose (e.g., pavement). There is a need to develop a decision-making framework (e.g.,
405 an updated LCA approach) for stakeholders to evaluate the advantages and disadvantages of
406 choosing RA and NA. Even though RAC containing RA could be improved by initial treatment
407 of RAs, the practical feasibility of procedures to remove impurities (e.g., Tam et al [47]) in RA
408 surfaces needs to be investigated, especially considering other factors such as labor and cost.

409 *4.3. Suggestions for enhancing RA adoption as sustainable construction materials*

410 The mainstream research topics in RAs and research limitations based on the scientometric
411 review of this literature sample indicate the interdisciplinary nature of adopting RAs for the
412 cleaner production in the construction industry. The industry is causing a significant impact on
413 the living environment based on the facts that: (1) it consumes a tremendous amount of natural
414 resources (e.g., NAs); (2) it contributes a significant portion of the carbon emission crossing
415 industries; and (3) it generates an overwhelming amount of C&D wastes causing shortages of
416 urban landfill space. The concept of cleaner production has been practiced for a few decades
417 and participating companies had shown some positive results in terms of material utilization,
418 lowered energy consumptions and reduced carbon emissions [11]. Implementation of the
419 cleaner production involves technological evolvement, business models, and public awareness
420 as indicated from existing studies [69, 137]. This has been somehow reflected in adopting RA
421 in the construction sector. For example, Jin et al. [126] provided the workflow in the production
422 line of using RAs from crushed C&D wastes to manufacture masonry bricks. Consistent with
423 the discussion provided by Kjaerheim [11], it was further inferred that the adoption of cleaner
424 production needs multiple driving factors, such as governmental policy, social acceptance, and
425 the market condition [126, 131].

426 A review of existing literature [11, 138, 139] indicates that LCA has been a commonly
427 adopted modeling approach in evaluating the outcomes of implementing sustainability. In the
428 context of utilizing wastes in the construction sector, LCA has been implemented to quantify
429 the environmental and technical effects of RA adoption [140, 141]. Based on the existing
430 studies of promoting cleaner production practice, as well as research on reusing RAs,
431 suggestions to enhance RA utilization to improve the sustainability are proposed herein:

- 432 • Information tracking system can be developed for sources of RAs in order to determine its
433 application. Sources of RAs could cause different engineering properties to new cement
434 composites as indicated from previous research [142, 143]. The information system of RAs

435 could include but be not limited to its parent concrete mechanical strength, building type,
436 and laboratory test results, etc.

437 • More site investigation and trial projects can be conducted for investigating the engineering
438 properties and new applications of construction products containing RAs. For example,
439 precast concrete members, as one type of off-site construction components, can be tested
440 of its resistance to natural disasters when RAs are adopted in its mix design. The
441 applications of RA in building construction could be more than just non-structural members.
442 For example, Japanese Industrial Standards [144, 145] provide some guides on the classes
443 of RAs to be applied in different types of concrete structures. A variety of applications for
444 RA-based construction products can also bridge the gap between scientific research
445 community and industry practice.

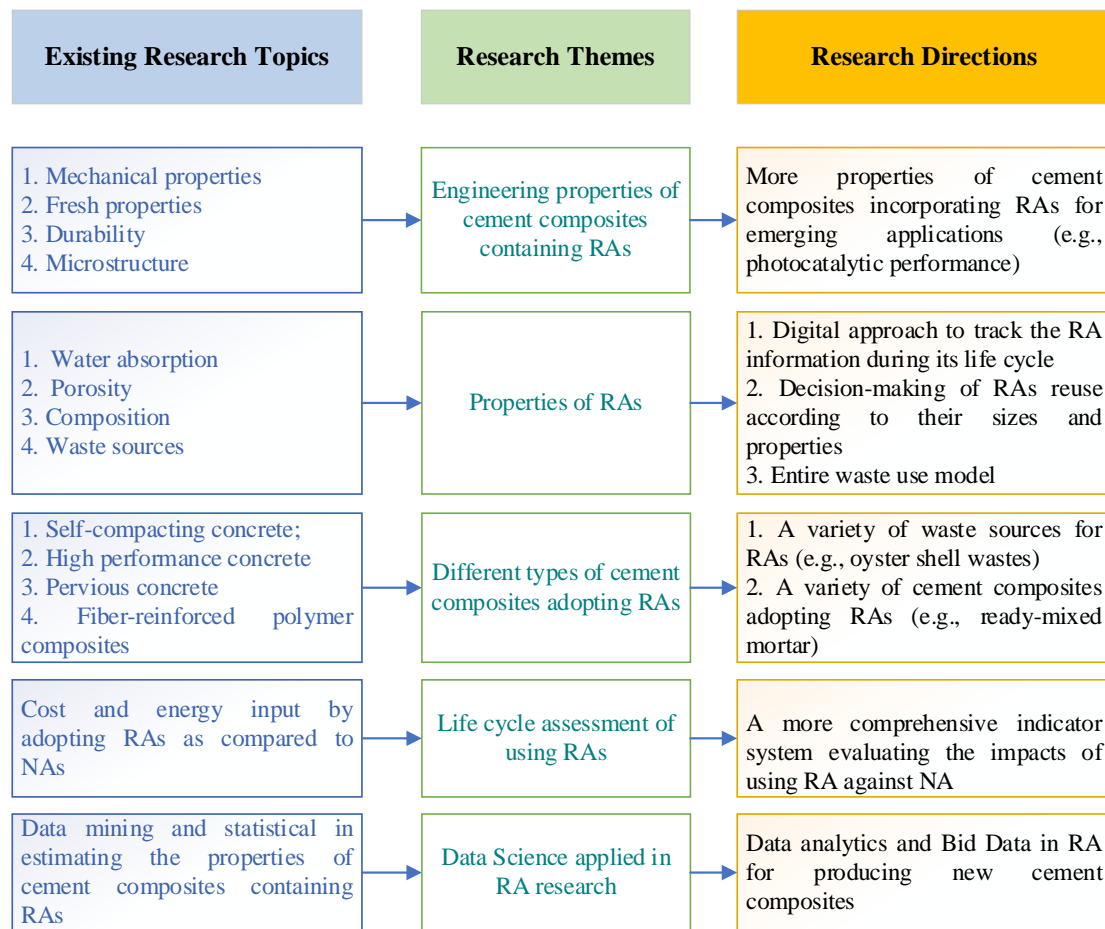
446 • Local availability and regional contexts should be considered for adopting RAs.
447 Stakeholders including policy makers, industry practitioners, and academic researchers
448 could promote the local “green” production by looking at regionally available waste
449 sources beyond the construction industry. For example, sea animal shells from food wastes
450 could be potentially recyclable resources to produce RAs in coastal areas. Agricultural
451 regions might also consider reusing local by-products for RA as indicated by Eziefula [22].

452 • Reusing these local wastes for productions of RAs should not be limited to C&D wastes,
453 but across industries. A comprehensive evaluation of the social, economic, technical, and
454 environmental indicators for adopting a certain type of RAs would be necessary. This
455 evaluation system, based on the life cycle assessment of RAs, should support the decision
456 making for not only whether or not to adopt a certain type of RA (e.g., RA from oyster
457 shells), but also for how to optimize its reuse and application. For example, oyster shells
458 may not only be used for coarse RAs in concrete production, but also as fine RAs for wall
459 finish or decoration.

- 460 • Determining the multiple uses of the same type of RA, or RA from mixed sources of wastes
461 (e.g., C&D waste) in order to enhance the reuse rate. It is important to minimize the
462 “secondary waste” generated by producing RAs from wastes. For example, fine particles
463 would become “secondary waste” if only coarse RAs are utilized from crushing C&D
464 wastes. Fine RAs could also be potentially applied in construction (e.g., mortar).
- 465 • Finally, public awareness towards building products containing RAs can be raised to
466 embrace the sustainability culture. The public might have a biased opinion towards recycled
467 products, but the mindset could be changed when they gain more knowledge of properties
468 of products containing RAs [126]. Pilot construction projects or a prototype of building
469 product such as Waste House [146] works a bridge between multiple stakeholders,
470 including researchers, industry practitioners, and the general public.

471 *4.4. Research directions for recycled aggregate*

472 Following the summaries of mainstream research topics, gaps from existing RA studies,
473 and suggestions to enhance RA adoption, the research framework in the RA domain is proposed
474 in Fig.3. The existing research topics in Fig.3 are generated based on the prior scientometric
475 analysis of keywords, for example, mechanical properties of new concrete containing RAs.



476

477 Fig.3. Research framework linking the existing research topics in RA to future research
478 directions

479 Five main themes are suggested in Fig.3 in the RA domain, linking the existing research
480 topics into future directions:

- 481 • Depending on the application of RAs, more engineering properties of RAs and a variety of
482 RACs could be developed. For example, applying RAs in photocatalytic pervious concrete
483 pavements for absorbing air pollutant particles. As suggested by Xu et al. [98], RAs have
484 their advantage of being more capable to absorb more photocatalysts for developing
485 environmentally friendly concrete.
- 486 • Besides the properties of RAs themselves listed in Fig.3 such as water absorption, the waste
487 treatment method is a key factor that affects the properties of RAs, and further influences
488 the properties of recycled products, as indicated from existing studies [81, 147]. A digital

489 platform, such as Building Information Modeling (BIM) and Geographic Information
490 Systems (GIS), could be adopted to identify or track the information (e.g., source) of RAs
491 before being applied. This information of RAs would be important for deciding how to
492 reuse the RAs (e.g., in non-structural building elements). Information tracked from the
493 source of RAs would also be useful to analyze the heterogeneous compositions of wastes
494 in order to enhance the reuse rate of RAs.

- 495 • The source of RAs and the application of RAs could be extended to other industries beyond
496 the construction field. Depending on local availability, more sources of RAs could be
497 identified besides the C&D sites, **for example, various types of industrial wastes as**
498 **introduced by de Brito and Saikia [148]**. GIS, as the information tool which has been
499 applied in the C&D waste treatment [149], could also be further developed in locating
500 potential sources of RAs and their applications, which may not be limited to cement
501 composites **but also geotechnical and road pavement materials [150]**.
- 502 • Digital approach to track the property information of RA throughout its life cycle including
503 its early stages [151] could be further developed. For example, during the design stage of a
504 concrete structure building, the amount of RAs in different sizes for reuse could be
505 estimated and stored as information in the BIM platform. **The properties of RAs would be**
506 **critical for applications in structural concrete especially from the life cycle perspective [152]**
- 507 • A more comprehensive sustainability indicator system for adopting RAs against NAs could
508 be developed by considering and weighting social, economical, environmental, and
509 engineering aspects.
- 510 • The existing data mining and Big Data approach [153] could be applied in estimating
511 properties of new cement composites containing RAs, **for example, the Analytical**
512 **Systemization Method newly developed by Obe et al [150] in building the data-matrix for**
513 **applying RAs**. The properties of cement composites should not be limited to mechanical

514 properties [154]. More properties of cement composites adopting RAs such as durability
515 could be evaluated using data analytics methods as suggested by Koo et al. [55].

516 **5. Conclusion**

517 This study extends the concept of Circular Economy by focusing on recycled aggregate
518 (RA) as the vehicle to bridge construction and demolition (C&D) wastes and their applications
519 during its life cycle. A comprehensive review of existing literature based on the sample of
520 1,639 journal articles was conducted to provide the big picture of the existing research status
521 in RAs, to discuss limitations in adopting RAs, as well as providing visions for future research
522 in RAs. The current study contributes to the body of knowledge in adopting RA as sustainable
523 construction materials based on the fact that the source of RA should not be limited to C&D
524 wastes, and the application of RA could be more than cement composites.

525 A holistic review approach consisting of three steps, namely bibliometric literature search,
526 text-mining-based scientometric analysis, and in-depth qualitative discussion, was adopted as
527 the research methodology. This holistic review methodology could be further adapted to assist
528 the review of other research domains. Major findings generated following this review
529 methodology can be summarized below.

530 *5.1. Findings from scientometric analysis*

531 Major findings from scientometric analysis are summarized below:

- 532 • Most existing research focused on adopting RAs in the studies of new concrete production,
533 with mechanical properties of recycled aggregate concrete as the most frequently studied
534 topic in RA.
- 535 • Articles with most citations were published in earlier years and focused on mechanical
536 properties of cement composites containing RAs. Articles with highest normalized citations

537 were published in more recent years and focused on review work, durability of recycled
538 aggregate concrete, and applying computing and modeling methods.

539 *5.2.The interrelationship between the scientometric analysis results and RA as sustainable*
540 *construction materials*

541 Following the scientometric analysis, this study summarized the mainstream research
542 topics in existing literature of RA, identified the gaps of existing studies, and provided
543 suggestions for enhancing RA usage. Existing research topics have been largely focusing on
544 adopting RAs from C&D wastes, applying RAs in concrete mix, and testing the engineering
545 properties of concrete containing RAs. A variety of concrete types had been studied, including
546 high-performance concrete, self-compacting concrete, fiber-reinforced polymer composites,
547 and pervious concrete. Life-cycle assessment approach had been applied in comparing the
548 environmental effects between RAs and natural aggregates. Limitations of these existing
549 studies were identified and discussed, including:

- 550 • the need to explore more engineering properties of cement composites containing RAs
551 beyond mechanical behaviour and durability, such as photocatalytic concrete for air
552 purification purpose;
- 553 • the need to have a variety of RA sources beyond C&D wastes;
- 554 • the need to enhance the reuse rate of RAs from C&D wastes;
- 555 • the necessity of having a variety of RA applications, such as ready-mixed mortar;
- 556 • academic studies of RA applications to bridge the gap between experimental research and
557 industry practice, such as the composite structure's fatigue performance;
- 558 • a comprehensive indicator system to evaluate the sustainability of RA adoption.

559 Barriers in adopting RA to embrace the cleaner production in the real world were discussed
560 among the research team, specifically: (1) uncertainty of waste sources for decision making of

561 proper application of RA in the construction industry; (2) lack of a comprehensive evaluation
562 of the properties of building products containing wastes; (3) limited applications of recycled
563 products; (4) the gap between academic research and industry practice of reusing RAs; (5)
564 insufficiently developed indicator system for decision making in adopting RAs. Corresponding
565 suggestions were provided addressing these existing barriers to promote the RA usage in the
566 construction sector, including: (1) an information tracking system to be developed to reduce
567 the risks of using RAs associated with its source uncertainty; (2) more site tests and
568 investigations to explore engineering properties of construction products adopting RAs; (3)
569 multi-stakeholder involvement in evaluating the proper type of RAs in the local context; (4) a
570 cross-industry vision to identify appropriate sources of RAs; (5) minimizing the “secondary
571 wastes” in the process of producing RAs; and (6) nurturing a sustainability culture by
572 demonstrating more pilot projects or prototypes to the public.

573 *5.3. Research framework guiding future research directions in RA*

574 Finally, a research framework was proposed to link existing research topics to
575 recommended future research directions:

- 576 • more engineering properties of cement composites to be explored depending on the RA
577 applications;
- 578 • information tools to be developed to track the source and quality of RAs;
- 579 • digital methods to obtain the RA information throughout its life cycle;
- 580 • a more comprehensive sustainability indicator system for adopting RAs against natural
581 aggregates;
- 582 • data analytics methods applied in estimating more properties of cement composites
583 containing RAs.

584 To move the academic research work forward, researchers in this study suggest that the
585 scholarly work of adopting RAs should not be limited to engineering properties of cement
586 composites containing RAs, but also a variety of RA sources, varied RA applications, as well
587 as interdisciplinary research incorporating data science, digital technologies, policy making,
588 and a comprehensive sustainability assessment in promoting RA research and practice.

589 *5.4. Research limitations*

590 This review-based study is limited to the English journal articles indexed in *Scopus*. It
591 excludes articles published in other languages and also other types of published resources such
592 as trade magazine. The literature sample in this study was limited to academic journal articles.
593 Another review focusing on latest industry practice from other reference sources (e.g., trade
594 magazines) focusing on RAs in would be useful to further identify the gap between academic
595 research and industry practice.

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