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REVOLUTIONIZING SUSTAINABLE CONSTRUCTION THROUGH RECYCLED CONCRETE AGGREGATE PRODUCTION: A SYSTEMIC REVIEW OF CODES, STANDARDS AND GUIDELINES

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Abstract — The significant rise in the production of construction and demolition (C&D) waste has increased dramatically in recent years, resulting in the entry of tons of concrete waste into the environment. Recycling and reusing C&D waste as a partial replacement for aggregate in building construction is practiced in other nations as a possible solution and waste management. However, few studies have identified how C&D waste can be utilized in the Ethiopian Construction Industry (ECI). In addition, the application of recycled concrete aggregate (RCA) in Ethiopia is limited owing to a lack of well-established standards and guidelines. Thus, the focus of this research is to investigate the opportunities and limitations of recycled concrete building materials based on legal design codes, standards, and government guidelines for utilizing recycled concrete waste as aggregates. This study systematically reviewed existing norms and standards for the potential use of recycled concrete aggregates and identified opportunities and limitations by incorporating them into current design and construction practices. This study evaluates the current state and utilization practices of RCA in economically comparable developing countries, drawing comparisons with Ethiopia. The findings revealed inconsistencies in the national standards concerning the permissible substitution of natural aggregates with recycled alternatives. Furthermore, the existing standards lack crucial parameters, such as the precise influence of the source concrete grade on the recycled material properties and the impact of service life on its characteristics. To address these shortcomings, it is essential to develop local design codes, laws, and standards, specifically for RCA in developing countries. Such measures will bolster stakeholder confidence in the sector's applicability, utilization, commercialization, and promotion of this sustainable material. This study is expected to contribute to the standardization of recycled concrete in Ethiopia and similar developing countries where such guidelines or standards do not exist.

***Keywords*:** recycled concrete aggregate, construction and demolition, standard, parent concrete, adaptation

1.0 INTRODUCTION

A widely popular building material in the Ethiopian Construction Industry (ECI) and other developing countries is concrete. Concrete has been in use in construction projects for quite some time owing to its availability robustness, economy and safety. However, concrete manufacture involves a significant quantity of non-renewable natural resources, including sand and gravel. Typically, the process consumes significant energy to extract, transport and crush the aggregate. According to Ittepie et al. [1], approximately thirty-five percent more energy is required to produce one ton of natural aggregate than recycled concrete aggregate (21,112 kJ/t vs. 16,178 kJ/t). In addition, the industry produces a significant amount of concrete waste, commonly referred to as C&D waste leading to waste landfills, massive energy consumption during transportation to landfills, and environmental degradation.

This waste production is raising a number of management problems. According to Kaarthik and Maruthachalam [2], the construction industry alone produces approximately 75 metric tons of concrete waste annually. In 2018, China generated a staggering 2.36 billion metric tons of construction and demolition debris, dwarfing the United States' 600 million and India's 530 million metric tons [3]. The European federation also produces significant amounts of construction and demolition waste, with France and Germany making the largest contribution with 240 and 225 million ton, respectively [3]. In Ethiopia, although there is lack of data on estimating the construction and demolition (C&D) waste, the amount is expected to be significant.

This is primarily due to a combination of factors, including infrastructure repurposing, structural failure, outdated construction practices, urban redevelopment, renovations, road expansions, new construction, demolition of old buildings, and natural disasters. Demolition of existing structures due to human activity or natural disasters such as earthquakes and floods also produces significant amount of concrete waste, which often ends up in landfills and presents a significant challenge to the construction sector [4].

Solid waste management is a persistent challenge in most developing countries, and construction debris is emerging as a significant environmental threat. Currently, in Sub-Saharan Africa, almost 50% of people reside in metropolitan areas, which results in an increase in waste production of up to 1 kg per capita [5]. The production of mixed solid waste from the municipality varies from 0.7 kg to 1.1 kg per person per day in other African nations like Zimbabwe, Tanzania, and Mauritius, with up to 30% of that debris coming from building and demolition [5].

Therefore, an international solution is required to solve the urgent issue of waste storage and removal, which has reached at alarming levels. The conventional practice of landfilling large amounts of C&D waste is increasingly hindered by escalating costs and severe environmental impacts [6]. In addition, these wastes commonly contain hazardous materials such as paints, sealants, adhesives, lead paint, and mercury that can contaminate soil and groundwater supplies. Thus, there is a need to adopt sustainable methods, practices and technologies such as recycling and waste conversion processes like recycling aggregate in order to effectively manage the vast amount of construction and demolition waste.

2.0 SUSTAINABILITY

A lifecycle assessment of the environmental influence of recycled aggregates (RA) from construction and demolition debris in Hong Kong shows that recycled aggregate concrete (RAC) may significantly lower climate change gases by up to 65% and usage of energy that is not renewable by 58% with contrast to natural aggregate concrete (NAC) [7]. Typically, most of the accumulated concrete demolition waste consists of aggregates, which are limited resources that will become scarce with increasing urbanization in developing countries [4]. The lack of these materials will undoubtedly have disastrous consequences in the future. Therefore, there is a need for the construction industry to adopt sustainable practices. One potential approach to judicious use of materials is to consume parts of the recycled concrete aggregate (RCA) from the demolished concrete debris in the production of new concrete. This approach can protect natural material reserves, minimize climate change gases emissions, reduce energy consumption at the time of natural aggregates (NA) production processes and prevent viable land from becoming a landfill, thus increasing the sustainability of the construction sector [8].

Nowadays, the growing world population increase is demanding for infrastructure and facilities, which in turn depend on limited natural resources and improved policies. As a result, various sectors and industries of economy, supported by laws & regulations, are now looking for alternative ways to make products or outputs. This approach has been advocated for several decades and the construction sector is working towards it [9]. Reuse or recycling of building materials began around 1940 in Europe and other developed countries. For example, bricks and other materials collected from the rubbles of World War II were used to rebuild infrastructure [10]. Thus, the C&D waste has been in practice in sustaining an environment.

According to Eurostat (2017, [11]), the percentage of C&D debris produced in the European Union (EU) in 2017 was estimated at 300 million tons. The whole changeover to RA in the 28 nations that make up the European Free Trade Association (EAA, 2018, [12]) would account for over 11% of the world's need for concrete aggregates (almost 2.7 billion tons in 2015). As concrete production is consumed by aggregates, there is a significant opportunity to further refine the current criteria for application of RCA in concrete manufacturing. The European Union Directive 2008/98/CE on waste mandates actions to reduce the unsustainable use of natural resources and to effectively implement waste management systems [13]. Additionally, it advocates for advancing the EU into a recyclable society with the goal to lessen debris generation and instead turn waste into an asset.

Despite the substantial amount of research that has been published on RCA over the past 20 years [14–20], little efforts have been observed on standards to incorporate the application of RCA on the characteristics of concrete.

Currently few countries have prepared standards and specifications to use recycled aggregates as natural aggregate replacements (Table 1).

Table 1 Recycled Aggregate Standards Across the Globe

Scope	Australia	Belgium	Brazil	China	Denmark	Germany	Hong Kong	Japan
Standard/ guidelines	CSIRO [21]	PTV 406 [22]	NBR 15116 [23]	DG/TJ07/008 [24]	DS 2426 [25]	DIN 4226-100 [26]	WBTC 12 [27]	JIS A 5021 [28]

Scope	Portugal	Spain	Switzerland	UK			Netherlands		Norway
Standard/ guidelines	LNECE 471 [29]	EHE-08 [30]	SIA 2030 [31]	BS 8500-2 [32]	BRE Digest 433 [33]	RIL EM [34]	CUR [35]	NEN 5905 [36]	NCA 26 [37]

Although the development of these standards and specifications are beneficial for the practical use of reprocessed aggregates in the construction industry, there are limitations in capturing the full description of RAC behaviors. In addition, there are limited standards and specifications governing the application of RAC in the construction industry in the majority of developing countries and some developed nations. Therefore, this study aims to investigate existing normative documents and identify the gaps and limitations in the application of RCA in the manufacturing of concrete for the construction sector. The goal is to enable the formulation of a more thorough and globally regarded specification in the future, and to overcome the negligence of stakeholders such as designers and contractors in using recycled aggregates in concrete. As a result, this study is expected to contribute to and be used as an input during the development of standards, guidelines, and specifications.

3.0 METHODS

This study adopts a systemic literature review (SLR) approach to meet the goal of the study. Academic databases such as Google Scholar, Scopus, and Web of Science were used as the main source of identification of relevant literature including journal articles, conference proceedings, book chapters, and reports. A combination of keywords like *'recycled concrete'*, *'standards'*, *'developed countries'* and *'specifications', 'legal regulations'* and *'recycled aggregate concrete', 'guidelines'* and '*recycled aggregates', 'recycled aggregate concrete'* and '*developing nations'* were used as domain. Manual search of relevant published articles, policies and standards were also assessed to identify additional sources. In addition, the study also focused on the potential and limitations of existing recycled concrete standards as input data for specification development in developing countries. Furthermore, unrelated studies were excluded such as studies examining the mechanical characteristics of RAC or the application of RAC in specific applications. A pre-screening method was used to review titles, abstracts and conclusions of identified articles to determine their relevance to the research question. Then, the main body of relevant articles and extracted data on standards and specification of recycled concrete in developing countries, barriers to using recycled concrete and the possibility of developing specifications based on existing standards were assessed as main screening method. The pre-screening and screening of selected papers was determined using the criteria of relevance, validity and reliability.

Based on the systemic literature review, the results of the included studies were summarized and presented in a descriptive form. Identified gaps and bottlenecks were also captured for further study. Overall, the review provided an extensive overview of the potential and limitations of existing RAC standards and specifications, which can be used as input for specification development in Ethiopia and similar developing countries.

4.0 CURRENT CODES, STANDARDS AND SPECIFICATION AND GUIDELINES

4.1. International Practice of Developed Nations

The construction industry in the developed world has long employed RA as construction material in concrete production. However, there is no strong foundation or base for quality assurance and control as there are not many standards. In an effort to further embrace current efforts and the utilization of C&D waste recycling, some nations have produced norms and specifications [38]. Because of the large variety of building resources that are commonly utilized in a range of locations and the beneficiation procedures used in every nation, these normative documents change dramatically when it comes to RA and may significantly differ in features. However, the primary type of particles in RCA has been agreed upon existing standards and specifications. These particles include RCA, which are found from demolished concrete elements and recycled masonry aggregates (RMA), which are found from lighter mass and air entrained concrete elements, blocks from blast-furnace slag, sand lime and ceramic bricks [39].

According to EN-12620:2002 1 A1:2008 [40], RA are evaluated and accredited based on their primary components. For example, Rc stands for crushed mortar and concrete, Ru stands for unlimited natural aggregates, Rb for crushed masonry, and so on. However, this standard offers a number of categories with a wide range of contents for each element [39]. As designers and concrete manufacturers are uninformed of the true implications of this variation on the performance of concrete, this effectively prevents the widespread use of RA in concrete manufacturing [41]. The current classification of RA is mostly based on the relative proportions of each of its components, which differ greatly amongst normative documents (Table 2).

The maximum amount of organic waste, pieces of masonry, and other impurities are typically limited in the specifications for certain recycled aggregate classifications utilized in the manufacturing of concrete, whilst the majority of the aggregate's weight being made up of an amalgam of NA and RCA. The majority of standards stipulate specified proportions for RCA and RMA in the aggregate material mixes, which vary depending on the material's intended grade (LNEC-E471, 2006 [29]; DAfStb, 2010 [42]; DIN-4226-101, 2017 [26]; PTV-406, 2003 [22]. Regarding total contamination in these situations, a 5% limit is often observed, however, greater quantities can be found in recycled aggregates of inferior strength; for instance, BS-8500-2:2015 1 A1:2016 (2016) [32] permits no more than ten percent of one of the RA classifications to be composed of asphalt.

Dry density, amounts of sulphate and chloride, and absorption of water are also listed as primary requirements in the standards (Table 3 and Table 4). The first two are regarded as a quick way to evaluate the RA's quality and potential impact on the concrete that results. To stop disruptive expansions and quick corrosion of steel reinforcements, respectively, the chloride and sulphate contents are restricted. The numbers for minimum dry density range is wide. This number is typically 2200 kg/m^3 for RCA and it can be as low as 1500–2000 kg/m^3 for mixed recycled aggregate (MRA) and RMA. Although some implement far harsher limitations for better property recycled aggregates 2450 and 2500 kg/m^3 for GB/T-25177 (2010) [24] and JIS-5021 (2016) [28], respectively, there are others that do not specify.

For high and poor grade RCA, the optimum moisture absorption limitations are normally limited within 3% to 10% and for MRA and RMA between 7% and 20%. Some specifications, such as BS-8500-2:2015 1 A1:2016, 2015, [32] does not place any restrictions on these two properties, assuming that the requirements set forth for the RA make up (such as RCA and RMA composition) are sufficient to guarantee excellence. OT-70085 (2006) [43] also place no restrictions on these two properties. The highest level of chlorides and sulphate, which, unless otherwise stated, refer to those soluble in acid, is typically in the range of 0.03% to 0.25%, 0.8% to 1.0% by mass of the aggregate, respectively. The Brazilian standard (NBR-15116, 2005) [23] has substantially higher limit level of chlorides since it fails to take into account the usage of recycled aggregates for the preparation of structural components in concrete.

Similarly, some rules have been developed for various classes for RA for use in the construction of roads. But, the scope of international laws that are now in place for the use of recycled aggregate concrete in the production of concrete layers is limited. When building stiff pavements, it is important to keep in mind that various layers are needed, including a concrete layer and a granular subbase that can be either treated by cement or made of loose granulated substances [39].

Table 2 Composition Based Classification of Recycled Aggregates (%) as Adopted from [44]

Guidelines	Class	C	M	N. A	O.M	Con.	L.M	F
CSIRO, Australia [21]	Class IA, RCA	<100			-	1	-	-
	Class lB, MRA	<70	<30		-	2	-	-
PTV 406, Belgium [22]	Crushed concrete debris, RCA	>90	<10		0.5	0.5(a)	-	-
	Crushed mixed debris, MRA	>40	>10		0.5	l(a)	-	-
	Crushed brickwork debris, RMA	<40	>60		0.5	l(a)	-	-
NBR 15116, Brazil [23]	ARC, RCA	>90		(b)	-	3	-	7
	ARM, MRA	<90		(b)	-	3	-	10
DG/TJ07/ 008, China (c) [24]	Type I, RCA	>95	<5		0.5	1	-	-
	Type II, MRA	<90	>10		-	-	-	-
DS 2426, Denmark [25]	GPl, RCA	>95	-	-	-	-	-	-
	GP2, MRA	>95	-	-	-	-	-	-
DIN 4226-100, Germany [26]	Type 1, RCA	>90	<10		-	l(e)	-	1
	Type 2, RCA	>70	<30		-	l(e)	-	1.5
	Type 3, RMA	<20	>80	<20	-.	l(e)	-	3
	Type 4, MRA		>80(d)		-	l(e)	-	4
WBTC 12, Hong Kong [27]	Type II, RCA	<100			-	1	0.5	4
JIS A 5021, Japan (c) [28]	ARH, RCA	-	-	-	-	3	0.5	4
CUR [35]	ARH, RCA	>95	<5		-	0.1	-	
NEN 5905, Netherlands [36]	ARH, RCA	<80		<20	-	-	0.1	3
NCA 26, Norway [37]	Type 1, RCA	>94	<5	(b)	-	l(e)	0.1	-
	Type 2, MRA	>90		(b)	-	l(e)	0.1	-.
LNECE 471, Portugal, [29]	ARB 1, RCA	>90	<10	(b)	-	0.2(f)	1	-
	ARB 2, RCA	>70	<30	(b)	-	0.5 (f)	1	-
	ARC, MRA	>90		>10	-	1 (f)	1	-
EHE-08, Spain [30]	RCA, RCA	-	<5	-	0.5	(g)	1	2
SIA 2030, Switzerland [31]	BC, RCA	-	<3	-	-	1	-	-
	BNC, MRA	-		-	-	2	-	-
BS 8500-2, UK [32]	RCA, RCA	>95	<5		-	1 (h)	0.5	5
	RA, MRA		<100	-	-	1 (h)	1	3
BRE Digest 433, UK [33]	RCA I, RMA		<20	>80	-	5	1	-
	RCA II, RCA	<20		>80	-	1	0.5	-
	RCA Ill, MRA	<10	<10	>80	-	5	2.5	-
RILEM, UK [34]	Type I, RMA		<100		1	5	1	3
	Type II, RCA	<100			0.5	1	0.5	2
	Type III, RCA	<20	<10	>80	0.5	1	0.5	2

Where C, concrete; M, masonry; N, A, natural aggregate; O. M, organic material; Con., contaminants; L. M, lightweight materials; F, fines; Recycled concrete aggregate (RCA); Recycled masonry aggregate (RMA); and Mixed recycled aggregate (MRA).

Significant number of C&D material manufacturers, both private as well as public were needed to create and put in place a C&D waste administration plan, aiming for recycling, reusing, or other sustainable areas, under the CONAMA 307 decision, which was approved in Brazil in 2002 [39]. According to the report by [39], the use of C&D waste administration strategies among craftsman was started, and in 2004 the ABNT released technical standards for the application of recycled aggregates in highway projects (NBR-15115 [45] and NBR-15116 [23]). The WBTC-No.12, [27] in Hong Kong offers guidelines to make it easier to employ RA to produce concrete for all structures including roads and buildings. The requirements for RA include a minimum dry density of 2000 kg/m3 and an optimal moisture absorption of 10%.

The restrictions set by distinct global legislations for every kind of property differs widely. The strictest rules for water absorption limit it to a maximum of 7% (Spanish, French and Japanese laws [28, 30]), but RILEM, German and Norwegian specifications [26, 34, 37] allow a maximum of 20%.

Table 3 Classification Based on Physical Properties and Exposure Class of Recycled Aggregates

Scope	Standard/ Guidelines	Standard Class	Unified Class	Strength Class (MPa)	Minimum Bulk Density (kg/m^3)	Water Absorption (%)	Maximum Grain Size(mm)	Type of Concrete or Exposure Conditions
Australia	CSIRO 1998 and H155-2002 [21]	Class I	RCA	-	2100	≤6	32	Nonstructural concrete
		Class lI	MRA	-	1800	≤8	-	Roads and pavements
Belgium	PTV 406 [22]	Crushed concrete debris	RCA, GBS B-II	C 30/37	>2,100	<9	-	Inside building; dry environment
		Crushed brickwork debris	RMA, GBS B-I	C 16/20	>1,600	<18	-	Inside of constructed building; dry environment
Brazilian code	NBR 15116 [23]	ARC	RCA	-	-	≤7	-	-
		ARM	MRA	-	-	≤12	-	-
China (c)	GB/T 25177-2010 [24]	Level I	RCA	Any strength	>2450	≤3	31.5	Structural concrete
		Level II	MRA	≤40	>2350	≤5	31.5	Structural concrete
		Level III		≤25	>2250	≤8	31.5	Structural concrete
Denmark	DS 2426, [25]	GPl	RCA	40	>2,200	-	32	Low to moderate aggressive conditions
		GP2	MRA	20	>1,800	-	32	Low aggressive conditions
Germany	DIN 4226-100, [26]	Type 1	RCA	C30/37 ≤C20/25	≥2000	10		Interior elements exposed to the normal environment
		Type 2	RCA	-	≥2000	15	-	-
		Type 3	RMA	-	≥1800	20	-	Nonstructural concrete
		Type 4	MRA	-	≥1500	n/a	-	Nonstructural concrete
Hong Kong	WBTC 12 [27]	Type II	RCA	35	2000	10	-	Structural concrete
			RMA	20	-	-	-	Less demanding structures
Japan (c)	JIS A 5021, [28]	ARH	RCA	Type I 30	2500	3	-	Heavily Loaded areas of structures
				Type II 27	2300	5	-	Medium loaded structures
				Type III 24	N/a	7	-	Small load structures
Portugal	LNECE 471 [29]	ARB 1	RCA	C 40/50	≥2200	≤7	-	-
		ARB 2	RCA	C 35/45		-	-	-
		ARC	MRA		≥2000	≤7	-	-
Spain	EHE-08 [30]	RCA	RCA	C40	-	-	-	Structural concrete

				-	-	-	-	Non-structural
Switzerland	SIA 2030, [31] OT70085 [43]	BC/ Classified concrete	Scenario A	≥C25/30	-	-	-	Outdoor element
				C30/37	-	-	-	Indoor element
				C20/30	-	-	-	Indoor element
				C15/20	-	-	-	Minor component
			Scenario B	≥C25/30	-	-	-	Outdoor element
				C30/37	-	-	-	Indoor element
				C20/30	-	-	-	Indoor element
				C15/20	-	-	-	Minor component
			Scenario C	≥C25/30	-	-	-	Outdoor element
				C30/37	-	-	-	Indoor element
				C20/30	-	-	-	Indoor element
				C15/20	-	-	-	Minor component
		BNC/ Unclassified concrete	Scenario A	Cement content 150–230 kg/m^3	-	-	-	-
				Cement content <150 kg/m3	-	-	-	-
UK	RILEM [34]	Type I	RMA	C16/20[a]	≥1500	≤20	-	Plain/reinforced
		Type II	RCA	C50/60	≥2000	≤10	-	Plain/Reinforced concrete
		Type III	RCA	unlimited	≥2400	≤3	-	Any strength concrete

-, Not available; RCA, Recycled concrete aggregates; MRA, Mixed recycled aggregates; RMA, Recycled masonry aggregates.

Most of the specifications match and align with what is needed by NA in terms of maximum water-soluble chlorides and sulfates. Recycled aggregates can be intended for low-end usage where the existence of these elements has no detrimental effects and therefore some restrictions are less severe. As concrete pavements must be constructed in accordance with strict aggregate-related qualities, limitations for the usage of RA in road concrete often emphasize their application in cement-treated and uncontrolled layers. When RCA forms the majority of concrete pavements and when replacement levels are relatively low, the use of RA is usually permitted [39].

For the manufacturing of a nonstructural concrete, the Brazilian code specification NBR-15116 [23] permits the use of both coarser and finer recycled aggregates. Less demanding requirements than those outlined in other standards apply to both forms of RA. Although the material is not designed for construction purposes, the fulfilment of the resultant RAC may be compromised as less stringent contaminant content standards are applied. According to the German standards for the application of recycled aggregates in reinforced concrete (DAfStb [42]), it is only allowed in structural elements of the concrete with a grade classification of at most C30/37 as defined in EN-1992-1-1 [40]. In the manufacturing of new structural concrete, only types I and II are allowed to be applied in accordance with DIN-4226-101 (2017) [26], while other lower RA classes are only allowed to be applied in non-structural components.

The physical properties and exposure condition of recycled aggregates, as well as the requirements and recommendations for using recycled aggregates in concrete making in various countries are shown in Table 3.

Chinese specifications (JGJ/T-240, 2011; GB/T-25177, [24]) state that type I coarse RA is capable of being employed to make concrete in any of the strength categories, but only types II and type III coarser RA could be used to prepare concrete with strength classes lower than C40 and C25 [39]. According to Chinese specifications, no recycled aggregates must be applied to create structural components of concrete structures that will be subjected to temperature variations. Only concrete classes below C40 can be integrated with premium Type I fine recycled aggregates. Type III fine recycled aggregates are not recommended for producing structural elements of a concrete structure, and Type II fine recycled aggregates should only be used in concrete below C25. Additionally, no recycled aggregates are accepted for creating prestressed concrete [39].

Table 4 Standard Recommendation on Application and Exposure Class of Recycled Aggregates

Country	Standard	Application	Acid Soluble Sulphates (%)	Water Soluble Sulphates (%)	Water Soluble Chlorides (%)	Exposure Class
Brazil	NBR-15116 (2005) [23]	Non-structural concrete				-
China	JGJ/T-240 (2011) [46]	Concrete grade under C40				X0, XC1 to XC4, XF1 to XF3, XA1
Germany	DAfStb (2010) [42]	Structural concrete with strength under C30/37				X0, XC1 to XC4, XF1 to XF3
Japan	JIS-5308 (2014) [47]	Ready-mix concrete				-
Korea	KS-F-2573 (2014) [48]	Concrete with compressive strength of 21 MPa				X0
RILEM	Recommendation (1994) [34]	Concrete with maximum grade of C 50/60	0.8-1.0	0.2-1.0	0.03-0.25	-
Netherlands	NEN-80051C1:2017 (2017) [36]	Concrete with strength class between C12/15 and C55/67				X0, XC1 to XC4, XF1 to XF3, XS1, XA1
Portugal	LNEC-E471 (2009) [29]	Concrete with strength class up to C40/50				X0, XC1 to XC4, XS1, XA1
United Kingdom	BS-8500 (2015) [32]	Structural concrete with strength class up to C40/50				X0, XC1 to XC4, XF1, DC-1

According to the Republic of Korea specification KS-F-2573 [48], coarse RAs that meet the criteria of Tables 2 and 3 can be applied at a volume not more than 30% in structural concrete that has a 27 MPa cube strength. In accordance with this specification, fine RA can be applied in concrete with 21 MPa compressive strength of up to a 30% replacement level. These materials have limited applications in nonstructural parts like concrete blocks, as their end use. RILEM (1994) [34] recommends three varieties of recycled aggregates (varieties I, II and III) for concrete with maximum grades of C16/20, C50/60 and unlimited strength concrete, respectively. During the construction of concrete structures, correction factors are determined for several qualities of concrete (Table 5).

Table 5 RELEM.1994, Adjustment Ratios for Specific RAC Properties as Adopted from [39]

RAC types	Required design value			
	Tensile strength (f_{ctm})	**Modulus of Elasticity (E_{cm})**	**Creep Coefficient ($\phi(N,t0)$)**	**Shrinkage (ε_{cso}))**
Recycled aggregate concrete Type I	1	0.65	1	2
Recycled aggregate concrete Type II	1	0.8	1	1.5
Recycled aggregate concrete Type III	1	1	1	1

If the MRA contains a huge number of masonry-oriented pieces (which is less than 50% of the recycled aggregates weight), the Dutch standard allows only 10% NA replacement (NEN-8005 1 C1:2017 (2017) [49]). This is the Dutch description of EN-206 (2013) [39]. Otherwise, the compensation of gross natural aggregates for gross recycled aggregates is as much as 20%. Concrete with a strength grade between C12/15 and C55/67 can only use RA elements. No deviations in the tensile and modulus of rapture of concrete are assumed for the same strength class in accordance with the RILEM guidelines. A correction factor of 0.9 was considered for the elastic modulus of the stated concrete grades. For recycled concrete aggregates with strength levels not less than C20/25 and less than C20/25, creep modification coefficients of 1.1 and 1.3 respectively were considered [39].

British BS-8500 [32] and German DIN-4226 [26] were the sources in the preparation of the Portuguese standard LNEC-E471 (2009) [29] specification. For the variations in the gross RCA (ARB1 and ARB2), it limits a highest value of 25% or less and 20% reimbursement. If the final product is plain concrete, there is no limitation on the replacement ratio. These aggregates have maximum strength classes C40/50 and C35/45 and are only permitted in exposure levels X0, XC1–XC4, XS1 and XA1. For the same strength class, the tensile and flexural behavior of concrete should not fluctuate.

Crushed Concrete Aggregate (CCA) and RA are the two categories into which preferred aggregates are divided in the latest version of BS-8500. CCA can be applied in structural concrete with a maximum strength class of C40/50 and exposure classes X0, XC1–XC4, XF1 and DC-1 if it meets the standards given in Tables 2 and 3 [39]. Unless explicitly stated in specifier, the substitution proportion is constrained to 20%. Fine, clean CCA is taken as excellent for making structural components of a concrete structure. Coarse RA can be used, but its effectiveness in concrete must be evaluated carefully considering its unique composition and effect on concrete properties.

Since most current regulations and specifications reference to the utilization of RA in concrete for buildings, Table 6 proposes a categorization of six types of RA that may be utilized for the production of concrete pavements and other layering in the construction of roads. A single kind of asphalt Recycled Aggregate (RAA), three MRA variations (MRAs-I, II, and III), and two kinds of reclaimed aggregate (RCA-I and RCA-II) are all included in this categorization [29].

This is the first, cautious version to unify all RA classifications for pavement construction until more information is gathered on the applicability of this classification, although only RA type may be applied in pavements made of concrete under the suggested categorization [29].

Table 6 Road Section RA Classification Suggested for International Requirements as Adopted from [29]

<table>
<tr><th colspan="2" rowspan="2">Aggregate Property</th><th colspan="6">Type of RA Proposed</th></tr>
<tr><th>RCA-I</th><th>RCA-II</th><th>MRA-I</th><th>MRA-II</th><th>MRA-III</th><th>RAA</th></tr>
<tr><td rowspan="4">Composition</td><td>Rc + Ru</td><td>>90</td><td>>85</td><td><0.7</td><td>>60</td><td>>40</td><td><50</td></tr>
<tr><td>Rb</td><td><10</td><td><15</td><td><30</td><td><40</td><td><60</td><td><10</td></tr>
<tr><td>Ra</td><td><5</td><td><10</td><td><10</td><td><20</td><td><30</td><td>>50</td></tr>
<tr><td>Others</td><td><1</td><td><3</td><td><5</td><td><8</td><td><15</td><td><3</td></tr>
<tr><td>Minimum density(SSD)</td><td></td><td>2200</td><td>2100</td><td>1900</td><td>1800</td><td>1650</td><td>2000</td></tr>
<tr><td>Water absorption (%)</td><td></td><td><6</td><td><8</td><td><8</td><td><12</td><td><15</td><td><8</td></tr>
<tr><td>Los Angeles abrasion (%)</td><td></td><td><35</td><td><37</td><td><40</td><td><45</td><td><50</td><td><40</td></tr>
<tr><td>Water soluble sulphates (%)</td><td></td><td><0.7</td><td><0.8</td><td><0.8</td><td><1.0</td><td><1.2</td><td><0.8</td></tr>
<tr><td>Proposed applications in road layers</td><td></td><td>Concrete pavement, cement treated or unbound granular subbases</td><td>Cement-treated or unbound granular subbases</td><td>Unbound granular subbases or capping of esplanades</td><td>of esplanades or subgrades</td><td>Subgrades and embankments</td><td>Unbound granular subbases and capping of esplanades</td></tr>
</table>

Note: Rc, crushed concrete and mortar; Ru, unbound natural aggregate ; Rb, crushed masonry; RCA, recycled concrete aggregates ; MRA, mixed recycled aggregates ; RAA, recycled asphalt aggregate.

Following a review of the various standards and WBTC 12/2002 [27], the specifications for RCAs based on the WBTC 12/2002 [27] have been added to the most recent standard for aggregate materials in concrete published by The Government of Hong Kong specific Administrative Region, "Construction Standard [50]". Table 7 lists the grading specifications for RCA according to CS3: 2013 [50].

4.2. International Practice of Developing Countries

Even though the ecological impact of concrete is significantly reduced when recycled aggregates from C&D waste are used, there are still limitations to RCA utilization in the construction industry of developing nations. This is mainly due to the lack of information, standards and/or specification, which creates lack of trust on how concrete remains can be recycled into fresh concrete or other building materials.

One of the emerging nations in Africa where C&D waste recycling is not practiced is Ethiopia, which has seen rapid economic growth primarily due to a construction boom. This growth has increased the demand for natural aggregates, leading to significant volumes of C&D waste that are typically dumped in landfills, posing challenges for infrastructure expansion [9].

Table 7 Recycled Coarse Aggregate Grain Size Distribution as Adopted from [50]

Nominal size		**sieve size (mm)**						
		50	37.5	20	14	10	5	2.36
Maximum size for graded aggregates (mm)	40 to 5	100	90–100	35–70	25–55	10–40	0–5	–
	20 to 5	–	100	90–100	40–80	30–60	0–10	–
	14 to 5	–	–	100	90–100	50–85	0–10	–
Maximum size of single-sized aggregates (mm)	40	100	85–100	0–25	–	0–5	–	–
	20	–	100	85–100	0–70	0–25	0–5	–
	14	–	–	100	85–100	0–50	0–10	–
	10	–	–	–	100	85–100	0–25	0–5
	5	–	–	–	–	100	45–100	0–30

Note: The percentage by mass passing 4-mm test sieve shall not exceed 5%, for coarse recycled 20 and 10-mm single-sized aggregates.

If adequate and prompt action is not taken, the existing issues will worsen, leading to general depletion of NA and waste accumulations in cities. Therefore, it is urgently necessary to conduct a practicability study of RCA for its application in the production of cement-based construction materials in Ethiopia.

Even though recycling concrete is a widely accepted concept in the construction sectors of developed nations, it is still limited in most under developed nations, including Ethiopia. There have been several works and procedures involving recycled concrete aggregates around the world; nevertheless, in the perspective of the construction sector in developing countries, these practices are still limited. A primary challenge is understanding why the utilization of Recycled Concrete Aggregate (RCA) remains low in Ethiopia and other developing countries, despite its potential for small-scale construction projects. The limited adoption of RCA can be attributed to several factors, including a lack of standardized practices, guidelines, and specifications, coupled with insufficient field experience and expertise. Furthermore, there is still uncertainty and lack of availability regarding the financial and ecological consequences of recycled concrete aggregates. There has been some research conducted in Ethiopia showing the economic advantages of appling RA in place of natural aggregates. Yehualaw and Woldesenbet [9] conducted a cost analysis and cost comparison of natural aggregates with recycled aggregates at different replacement levels compared to the natural aggregates in Ethiopia. Consequently, they found that the total cost of recycled aggregates is significantly less compared to the cost of natural aggregates (Fig. 1). This shows that the application of RCA in the Ethiopian building sector not only preserves natural aggregates, avoids environmental pollution, and minimizes energy consumption, but also positively impacts the country's economy.

4.3. Constraints in the Use of RA in Concrete in Developing Countries

The application of RCAs has advantages for the economy and the environment of developing nations, but there are significant limitations during implementation in terms of legal rules, awareness creation, technology, and management. One of the constraints to apply concrete recycled aggregates in construction industry of developing countries especially Ethiopia is the absence of appropriate rules, specifications, guidelines, codes, and standards. To control the usage of recycled materials, adequate legal regulations are required [51]. Due to the absence of the regulations, the construction sector in Ethiopia is reluctant to embrace recycled items, which require funding for development, manufacturing, and consumption. For conventional concrete, there are sufficient standards and guidelines in Ethiopia. Few developing nations have recently released the criteria and standards for the application of recycled aggregates in concrete applications, both structural and non-structural. However, these are countries, including Ethiopia, that have not taken steps in this direction. Recycled aggregate application in the construction sector is therefore impossible without having regulations and guidelines.

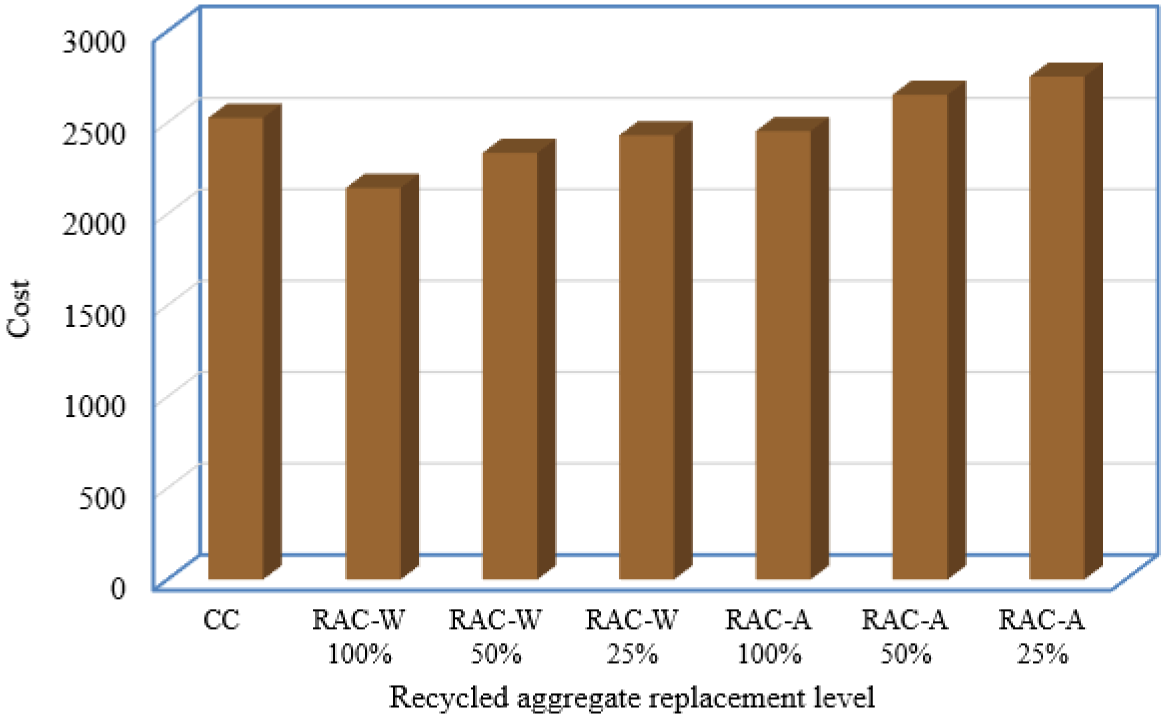


Figure 1 Cost analysis and comparison of recycled aggregates with natural aggregates in Ethiopia (Yehualaw & Woldesenbet, [19])

Note: CC represents conventional concrete, RAC-W represents recycled aggregate concrete with no admixture, and RAC-A represents recycled aggregate concrete with admixtures. The numbers with % represent the aggregate replacement level (i.e., 100% represents 100 replacements of natural aggregates with recycled aggregate). ETB stands for Ethiopian Birr

The second barrier is the lack of experience. The usage of RCA is hampered by the lack of experience necessary to ensure the safety of any new materials. There is limited experience related to the application of RA in the Ethiopian building sector thus far. There are still certain technical issues with RAC, which are primarily caused by the subpar performance of recycled aggregates, even though there are many research that proposed novel strategies for increasing the standards in the developed countries. The technological problems related to extraction of the aggregates from the C&D waste, impurity removal, production of aggregates, and methods for property enhancement are also constraints in the use of recycled aggregates in Ethiopia.

4.3.1. Limitations and barriers to apply RCA and RAC in the construction industry worldwide

Although, employing RA in structural concrete is proven to be technically feasible, a number of obstacles have been found that impede its widespread manufacturing worldwide. However, merely listing these obstacles and trying to think of a reasonable solution is not the same as getting through them. In reality, despite the fact that the reincorporation of treated C&D waste is totally rational for conventional construction practice, many of the impediments are still there, primarily for financial reasons [52]. Because effective taxes that takes into consideration the environmental impact of their extraction is not imposed and the C&D waste gate charge in recycling plants is not alluring enough to deter unlawful dumping, several countries continue to commercialize NA at extremely low costs. Clients and contractors commonly express skepticism regarding the technical feasibility of employing RA in concrete applications. In many other scientific domains, as in this one, a lack of trust is typically coupled by a lack of understanding. Insofar as the components are of known high quality, the use of RA in the production of structural concrete has been thoroughly investigated and is assumed as a workable substitute for NA (Nagasaki et al., 2004 [53]; Pedro et al., 2014 [54]). The significant unpredictability of RA features is, in fact, one of the firsthand justifications for not employing them. Numerous recycling facilities either lack motivation to create RA of a high enough standard for high-grade applications or are unaware of the best practices to acquire RA with the best possible quality. In any situation, the finished product's quality can change daily or might not be suitable for use in structural concrete, creating another significant barrier. Furthermore, some people continue to believe that turning C&D waste into RA has a bigger ecological impact than processing NA productions. Although this might be the case when mechanical and thermal processing phases are combined in an effort to lessen the amount of adhered mortar in RAC, during processing by applying identical mechanical methods to those used for natural aggregates, RA display lower ecological pollution [55].

The cost of transportation has a huge influence on the financial and environmental advantages of adopting RA as a viable substitute for NA [55]. In reality, depending on how far away from the recycling facility building and demolition sites are, the environmental impact and expense of RA may be significantly increased by road haulage distances, decreasing their appeal to builders and concrete producers. Nevertheless, it is conceivable to deploy mobile recycling machines and essentially do away with road transport operations depending on the desired use and the accessibility of raw materials on site [52].

4.3.2. Code limitations

Although some current standards and specifications (BRE Digest 433 [33], RILEM, 1994 [34], and NEN-EN 12620+A1, 2010 [36]) permit the use of RA in the manufacturing of concrete, the majority either contain extremely tight restrictions or convey an imprecise understanding of the potential behavior of RAC. In actuality, there is no subsection that can be taken to explain the structural behavior of the RAC element in the main codes (EN-1992-1-1, Eurocode 2 [40] and ACI 318-14, 2014 [56]) for design and analysis of load bearing concrete [38]. Because designers and concrete manufacturer strictly adhere to these regulations, its change is essential to help them comprehend the effects of employing RA on concrete performance and permit a higher usage of processed C&D waste.

Although there are criteria that permit the usage of RA, as indicated, many of them are outdated and insufficiently thorough to inspire good trust in the main actors in the sector [38]. Recent endeavors have focused on establishing a connection between the current understanding of recycled aggregate concrete properties and its structural performance to address this challenge. Assuming there are already enough incentives to overcome the barriers outlined above, designers will need a performance-based strategy that enables them to adapt how recycled aggregates are applied to a variety of situations.

The inability to manufacture of the aggregate with known capacity has been one of the top difficulties in using RA in concrete so far. Silva et al. [57] created a performance-based classification for measuring the property of recycled aggregates on the basis of the physical properties in a prior study (Table 8). Strong connections between the suitability of recycled materials and the capacity of the produced concrete were discovered using this categorization [58, 59], enabling designers to anticipate the crushing strength of RAC with ease.

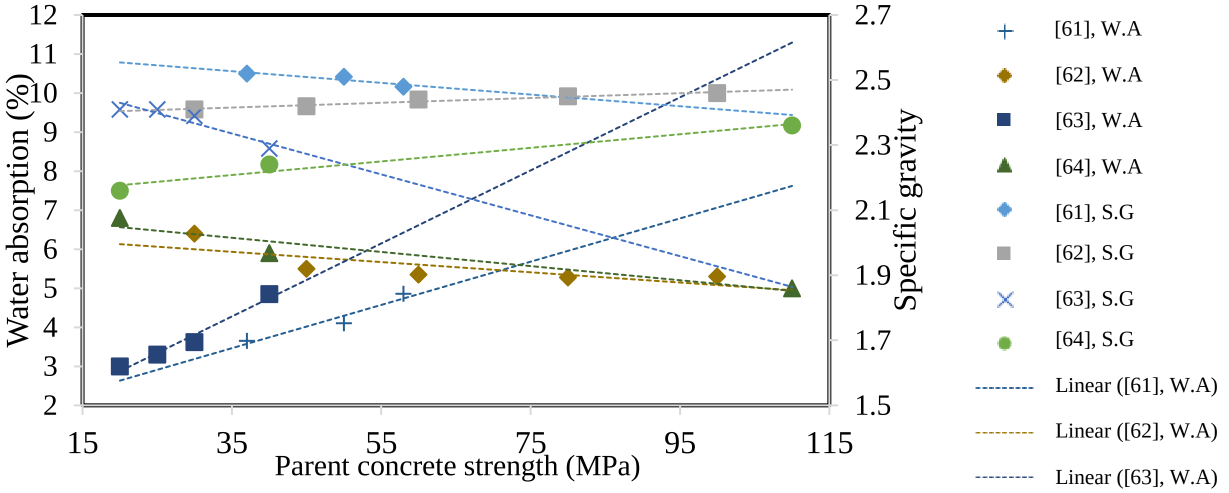
Another limitation of the existing codes is the impact of source concrete strength on the quality of RCAs. The quality of the parent concrete that was used and the type of structure that was demolished varies from site to site and structure to structure. As a result, the grade of recycled aggregates varies greatly [51]. Numerous studies have been conducted to demonstrate the effect of source concrete strength from diverse sources on the properties of RCAs and RACs. However, there are inconsistencies in the findings of these literary works.

Some reports suggest that the utilization of high-strength parent concrete RA can result in superior quality RAC as the RA obtained from high-load carrying capacity source concrete has less porosity and better density than low-load carrying capacity source concrete, causing a lower moisture absorption and higher resilience to disintegration of the resulting RAC. Conversely, other studies have found that RCAs manufactured from low-load carrying capacity source concrete offer better-quality RA and RAC as the mortar adhered to the aggregates in low-strength parent concrete can easily detach during the aggregate production process by crushing, leading to mortar free aggregates. These and other such inconsistencies in the literary work may pose difficulties for scholars and stakeholders involved with construction in deciding whichever of these ideas to adopt in their practical applications. Fig. 2 shows the variability of the results on moisture absorption and specific gravity of RCAs in the literature studies. Existing regulations and standards do not consider the inconsistency of results in the literature, on the impact of source concrete strength on the quality of the RCAs and RAC. Accelerated carbonation and other treatment methods for the enhancement of the RCA quality and facilitated carbonation with chloride ion penetration and deformation of the RAC induced by shrinkage and creep, were not included in the existing regulations and standards.

Table 8 Requirements for Physical Characterization and Performance-Based Classifications (Taken from [57])

Aggregate class		Minimum oven-dried density (kg/m3)	Nominal expected water absorption (%)	Expected LA abrasion mass loss (%)
	I	2600	1.5	
A	II	2500	2.5	40
	III	2400	3.5	
	I	2300	5	
B	II	2200	6.5	45
	III	2100	8.5	
	I	2000	10.5	
C	II	1900	13	50
	III	1800	15	
D			No limit	

One more limitation of existing codes and standards on RAC are evident in its performance against sulfate attack, which is highly dependent on the new cement matrix properties [60]. Well-designed RAC can perform well with significant RA usage, but generally, RCA reduces sulfate resistance due to increased transport properties. RCA's potential to compensate for increased porosity remains unclear, necessitating further studies with detailed characterization and performance tests. The synergy between RA and Supplementary Cementitious Materials (SCM) can enhance eco-efficiency, and pretreatment techniques can improve sulfate resistance. Current SO_3 regulations for natural aggregates may be inadequate for RCA, suggesting the need for higher limits if special design precautions are implemented, such as using sulfate-resistant cement or SCM. Further research should address internal restraint, RA reactivity, and the development of a standardized testing method to evaluate various RA types, qualities, and quantities in cementitious mixtures [60].



Note: W.A in the legend of this table represents the water absorption value of recycled aggregates; S.G. represents the specific gravity of recycled aggregates and values in square brackets are the reference numbers [65].

Figure 2 Sample findings from the literature demonstrate how the water absorption and specific gravity of recycled aggregates incorporating varying strengths of parent concrete vary inconsistently.

5.0 CONCLUSIONS

Owing to the vast quantity of C&D waste generated, the depletion of natural aggregates, the high energy consumption associated with natural aggregate mining, and the environmental impact of C&D waste, it is necessary to explore a cost-effective and environmentally responsible method for utilizing C&D waste. Currently, extensive efforts are underway to recycle concrete waste into various products and structural components. The utilization of recycled concrete has gained widespread acceptance in the construction industries of developed countries. Despite the considerable amount of research that has been disseminated regarding RCA over the preceding two decades, there have been limited efforts observed within the existing standards and specifications to incorporate the impact of RA on the properties of concrete. At present, only a few countries, such as Australia, Belgium, Brazil, China, Denmark, Germany, Hong Kong, Japan, the Netherlands, Norway, Portugal, Spain, Switzerland, and the UK, have formulated standards and specifications for employing recycled aggregates as replacements for natural aggregates. Although this advance was favorable for the pragmatic usage of RCAs in the construction industry, these standards also possess limitations in the complete depiction of RAC behaviors. While existing standards and specifications for RCA usage are limited and vary among countries, there is a need for more comprehensive and internationally acceptable specifications to overcome barriers and encourage the widespread adoption of RCA in RAC. Furthermore, addressing concerns related to the variability of RCA properties, impact of parent concrete strength, and lack of trust and understanding regarding the technical viability of RCA in concrete are crucial for its successful implementation. Future research should focus on developing performance-based strategies and quality control measures throughout the life cycle of RCA to ensure consistent and reliable performance in construction applications. Nonetheless, its use remains limited in most developing countries including Ethiopia. The absence of established procedures, standards, specifications, field experiences, and know-how has limited the use of recycled aggregates in these countries. Furthermore, the environmental and economic implications of Recycled Concrete Aggregate (RCA) in these regions remain largely undefined. Developing nations have made minimal progress in establishing the necessary legal frameworks and standards for RCA utilization. Therefore, it is imperative for the relevant authorities of these nations to contemplate the formulation of legal statutes and regulations, accompanied by standards and directives, to ensure that the construction industry places significant emphasis on this matter. Furthermore, disseminating knowledge about the utility of RAC to the populace will aid in augmenting their understanding of the significance of integrating recycled aggregates in construction. This study reviewed the existing legal regulations, standards, and guidelines and identified the opportunities and limitations of these standards so that nations with no standards can use this paper as an input in their own standards and guideline developments.

Conflict of interest

The authors declare that there is no conflict of interest regarding the research, authorship, and/or publication of this article.

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