Construction and Building Materials 172 (2018) 272–292

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A review of recycled aggregate in concrete applications (2000–2017)

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HIGHLIGHTS

- The paper reviews the production and utilisation of recycled aggregate in concrete.
- Critically analysed the globally published data on recycled aggregate standards.
- This review may help to alleviate the concerns of consumers.
- This paper can encourage and further promote the use of recycled aggregate.

ARTICLE INFO

Article history:
Received 17 January 2018
Received in revised form 12 March 2018
Accepted 26 March 2018

Keywords:
Construction and demolition waste
Recycled aggregate
Legislation
International norms

ABSTRACT

Solid waste has been an inevitable by-product of the operations of industrialised societies. One result of economic growth is an increase in generation of solid waste which normally was dumped in landfills and caused contamination of soil, water and air from toxic substances such as polychlorinated bi-phenyls (PCB's), asbestos, construction chemicals, heavy metals, but the scarcity of land-filling areas, industrial growth as well as strict environmental regulations in developed and developing economies has led to the global re-assessment of the methods employed to recycle and utilise construction and demolition (C&D) waste as recycled aggregate for civil engineering projects i.e. construction and infrastructure development. Depending on their quality, recycled aggregate produced from C&D waste can be employed in various civil engineering works, which can help in a long way the economic and environmental sustainability of respective countries. With further research and development into overcoming technical as well as market barriers, considerable increase in recovery rates can be achieved with the existing technologies in developed economies. The main aim of this study is to review the literature on the production and utilisation of recycled aggregate in concrete, concrete pavements, roadway construction, and other civil engineering works and some discussion on the savings on CO_2 emissions have been included. The globally published data on recycled aggregate standards (normative documents) of various countries have been systematically analysed and evaluated, and some barriers mentioned. This review may help to alleviate the concerns of consumers and encourage and further promote the use of recycled aggregate on a larger scale in civil engineering projects.

1. Introduction

Population growth, continuous industrial development, construction of infrastructure and house building activities create huge amounts of the C&D waste and hence, dire need for waste recycling. Construction industry is a major consumer of natural resources and the global aggregate production almost doubled from 21 billion tons in 2007 to 40 billion tons in 2014. Countries such as China, India, Indonesia, Malaysia, Thailand, Gulf States, Turkey, Russia, Brazil and Mexico have recorded some of the strongest increases in the demand for waste recycling. Hence, progressive depletion of natural resources and growing awareness of sustainable waste management by the developed and emerging economies, have given ever-increasing relevance to recycle and re-use C&D waste in civil engineering projects.

Although much higher portion of construction material could be replaced by recycled and re-processed C&D waste, these options are not yet considered and applied in most of the developing

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https://doi.org/10.1016/j.conbuildmat.2018.03.240
0950-0618/

economies, due to insufficient regulatory frameworks and lack of knowledge. Meanwhile, in developed countries, the process of stimulus on the utilisation of C&D waste varies in scale from country to country, it is hoped and expected that the utilisation of recycled aggregate coming from C&D waste will increase and become substantial part of the market in the near future.

The global aggregate production of 40 billion tons (Fig. 1) is an indication of the vast development projects which are materializing around the world [1]. As the land for landfill becomes scarce and the world demand of aggregate reaches to an enormous 40 billion tons annually, ways to use C&D waste is gaining importance due to legislation, it is cheaper and available. However, research & development is highly needed to sustainably utilise alternative materials in the production of concrete containing recycled aggregate. The current tendency in several developed economies is to view waste as resource or by product that can be used for a variety of useful purposes.

In the developed economies, the first initiatives for minimizing and recycling C&D waste began in the 1980s, In Germany, the Federal Quality Association for Recycled Building Materials was established in 1984 and had its headquarters in Berlin. The main function of the association was to unite the major recycling companies in Germany and in 2006 it also became the headquarters of the European Quality Association for Recycling, which is the umbrella organization of quality associations of the European Union.

Since 1980's, there has been considerable progress in C&D waste management systems in the developed economies, particularly in Australia, Western Europe and North America.

In the present decade, Asia/Pacific, Russia and South American regions have demonstrated as one of the largest producers of aggregate as well as its sales, because of its rapidly rising construction activity, particularly in China, India, Indonesia, Malaysia, Thailand, Gulf States, Turkey, Russia, Brazil and Mexico. China alone accounts for half of all the new aggregate demand worldwide during the 2010–2015 periods [2]. The global recycled aggregate consumption estimates (by regions) are shown in Fig. 2 [3].

The tendency of environmentally conscience communities and enterprises is not only to recycle a large percentage of C&D waste, but to aim for zero waste, which means ensuring that all products are made to be reused, repaired or recycled back into the marketplace or nature and eliminating all discharges to land, water and air. While this concept first emerged in California, USA, in 1975, zero waste plans have been adopted around the world, especially by local governments in Australia and New Zealand.

As the plentitude of research work shows, there has been notable increase not only in the methods of recovery from C&D waste into recycled aggregate but on the ways and techniques of its utilisation in construction industry [4].

Regulations and legislation by the governments in various countries around the world have structured and constituted a market for building material and products derived from the C&D waste streams. According to [5] the C&D waste generation occurs during all the main phases of the building life cycle: construction, renovation and demolition. The demolition phase therefore seems to be the specific key to be considered for the adoption of more sustainable practices, to contribute higher percentages of the C&D waste generated.

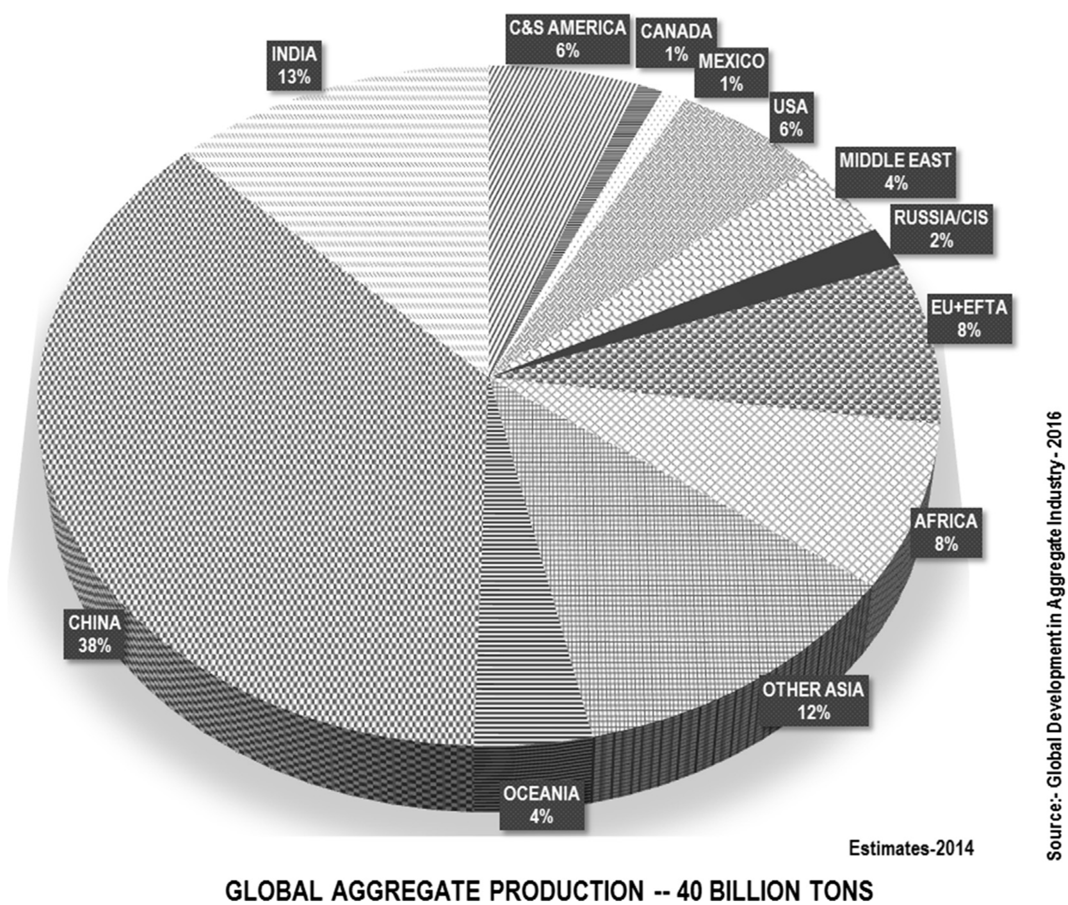

Fig. 1. Global aggregate production [1].

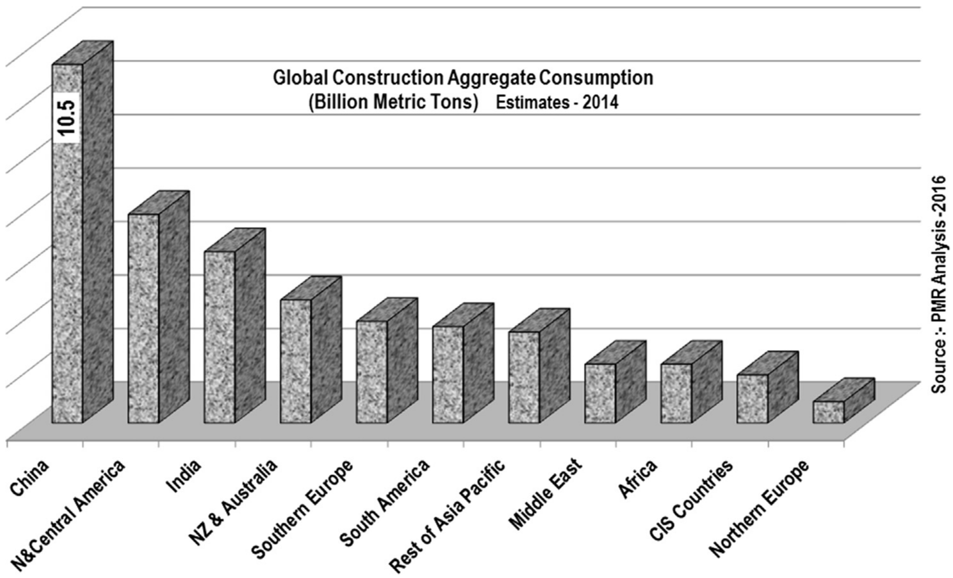

Fig. 2. Worldwide consumption of recycled aggregate (by regions) [3].

In European Union, the revised Waste Framework (Directive 2008/98/EC) [6] stated that the member states set an ambitious goal of achieving a 70% level of recovery for the recycling and reuse of non-hazardous C&D waste generated at buildings and public works construction sites by the year 2020. But, the 2011 statistics for the countries in European Union showed that the level of recycling and recovery of material from C&D waste fluctuated considerably i.e. between <10% and over 40% across the European Union [7]. In Denmark, the main focus has been put in obtaining a better quality of recycling C&D waste together with maintaining a high recycling rate but on the contrary, in France C&D waste management is an emerging issue and lacks political will and customer interest [7].

The "Union Européenne des Producteurs de Granulats" UEPG, (European Aggregates Association) was formed in 1987 to work for the promotion of interests of the European Aggregate Industry and continues to aim for sustainable supply of aggregates and towards its competitiveness and its growth. In 2014, production from recycled and re-used aggregate increased to 228 million tons representing 8.6% of the total output of 2.65 bil lion tons [8].

In Australia, the management of C&D waste is not legislated by the Central Government but the environmental issues, including all waste streams, is primarily the responsibility of Australian state and territory governments. In 2006–2007, in Australia 43.78 mil lion tons of waste was generated, 38 percent of which was from the C&D stream [9].

Yang et al. [10] reported that with China's rapid urbanization, an increasing amount of C&D waste is being generated, especially in the major cities. In total, China produces around 30% of the world's municipal solid waste and of this about 40% is C&D waste, the construction of new buildings generate around 100 million to ns annually while demolition of old properties generate 200 mil lion tons of waste annually. There are regulatory policies in China for handling waste, but there is lack of explicit national legislation governing C&D waste management.

In Hong Kong, according to the Waste Statistics 2015 [11] the overall construction waste was about 1.533 million tons, which was 28% of the total disposal and include waste arising from construction activities e.g. site clearance, renovation, demolition, refurbishment, road works etc. It also includes waste concrete generated from concrete batching plants and cement mortar/plaster plants. The overall construction waste is sorted into inert materials (rubble, debris, concrete and earth) which are reused in construction sites (public fill) and non-inert C&D waste which are disposed of at landfills [11]. However, the materials delivered to the public fills are not being recycled in Hong Kong, but are shipped to Mainland China for dumping as reclamation fills. The actual recycling rate of C&D waste is very low in Hong Kong.

The review [11–14] indicated that tax is just one of the major factors among many influencing recycled aggregate applications, including policies and national conditions; however, the motive for taxing aggregate is the desire to encourage the use of alternative and recycled material. Regulations on C&D waste disposal and especially fees on the landfill tipping are considered to be significantly important factors which contribute to the suitable management and recycling of C&D waste for the adequate management of C&D waste.

Söderholm [16] reported that in three European countries (Sweden, Denmark and the United Kingdom) there is minor variation in aggregate taxes. In Denmark and United Kingdom, the taxes cover a broader range of aggregate (e.g., sand, gravel, stone, etc.) while in Sweden only natural gravel is taxed. The analysis by Söderholm [16] indicated that the aggregate taxes have had significant effects on the use of aggregate and material substitution behavior. Countries with relatively high tax rates (e.g., the United Kingdom) have higher recycling rates.

Many countries have recycling schemes to recover recycled aggregate from C&D waste which can be reused as recycled aggregate, while in many other countries concrete recycling is a well-established industry and most of the C&D waste is being crushed and reused as aggregate. Recovery rates of recycled aggregate vary from almost 100 percent in some parts of the world to nearly zero in countries where most construction waste ends up in the landfill. For example, Japan is a leading country in recycling concrete waste and has been implementing 98% recycling and using it for structural concrete applications [17].

C&D waste could be demolished concrete structures, broken waste concrete, rejected concrete products on production line, broken pavements and bricks from buildings. Thus, recycled aggregate could come from demolition of concrete structures, airport runways, bridge supports, concrete roadbed or rejected concrete products on the production line, etc. Concrete made using such aggregate is referred to as recycled aggregate concrete (RAC).

Existing technology for producing recycled aggregate from C&D waste by means of mechanical crushing is relatively inexpensive and readily available; therefore, the process of converting C&D waste to recycled aggregate can be done both in the developed and developing countries [18]. There are two categories of plants available for processing C&D waste: stationary and mobile [19]. The same processes take place in both the plants to separate the contaminants from bulk material and to obtain a useful grading [20]:

- Separation;
- Crushing;
- Separation of ferrous elements;
- Screening; and
- Decontamination and removal of impurities (i.e. wood, paper, plastics).

Hansen cited in De Brito [21] reported that recycled aggregate is generally used as bulk backfill, in sub-base, base or surface material in road construction, lean concrete bases, hydraulically bound materials and in the manufacture of new concrete. Depending on its quality, recycled aggregate can be used in hydraulically bound material or in the production of new concrete, only if, the recycled aggregate coming from waste materials do not have hazardous contaminants. The contaminants in most cases may be found only on the surface layers of old concrete, so that no more than traces of potentially harmful contaminants will be found in the bulk of recycled aggregate. Under other circumstances potentially harmful contaminants may not be water-soluble, which in reality makes them harmless in recycled aggregate concrete.

In Australia, recycled aggregate (both as coarse and as fine aggregate) has been the most common C&D waste used in concrete production. About 5.0 million tons of recycled concrete and masonry are available mainly in Sydney and Melbourne, out of which 0.5 million tons is recycled aggregate [22]. In Europe, recycled aggregate from C&D waste accounts for 6–8 percent of aggregate in Europe, with significant difference in countries [23]. The big users are the United Kingdom, the Netherlands, Belgium, Switzerland and Germany [24].

In the United Kingdom, the quantities of recycled aggregate produced have increased gradually over the last 30 years and are being used in a wide range of construction applications. In 1980, the estimated use of recycled aggregate was 20 million to ns annually, in 2007 the usage increased to 71 million tons annually but decreased to 50 million tons annually in 2009, which accounts to 26% of the total aggregate used in the United Kingdom [25].

A study by the National Ready-mix Concrete Association (NRMCA) in the United States, concluded that up to 10 percent of recycled aggregate is suitable as substitute for virgin aggregate for most concrete applications including structural concrete [26]. United Kingdom research indicated that up to 20 percent of recycled aggregate can be used for most applications including structural [27]. Australian guidelines state that up to 30 percent recycled aggregate including structural concrete can be used [24]. German guidelines stated that under certain circumstances, recycled aggregate can be used for up to 45 percent of the total aggregate, depending on the exposure class of the concrete [28].

Significant potential remains for increasing the use of coarse recycled aggregate in concrete. In some countries, notably Germany, Switzerland and Australia, pre-mix concrete containing recycled aggregate is now being marketed. Boral's "Green" concrete is pre-mixed concrete using recycled aggregate that has been used in a number of building projects in Australia [24].

2. Research significance

One of the earliest uses of recycled aggregate concrete was in Europe after World War II, however, in the last few years, it has appeared that the perception and tendency to use recycled aggregate in concrete is increasing worldwide, thereby reducing the environmental impact due to landfills and quarrying of virgin aggregate and also making the construction projects economical and environmentally sustainable.

Although much higher portion of construction material could be replaced by recycled and re-processed C&D waste, these options are not yet considered and applied in most of the developing economies, due to insufficient regulatory frameworks and lack of knowledge.

Depending on their quality, the recycled aggregate produced from C&D waste can be employed in various civil engineering works. The significance and aim of this research study is to review the literature on the production and utilisation of recycled aggregate in roadway construction, concrete pavements, load bearing concrete structures and other civil engineering works and some discussion on the savings on CO_2 emissions have been included.

The Standard Specifications (normative documents) regulate and maintain the quality and provide producers as well as consumers, an assurance of uniformity and consistency in quality of the recycled aggregate. Conforming to the standard specification criteria, the recycled aggregate produced is a technically viable alternative which can be utilised in non-structural and structural concrete elements.

The globally published data on recycled aggregate standards (normative documents) of various countries have been systematically analysed and compared in tabulation form to provide producers, consumers as well as researchers a wider outlook on the properties of recycled aggregate which are desired and specified in legislation of various countries.

This review may help to alleviate the concerns of consumers and encourage and further promote the use of recycled aggregate on a larger scale in civil engineering projects.

3. Research methodologies

This section represents methodologies based on the;

- The review of the literature as well as data collection related to generation, recovery, processing (Sections 4 and 5) in twenty-four developed economies, spread around five continents (Oceania, Asia, Europe, Africa and America) which are taken as a role model as well as utilisation of recycled aggregate (Sections 6 and 7), additionally, some data on the CO_2 emissions have been included (Section 8).
- From the availability of data, these countries seem to be committed and active in promoting the usage of recycled aggregate through legislation (standards and normative documents) and media (reports, brochures, newspapers, television and radio) to reduce landfills (source of contamination of soil and water), reduce the exploitation and consumption of natural resources which are getting scarce by the passing day and by utlising the recycled material in concrete, concrete pavements, roadway construction, and other civil engineering projects.
- Analysis and comparison in tabulation form of the legislation through normative documents (Standard Specifications) to effectively control their quality parameters have been made (Section 9). These parameters which can substantially affect the recycled aggregate concrete properties and performance are; composition, dry density, water absorption, limitations on the chloride and sulfate content, limitations on the percentage

of recycled aggregate to be used and its maximum strength class which can be attained as well as environmental conditions in which recycled aggregate can be used.

4. Generation and recovery of construction and demolition waste

C&D waste constitutes a major portion of total solid waste production in the world, some studies have estimated that up to 90% of demolition waste going to the landfills can be recycled and reused. However, such studies need to be tested in a more comprehensive manner with indicative analysis of the actual practice. During the last 20 years the recycling of C&D waste has emerged as socio-economic priority mainly in the developed countries and in the present decade, developing countries are also gradually joining in.

Construction Waste occurs on account of building constructions and building renovations and results from surplus material (excess supplies), damaged or broken material (thus unusable), cut-off pieces, processing waste (saw dust, metal spoils) dismantled shuttering, used-up tools and accessories, packaging and garbage generated by the people on construction sites.

Demolition waste results from demolition of built structures, bridges, roads etc. their complete removal or renovation. It also includes demolition debris caused due to natural disasters (earthquakes, hurricanes and tsunamis), civil conflicts, vandalism, explosions, fires, collapse of weak structures etc.

C&D waste is divided into five main fractions i.e. metal, concrete and mineral, wood, miscellaneous and unsorted mixed fractions. More precisely, it may contain:

- Concrete
- Bricks, tiles and ceramics
- Wood
- Glass
- Plastic
- Bituminous mixtures and tars
- Metals (ferrous & non-ferrous)
- Soils (contaminated) and stones
- Insulation materials (including asbestos)
- Gypsum based materials (including plasterboard)
- Waste electronic and electrical equipment
- Chemicals (including solvents)
- Packaging materials
- hazardous substances

Some material in the list, if not managed responsibly can pollute the environment, pose a public health risk and pose amenity issues. Hazardous substances are generally present in building material because they are used, together with concrete, for completing the structure and for realizing the finishes. These substances are asbestos (found in insulation, roofs and tiles and fire-resistant sealing), lead based paints (found on roofs, tiles and electrical cables), phenols (in resin-based coatings, adhesives and other materials), polychlorinated biphenyls (PCBs) (which can be found in joint sealing and flame-retardant paints/coats, as well as electrical items) and polycyclic aromatic hydrocarbons (PAHs) (frequently present in roofing felt and floorings). Hazardous waste has to be separated at source, since even small amounts if contained in C&D waste can pose particular risks to the workers and the environment and also can hamper recycling.

There is a high potential for recycling and re-use of C&D waste, since some of its components have a high resource value. In particular, there is a re-use market for aggregates derived from C&D waste in roads, drainage and other construction projects. Technologies for the separation and recovery of C&D waste are well established, readily accessible and in general inexpensive. Despite its potential, the level of recycling and material recovery varies greatly (between <10% and over 90%) in countries across the globe.

In European Union, about 850 million tons per year of C&D waste are generated across Europe [29,30], among European Union countries, France has an average of 349 million tons per year in 2014 [31] and the United Kingdom has an average of 90 million t ons per year [32]. The United States produces about 534 million t ons per annum [33], Japan produces 77 million tons per year of C&D waste [34], in Australia, approximately 20 million tons per year of building and demolition waste are generated [35] while, 15.4 million tons per year are produced in Hong Kong [36], 200 mil lion tons of C&D waste generated in China, 17 million tons in India and approximately 7.0 million tons in each Dubai and Abu Dhabi [34].

For most parts, C&D waste is recoverable and is recycled and reused for both economic gain and environmental benefit, hence, in Germany the resource recovery rate was 91%, in 2011, in France the recycled rate was 50% of the total generated amount of the C&D waste in 2014. In the United Kingdom approximately 62% of C&D waste was recycled per year in 2011, while in the United States the resource recovery rate was 48% in 2011 [37]. In Australia, approximately 64% of C&D waste was recycled in 2014 [35] and in Hong Kong about 38% of solid waste is contributed from construction industry [38].

However this percentage of concrete recovery varies from one region of the world to the other due to vast differences in construction traditions, the legislation on landfills, and due to the perception and acceptance level of the constructors/contractors and builders.

Concerning waste management operations practiced in Australia, European Union (EU-27 member countries Belgium, France, Germany, Italy, Luxembourg, Netherlands, Denmark, Great Britain, Ireland, Portugal, Spain, Greece, Austria, Finland, Sweden, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Malta, Cyprus, Bulgaria, and Romania), Hong Kong and the United Kingdom.

Tam and Lu [39] showed that there has been a clear decrease in the amount of generated waste as a result of increasing efforts by the Governments and Councils through their legislations and by giving positive perception to the constructors and builders to move towards a "greener" construction industry.

Initially, recycling of demolition waste was first carried out after the Second World War in Germany [40], since then, research work carried out in several countries has demonstrated sufficient promise for developing and using the construction waste as a constituent in new concrete.

Article 11.2(b) of Waste Framework Directive (2008/98/EC) of European Union and EU Parliament [41] stated that "*Member states shall take the necessary measures designed to achieve by 2020 a minimum of 70% (by weight) of non-hazardous C&D waste, excluding naturally occurring material defined in category 17 05 04 (Soils and stones, other than those mentioned in 17 05 03) in the list of wastes shall be prepared for reuse, recycled or undergo other material recovery*". *This also includes backfilling operations using waste to substitute other materials*".

RILEM in the late 70's, and later many Universities and Research Centers in Europe and in many other parts of the world, for example Portugal and Brazil, started several research projects on recycling technology concerning material coming from building demolition. In 1981 the RILEM designated a Technical Committee 37-DRC (Demolition and Reuse of Concrete) which was replaced by new Technical Committee 121-DRG (Demolition and Reuse

Table 1
Recovery of construction & demolition waste [24].

Countries	Total construction and demolition waste (million tons)	Total construction and demolition waste recovery (million tons)	Construction and demolition waste recovery (%)	References
OCEONIA				
Australia	19.30	12.00	62.20	[43]
ASIA				
China	300.00	120.00	40.00	[10]
Hong Kong	24.30	6.80	28.00	[11]
Japan	77.00	62.00	80.50	[34,43]
Taiwan	63.00	58.00	91.00	[44,45]
Thailand	10.00	3.20	32.00	[46]
EUROPE				
Belgium	40.20	34.57	86.00	[47]
Denmark	21.70	20.40	94.00	[48]
Finland	20.80	5.40	26.00	[48]
France	342.60	212.40	62.00	[48,49]
Germany	192.30	165.40	86.00	[48]
Ireland	16.600	13.30	80.00	[48]
Italy	46.30	n.a	n.a	[48]
Netherlands	25.80	25.28	98.00	[48]
Norway	1.30	0.87	67.30	[48]
Portugal	11.4	5.52	48.40	
Spain	38.50	5.39	14.00	[48,50]
Sweden	10.20	n.a	n.a	[48]
Switzerland	7.00	2.00	28.00	[48]
United Kingdom	114.20	74.23	65.00	[48]
AMERICAS				
Brazil	101.00	6.20	6.14	[51]
Canada	0.66	0.20	30.00	[52]
USA	534.00	256.30	48.00	[33]
AFRICA				
South Africa	4.70	0.76	16.00	[9]

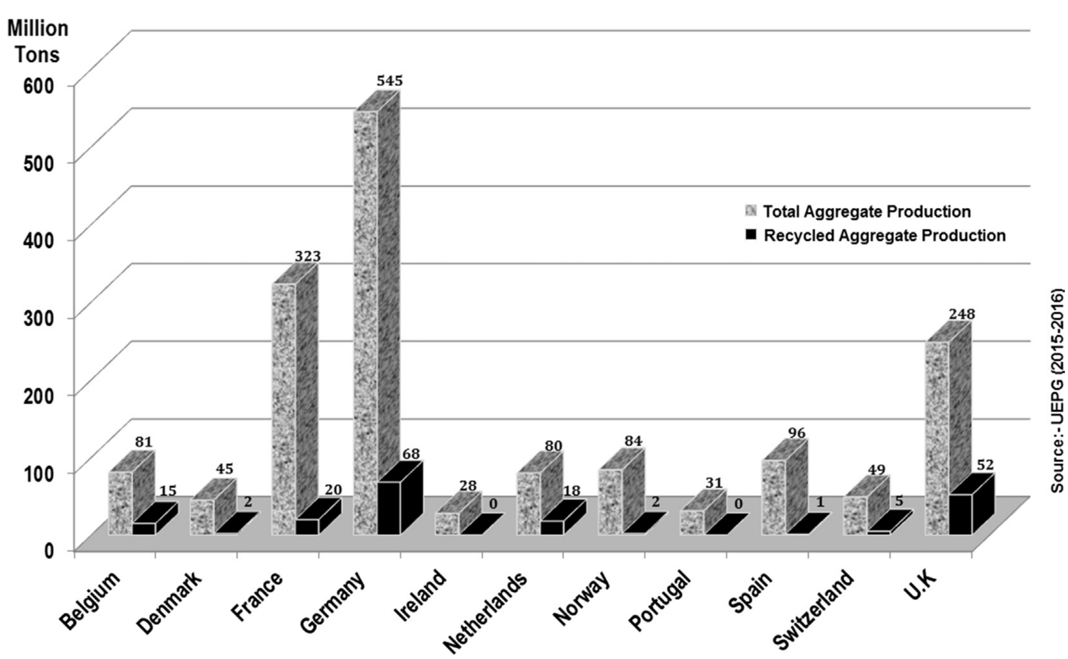

Fig. 3. Comparison of total aggregate vs recycled aggregate production of some European countries in 2015 [8].

Guidelines) which drafted guidelines published in 1993. Since 2001, a RILEM Technical Committee is operating about the "Use of Recycled Materials in Construction" [42].

C&D wastes are characterized by high potential for recycling and reuse because some of their components have high resource value, particularly the reuse market for recycled aggregate. Depending on their qualities, the recycled aggregate produced from C&D wastes can be employed in roads, drainage, construction projects, structural concrete and in the production of concrete products.

An overview and summary of the current concrete recycling recovery data around the world is shown in Table 1. Many developing countries as well as emerging economies have yet to collect the recovery data of their countries, the less populated countries and the large countries are expected to have lower achievable recovery rates.

With existing technologies, considerable increase in recovery rates can be achieved in some countries with further research and development, improvement in legislation, by increasing the public awareness and acceptance as well as by reducing the misconceptions and ignorance about the possibilities of its use.

In Europe in 1995 a working group "Construction and Demolition Waste Project Group" drafted a document, "Recommendations", which suggested a series of measures and actions that if undertaken by various member states, could widely develop the recycling of C&D waste. It was proposed the following;

- Prevention: informed about new ways to design materials by keeping into account their disposal and recycling and their environmental impact.
- Separation: encouraged recycling and deterring disposal in landfill
- Treatment: it proposed the introduction of a system based on permissions and licenses issued to those businesses involved in the production of C&D waste. The qualified contractor must indicate the produced waste amount, the adopted measure for treating it and its final destination.
- Market: the market for C&D waste could develop, if the suburban public administrations exercise a model role as a purchaser.

Concrete recycling from C&D waste in many developing countries has not been a high priority, mostly because of abundant supplies of natural aggregates and relatively more limited environmental benefits, therefore in the legislation the energy advantages in the use of recycled aggregate and the long life of concrete should be emphasized and recognised since recycling is one of the important component of sustainable development [42].

5. Processing of construction and demolition waste

Significant potential remains for increasing the use of recycled aggregate in concrete. In some countries, notably Germany, Switzerland and Australia, concrete containing recycled aggregate is now being marketed. The most common method for recycling dry and hardened concrete involves crushing. Mobile sorters and crushers are often installed on construction sites to allow on-site processing. In other situations, specific processing sites are established, which are usually able to produce higher quality aggregate [24].

The best estimates for 2015, of total aggregate production and recycled aggregate production of European Union countries including Ireland and the United Kingdom are depicted in Fig. 3 while Table 2 shows values for 6 years from 2010 to 2015.

In European Union, the processing of construction waste (concrete, brick, asphalt and stone) into aggregate to comply with European Standards for aggregate as well as the development of material specifications enabling this aggregate to be used in construction applications is essential for meeting the Waste Framework Directive of European Union of 70% recycle and recovery target for 2020 [45].

The Environment Agency, the Northern Ireland Environment Agency (NIEA) and Waste & Resources Action Programme (WRAP) in consultation with industry and other regulatory stakeholders developed a Quality Protocol applicable in England, Wales and Northern Ireland. The process of converting inert waste material into a product is classified as a waste recovery operation and is subject to the waste management controls set out in the Waste

Table 2
The best estimates of recycled aggregate production data of European Union [53–56,8].

Countries	Total aggregate produced in 2010 (million tons)	Production of recycled aggregate in 2010 (million tons)	Total aggregate produced in 2011 (million tons)	Production of recycled aggregate in 2011 (million tons)	Total aggregate produced in 2012 (million tons)	Production of recycled aggregate in 2012 (million tons)	Total aggregate produced in 2013 (million tons)	Production of recycled aggregate in 2013 (million tons)	Total aggregate produced in 2014 (million tons)	Production of recycled aggregate in 2014 (million tons)	Total aggregate produced in 2015 (million tons)	Production of recycled aggregate in 2015 (million tons)
Belgium	82	15	88	15	82	15	82	15	81	15	81	15
Denmark	49	1	51	6	45	2	39	2	41	2	45	2
Finland	85	1	89	0	90	1	85	1	81	1	78	2
France	365	17	379	19	360	20	376	25	354	20	323	20
Germany	535	60	598	65	564	68	546	66	564	68	545	68
Ireland	50	0	32	0	29	0	25	0	26	0	28	0
Italy	300	0	240	0	195	0	155	5	152	5	155	4
Netherlands	76	20	73	18	83	17	64	16	73	25	80	18
Norway	67	0	77	0	79	0	82	2	82	2	84	2
Portugal	67	0	56	0	43	0	29	0	29	0	31	0
Spain	208	0	173	0	113	0	93	1	92	1	96	1
Sweden	81	1	81	1	79	0	76	0	79	0	88	0
Switzerland	51	5	51	5	50	5	56	5	52	5	49	5
United Kingdom	226	49	225	50	202	44	216	46	237	51	248	52
Total	2242	169	2213	179	2014	172	1924	184	1943	195	1931	189

Framework Directive and domestic legislation whereas the aggregate must be produced in compliance with the criteria outlined in Sections 2.3–2.5 considering: acceptable input materials, BS EN aggregate standard and the aggregate must require no further processing [27].

6. Pavements, footpaths and other civil engineering applications of recycled aggregate

6.1. Roadway infrastructure

A pavement is a multi-layer system which directly supports traffic and transmits the vehicular load to the road base. It consists of a concrete slab or asphalt slab resting on the foundation system formed by several overlapping layers of finite thickness i.e. concrete or asphalt surface (top), base (high quality compacted aggregate), sub-base (low quality compacted aggregate) and sub-grade (bottom). Conventionally crushed virgin aggregate were used in the road base and sub-base, but research carried out in recent decades made it possible to utilise recycled aggregate from C&D debris in the sub-base and sub-grade levels of the road way. In this role, the absolute strength needed to support the intensity of loading, is less important, but the consumption of the recycled concrete aggregate will be high due to the volume of material required in lower layers.

Worldwide numerous studies were conducted to evaluate the possibility of using recycled C&D waste, specifically recycled concrete aggregate (RCA) and recycled crushed bricks (RCB) in the construction of lower layers of roadways.

In Australia, it is common to mix recycled concrete aggregate with small amounts of crushed bricks and soil to obtain a suitable recycled product for use in pavements [57], in some European countries, the use of recycled concrete aggregate have been used since late 1970s and in the Netherlands, the use of recycled aggregate coming from concrete and bricks as a road base is a common practice [58].

In USA, the specifications for Texas, Minnesota and Michigan allow the use of recycled concrete aggregate in concrete pavements. The Texas Department of Transportation (Tx DOT) has found that the use of recycled concrete aggregate in concrete pavements gave a satisfactory performance. In their specifications, San Francisco allows the use of recycled concrete aggregate in all non-structural works, which include sidewalks, curbs and other features other than pavements (See Fig. 4).

Arisha and Gabr [59] evaluated the feasibility of using C&D waste materials, particularly blends of recycled concrete aggregate (RCA) with recycled crushed bricks (RCB) as unbound granular material for road construction in Egypt. They evaluated 8 blends of recycled concrete aggregate with crushed recycled bricks in terms of simple and advanced engineering properties. They found that the recycled unbound granular material showed better pavement performance in terms of rutting and fatigue cracking as compared to virgin aggregate (See Fig. 5).

Haider et al. [60] and Kolay and Akentuna [61] studied the feasibility of using RCA as replacement material for virgin aggregate in the construction of base layers. They concluded that RCA materials showed similar geo-mechanical and physical performance to conventional graded base material. These studies concluded that, the RCA materials performed similar to, if not better than the typical virgin aggregate and therefore the authors recommended RCA for use as base material. The authors also mention that use of RCA materials in highway construction is more economically profitable as compared to conventional aggregate and helps in reducing the demand for virgin aggregate thereby helping the environment.

Diagne et al. [62] investigated the use of blends of recycled concrete aggregate (RCA) with recycled crushed bricks (RCB) as unbound base course in pavement construction. The authors used various proportions of RCA and RCB in their experiments; they found that the Los Angeles Abrasion results of 100% RCA and 100% RCB were 29.9% and 36.8% respectively.

Jia et al. [63] evaluated the engineering properties of concrete waste and recycled crushed bricks stabilised with cement. The Benkelman beam deflection test results showed that waste materials stabilised with cement can be successfully used as base layer in low volume roads.

Neves et al. [64] evaluated the use of C&D materials as recycled aggregate in sub-base and base layers of roadway. He used recycled concrete aggregate mixed with ceramics and reclaimed

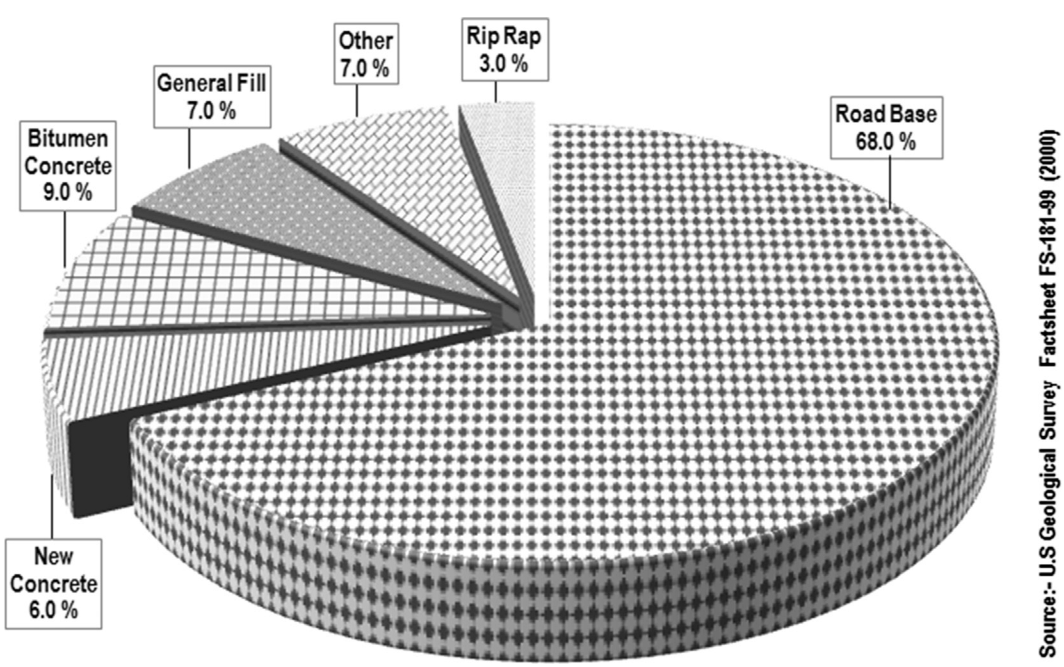

Fig. 4. End uses of recycled aggregate in U.S.A.

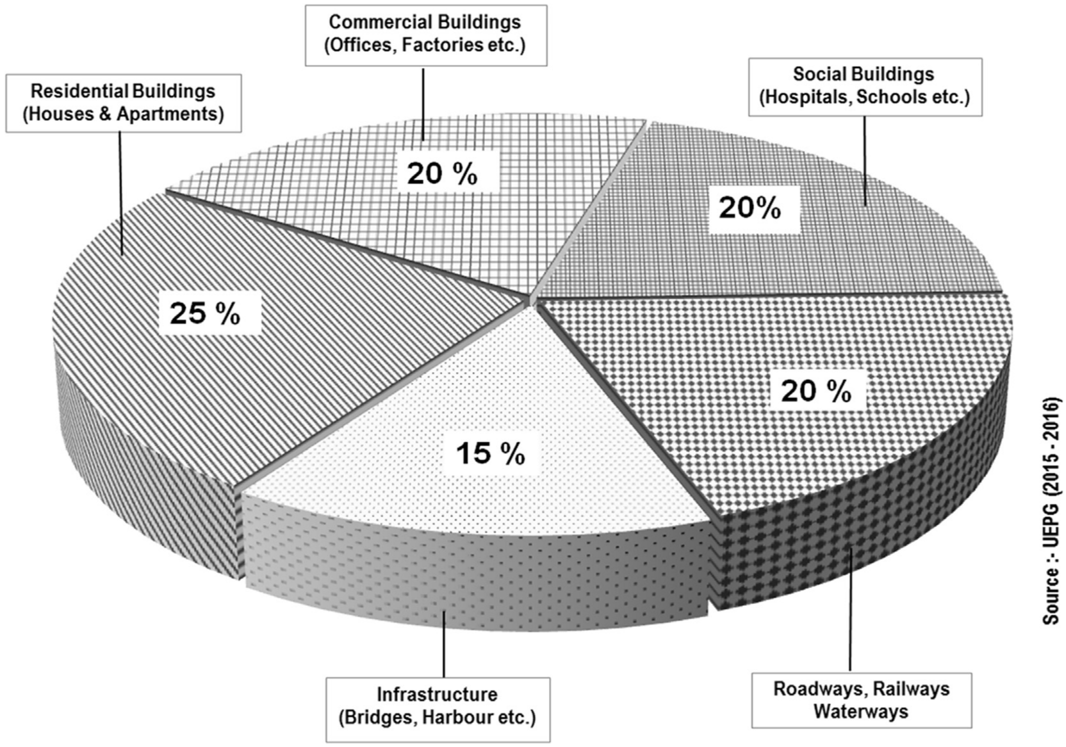

Fig. 5. End uses of recycled aggregate in European Countries.

asphalt material in his experiments, crushed limestone was used as a reference material. The authors found that recycled materials have a different behavior compared to natural materials, but in general, all the recycled materials tested showed an acceptable performance.

Azam and Cameron [65] determined the engineering characteristics of blends of recycled aggregate concrete (RAC) and recycled crushed bricks (RCB) acquired from producers in South Australia. Based on the laboratory testing program, the blends of RCA with RCB appeared to be suitable for application as sub-base in unbound pavement construction.

Arulrajah and Piratheepan [66] evaluated the geotechnical properties of five types of C&D waste materials (i) recycled concrete aggregate (ii) crushed recycled bricks (iii) waste rock (iv) reclaimed asphalt pavement and (v) fine recycled glass. The authors concluded that the geotechnical properties of recycled concrete aggregate and waste rock were equal or superior to quarried conventional aggregate used in the sub-base.

Barbudo et al. [67] studied the possible relation of mixed recycled aggregate (MRA) containing crushed concrete and crushed bricks and their mechanical behavior for possible application in the roadways in the Mediterranean area. The authors found that the recycled aggregate containing <25% of crushed bricks can be used in roadway sub-bases. Also recycled aggregate mixed with ceramic showed good mechanical performance due to their high bearing capacity (measured by CBR Index) for use in sub-bases in low traffic roads.

6.2. Capping layer

On weak sub-grades, it is common practice to use a capping layer between sub-grade and sub-base layers. This reduces the thickness of sub-base and provides a suitably firm surface for the placement and compaction of the sub-base. The capping layer can be constructed from low-cost granular material to a lower specification than the sub-base [68].

6.3. Selective fill

Selective fills have to meet stringent requirements as compared to bulk fills, since they are used in situations such as bedding material for drains and as the full placed in the immediate vicinity of bridges and structures. Crushed concrete can be used for most applications. Limits for use which are not stringent, are specified in terms of grading, plasticity, particle strength and chemical properties [68].

6.4. Bulk fill

If the required level of new road is not the same as that of the ground over which it has to be built, and has to be lowered or raised, the processes required are known as “cut” or “fill”. The fill required may be in large quantities and easy to place and compact. After compaction, it shall provide a stable bed, strong enough to receive the layer above it, which may be the capping layer or the sub-base depending on the circumstance. Although, crushed concrete and crushed brick can be used as bulk fill, it is thought such use is wasteful because the material is suitable for use in more demanding situations [68].

7. Other civil engineering applications

7.1. Concrete pavement

Nassar and Soroushian [69] investigated the field performance of recycled aggregate concrete (RAC) in pavement construction subjected to heavy traffic loads under aggressive weather conditions. Test results of cores drilled from pavement sections after 270 days of concrete age showed that RAC show performance at par or even better than that of corresponding control concrete. Later age enhanced strength and durability attributes of RAC concrete suggest its suitability for use in concrete based infrastructure such as pavement construction.

7.2. Hardcore filling

Recycled concrete aggregate is also utilised as hardcore filling in building construction provided that, the grading of the recycled aggregate is checked to suit the condition of the soil.

7.3. Molded concrete bricks and blocks

A study carried out by [70] concluded that the replacement of coarse and fine natural aggregate with recycled aggregate at levels of 25% and 50% had little effect on the compressive strength of the block and brick specimen, but higher levels of replacement reduced the compressive strength. Using recycled aggregate at the replacement levels of up to 100%, concrete paving blocks with 28 day compressive strength of not <49 MPa can be produced. The performance of the blocks and bricks was also found satisfactory for shrinkage and skid resistance tests.

7.4. Oyster beds

In the USA, Virginia State has found a novel way for the utilisation of recycled aggregate. An artificial reef is created using recycled concrete aggregate, which is then covered with crushed oyster shells, creating an oyster bed. Since the recycled material is being placed in marine environment, concrete particularly with high chloride content is acceptable.

8. Carbon emissions & embodied energy of recycled aggregate

Studies have shown that re-processing of C&D waste to recycled aggregate brings considerable environmental benefits. These environmental gains are dependent on an efficient recycle aggregate collection and re-use supply chain. The re-use of recycled aggregate brings substantial gains in the following areas;

- Reduced Resource Consumption

Substitution of quarried virgin aggregate with recycled material means, conserving primary virgin aggregate for future generations.

- Reduced Quarrying

By reducing the quarry of natural aggregate the costs for amenity and bio-diversity will reduce.

- Reduced Greenhouse Gas (GhG) Emissions

Recycled aggregate can have lower embodied energy in addition to reduced transport emissions, especially where recycled materials are re-used in close proximity to the site of re-processing.

The energy consumption and the resulting GhG emissions from recycling of aggregate has been calculated to be around 4.0 kg CO_2 per ton, which represents between 22% and 46% fewer emissions than an equivalent conventional quarry product (based on Australian data) [71].

In another study for CO_2 emissions [72] evaluated that for the production of 1 ton natural aggregates 0.046 tons of CO_2 is emitted as compared to 0.0024 tons of CO_2 emitted in the production of 1 ton recycled aggregates. When compared to natural aggregates, recycled aggregates reduce carbon emission by 23–28%.

Similarly, US studies have found recycled aggregate to have around 30% less embodied carbon emissions than primary aggregates. However, it is important to register that in comparing greenhouse emission figures it presents differences depending on the methodologies used and local electricity generation factors between jurisdictions, both across Australia and worldwide. For example, in the UK [73] report a 2.42 kg CO_2 eqv./ton, considering the distance of source to recycling site was set at 10 km and it was assumed that the material was transported using 20 ton trucks consuming diesel at 0.4 L/ton/km [74].

Replacement of 50% of the quarried virgin aggregate with recycled aggregate in a road construction project could reduce the embodied energy and resulting GhG emissions of the material component of the road construction, by around 23.0% [74].

The embodied energy of recycled aggregate was evaluated to be approximately 30% less than quarried aggregate while CO_2 emissions of recycled aggregate were approximately 60% less than the quarried aggregate (based on the production of 150 tons per month) [75] (See Fig. 6).

In a case study a comparative evaluation was carried out by [75] for CO_2 emissions and the embodied energy of recycled aggregate vs. quarried virgin aggregate based on the construction of one kilometer of roadway, keeping all the other conditions constant. The following comparison makes it clear that recycled aggregate do have very positive incentives when utilised either in road way construction or in concrete production.

(i) Comparative CO_2 Emissions per kilometer in road base construction

- Recycled road base (100%) = 24.0 tons/kilometer (approximately)
- Quarried road base (100%) = 72.0 tons/kilometer (approximately)

(ii) Comparative Embodied Energy per kilometer in roadway construction

- Recycled road base (100%) = 165.0 GJ/kilometer (approx.) is embodied energy, while 186.0 GJ/kilometer is operational energy (total energy impact = 351.0 GJ/kilometer)
- Quarried road base (100%) = 762.0 GJ/kilometer (approx.) is embodied energy, while 191.0 GJ/kilometer is operational energy (total energy impact = 953.0 GJ/kilometer)

Hossain et al. [77] presented the LCA (Life Cycle Assessment) analyses of recycled aggregates production from C&D waste in Hong Kong and their results revealed that compared with natural coarse aggregates, recycled coarse aggregates leads to a reduction of up to 65% greenhouse gas (GhG) emissions with savings of up to 58% non-renewable energy consumption and the same was observed for producing recycled fine aggregates from C&D waste.

Serres et al. [78] reported the environmental impact contribution of recycled aggregate (20 mm) used for concrete production. The consumption of energy resources was $1.39 \cdot 10^3$ MJ for recycled concrete and $2.14 \cdot 10^3$ MJ for conventional concrete and the CO_2 emissions were 3.35 kg CO_2 eqv./ton and 4.44 kg CO_2 eqv./ton respectively. The authors concluded that the 20-mm recycled concrete sample (RAC) presented the best environmental behavior in comparison with the conventional 20-mm concrete sample.

Wijayasundara et al. [79] presented a study evaluating a "cradle-to-gate" embodied energy (EE) of recycled aggregate concrete (RAC) from construction site, in comparison to natural aggregate concrete (NAC) using the input-output-based hybrid approach in an Australian context, the authors reported that Embodied Energy of RAC was within 4766–5401 MJ/m3 for all concrete mixes and the variation was contained within +11.4% to −6.8%, compared to that of NAC. The authors concluded that, the EE of RAC is within a range of −6.8% to +11.4% of NAC, and it was highly dependent on

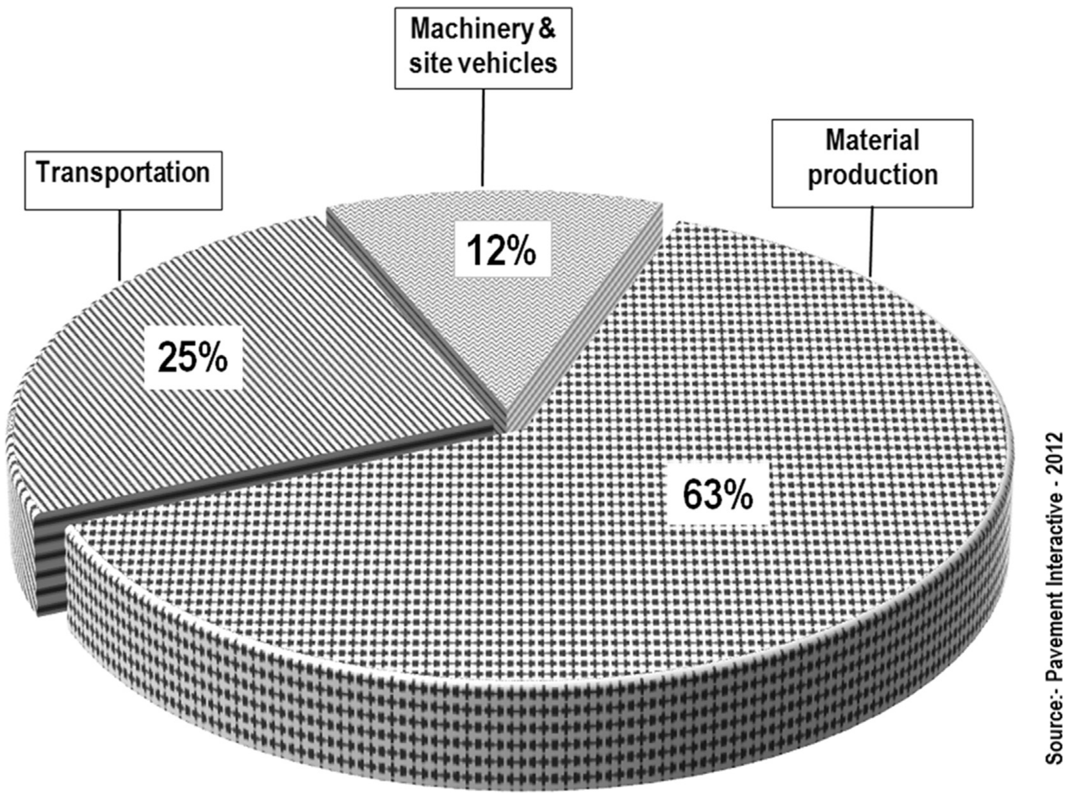

Fig. 6. Typical energy consumption breakdown for a roadway construction project [76].

the mix constituents investigated, mainly the cement content in the RAC mix (See Table 3).

9. Quality criteria for recycled aggregate in standards and guidelines

9.1. Comparison of specifications in international standards for recycled aggregate

The collected and compared legislation of various countries around the world on the utilisation of recycled aggregate in several of their construction engineering applications is shown in Table 4. This table gives an overall view of how different countries have introduced and instituted standards and specifications to regulate the use of recycled aggregate.

9.2. Additional information to the standards

Worldwide, several codes, regulations and guidelines dealing with the use of recycled aggregate in concrete applications around the world are available, out of which documents from the countries such as Japan, Hong Kong, Portugal, Brazil, European Union and recently Australia are most comprehensive. In these countries, disposal of C&D waste represents a crucial problem due to rapid urban expansion, industrialization, the scarcity of land filling areas and stringent environmental regulations. This section presents a general analysis of the norms of different countries around the world for regulation and utilisation of recycled aggregate produced under their domains.

9.2.1. OCEANIA

9.2.1.1. Australia. Commonwealth Scientific and Industrial Research Organisation (CSIRO) [81] in their report divided coarse aggregate in two classes (a) RCA-class 1A and (b) RCA-class 1B but the Cement, Concrete and Aggregate Australia (CC&AA) [124] classified recycled aggregate in five types i.e. recycled concrete aggregates (RCA), recycled concrete and masonry (RCM), reclaimed aggregate (RA) reclaimed asphalt pavement (RAP) and reclaimed asphalt aggregate (RAA). However, in Australia, RCA is the most common C&D waste used in concrete production.

9.2.2. ASIA

9.2.2.1. Hong Kong. The compressive strength of four concrete cubes cured for 7 and 28 days is a requisite, two cubes to be crushed at 7 days to show minimum compressive strength of 14 MPa while the other two crushed at 28 days, to show minimum compressive strength of 20 MPa. Regarding workability of fresh concrete, only pre-soaked recycled aggregate is allowed to be used, and it is recommended that the slump of recycled aggregate concrete must be greater or equal to 75 mm at the time of casting.

9.2.2.2. Japan. The Japanese standards restrict the use of recycled aggregate in concrete with design strength of over 18 MPa and have not placed any requirements on the source of recycled aggregate. It may contain a mixture of aggregates from demolished concrete and low density ceramics without any specified ratios.

9.2.3. EUROPE

9.2.3.1. Belgium. Belgium norms PTV-406 “Classification of Recycled Aggregate” [93] allows the use of leftovers of natural aggregate and aggregates derived from C&D waste.

9.2.3.2. Denmark. The Danish Standard (DS 2426 – EN 206-1) [98] recommend that; RCA (tested and un-tested) can be used for reinforced and non-reinforced concrete with compressive strengths up to 40 MPa in moderate and passive environmental conditions. RMA can be used for reinforced and non-reinforced concrete with compressive strengths up to 20 MPa in passive

Table 3
Comparision of international standards for recycled aggregate.

National standard	Recycled aggregate type	Dry density (kg/m3)	Water absorption (%)	Cl & SO4 content	Limitations	Percentage of recycled aggregate allowed	Conditions of application	Notes	References
OCEANIA									
Australia (HB 155:2002) (AS 1141.6.2)	RCA (Class 1A)	≥2100	≤6	Cl & SO4 (Equivalent specifications as for natural aggregates)	Coarse aggregate size (4–32 mm)	30%	40 MPa (28 days Comp. strength)	Well graded RCA with no >0.5% brick content Total contaminants* <1.0% (by wt.)	[80,22,81–84]
	RCA (Class 1B)	≥1800	≤8	Cl & SO4 (Equivalent specifications as for natural aggregates)		100%	25 MPa (28 days Comp. Strength)	RCA blended with no >30% crushed bricks Total contaminants* <2.0% (by wt) * (Brick, stony material, gypsum, wood, clay lumps, plate glass)	
ASIA									
China (DG/TJ 07/008) (GB/T 25,177 & 25176:2010)	RCA		<10	Cl^- (0.03 – 0.25%) (acid soluble) SO4 (0.8–1.0%) (acid soluble)		≥95% Plus <5.0% Masonry		Impurities Content <2% which include Organic matter <0.5% Contaminants <1.0%	[85,86]
	RMA					≤90% Plus >10.0% Masonry		n.a	
Hong Kong (CS-3:2013) (HKBD 2009) (WBTC-12: 2002)	RCA	≥2000	≤10	Cl (<0.05%) (acid soluble), SO4(<1.0%) (acid soluble),	Coarse aggregate for structural & non-structural use	20% For Structural concrete	25–35 MPa (28 days Comp. strength)	Contaminants (Wood or similar material) less dense than water <0.5%, Other contaminants* (metals, plastic, glass etc.) <1.0%, Sieve 63 µm passing ≤ 4%	[87,80,38,88,82,21,89]
						100% For non-structural concrete	20 MPa (28 days Comp. strength)		
Japan (JIS A 5021, JIS A 5022, JIS A 5023)	RCA-Coarse	≥2500	≤3	Cl (<0.04%)	Structural			No limitations on the type & segment for concrete & structures with a nominal strength of 45 MPa or less. Sieve 75 µm passing ≤4% (coarse) and ≤7% (fine)	[80,82,21,88,90,28]
	RCA-Fine (High Quality)	≥2500	≤3.5	Cl (<0.04%)					
	RCA-Coarse	≥2300	≤5	Not mentioned	Structural			Members not subjected to drying or freezing & thawing such as piles, underground beam & concrete filled steel tubes	
	RCA-Fine (Medium Quality)	≥2200	≤7	Not mentioned					
	RMA-Coarse	No Limit	≤7	Not mentioned	Non-Structural			Backfill concrete, blinding concrete & concrete filled in steel tubes	
	RMA-Fine (Low Quality)	No Limit	≤13	Not mentioned					
EUROPE									
Belgium PTV 406-2003 (NEN EN 12620: 2013) (NBN B 11-255)	RCA (Mainly concrete)	≥2100	≤9	Cl (<0.06%) (acid soluble) SO4 (<1.0%)	Fine aggregate Not allowed		Concrete strength class C 30/37, similar as RILEM Inside building, dry environment	Contaminants- non mineral* content <1.0%, organic materials <0.5%, Sieve 80 µm passing ≤3% *(metals, glass, bitumen, soft material)	[80,88,91–95]

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Table 3 (*continued*)

National standard	Recycled aggregate type	Dry density (kg/m3)	Water absorption (%)	Cl & SO4 content	Limitations	Percentage of recycled aggregate allowed	Conditions of application	Notes	References
	RMA (Mainly masonry)	≥1600	≤18	Cl (<0.06%) (acid soluble) SO4 (<1.0%)	Coarse aggregate allowed	Coarse <100%	Concrete strength class C16/20, similar as RILEM Inside building, dry environment	Contaminants- non mineral* content <1.0%, organic materials <0.5%, Sieve 80 µm passing ≤5% + (clay particles, refractory bricks or vegetable matter)	
Denmark (DS 2426 – EN 206-1) (DS EN 12620: 2013)	RCA (without testing)	≥2200	n.a		95% aggregates must come from clean concrete, masonry or roofing tiles	Coarse <100%		Without quality control, particle size 4–32 mm	[87,96,21,82,97,98]
	RCA (with testing)	≥2200	n.a					With quality control, particle size 0–32 mm	
	RMA (mix of concrete & masonry)	≥1800	n.a			Fine <20%			
Finland (By-43-2008) (SFS EN 12620)	RCA 1	–	≤10					Max. content of bricks = 0%, Max content of other materials* 0.5% wt	[96,82,21]
	RCA 2	–	≤12					Max. content of bricks <10% Max content of other materials* 1.0% wt	
	RMA	2550–2650	≤12					Max. content of bricks <10% Max content of other materials* 1.0% wt *(wood, plastic etc.)	
Germany (DIN 4226-100: 2002) (DIN 12620: 2015/prEN 12620:2015) (DafStb-2010)	RCA (Concrete waste)	≥2000	≤10	Acid soluble Cl (<0.04%), SO4(<0.8%)	Can be used in new Structural Concrete	Aggregate ≥90% Bricks + Sandstone ≤10		Concrete chipping plus crusher sand, Contaminant– Minerals + ≤2% non-minerals* ≤0.2%, Asphalt ≤1%	[80,82,21,88,90,28,99]
	RCA (Demolition waste)	≥2000	≤15	Acid soluble Cl (<0.04%),	Can be used in new Structural Concrete	Aggregate ≥70% Bricks + Sandstone ≤30%		Construction chipping plus crusher sand Contaminant– Minerals + ≤3% non-minerals* ≤0.5%, Asphalt ≤1%	
	RBA (Brick Rubble)	≥1800	≤20	Acid soluble Cl (<0.04%),		Aggregate ≤20 Bricks ≥80% Sandstone ≤5%		Masonry chipping plus crusher sand Contaminant–Minerals + ≤5% non-minerals* ≤0.5%, Asphalt ≤1%	
	RMA (Mixed material)	≥1500	Not specified	Acid soluble Cl (<0.15%)	Can only be used in non-structural elements	Aggregate + bricks + Sandstone ≥80%		Mixed chipping plus crusher sand Contaminant – minerals+ + asphalt ≤20 non-minerals* ≤1.0 + (porous bricks, lightweight concrete, aerated concrete, porous concrete, plaster mortar, porous slag, pumice) *(glass, ceramics, gypsum, rubber, plastics, wood, metals, paper, plant remains, non-ferrous slag etc.	

Table 3 (*continued*)

National standard	Recycled aggregate type	Dry density (kg/m3)	Water absorption (%)	Cl & SO4 content	Limitations	Percentage of recycled aggregate allowed	Conditions of application	Notes	References
Italy (NTC – 2008) (UNI EN 12620: 2013)	RCA Coarse	–	–	–	Structural	30%	30 MPa (28 days Comp. strength)	Source of material and particle size must be specified.	[82,85,100,21,101]
		–	–	–		60%	25 MPa (28 days Comp. strength)		
	RMA Coarse	–	–	–	Non-structural	100%	10 MPa (28 days Comp. strength)	–	
Netherlands (NEN 5942, 5921, 5930) (NEN EN 12620:2013)	RCA	≥2100	n.a	RCC = Cl (<0.1% for <4 mm),(<0.05% for >4 mm) SO4 (<1.0%) for ≤4 mm, for ≥4 mm no requirement of SO4	Structural	Coarse ≤20% By Volume	45 MPa (28 days Comp. Str.)	Non-mineral components* <0.5% for RCA ≤4.0 mm and <0.1% for RCA ≥4.0 mm CaCO3 content = 25% for <4 mm and 10% for >4 mm	[87,80,96,88,94,85,21,102]
	RMA	≥2000	n.a	PC = Cl (<1.0% for <4.0 mm, & >4.0 mm) RCC = Cl (0.1% for <4 mm & 0.05% for >4 mm) Pre-str. = Cl (<0.015% for <4.0 mm), & (0.007% for >4.0 mm) SO4 (<1.0%) for ≤4 mm				Non-mineral components* <1.0% for RCA <4.0 mm *(wood, paper, cloth, vegetable etc.)	
Norway (NS EN 12620:2008) RESIBA (2002)	RCA (Crushed concrete)	≥2000	≤10					Crushed concrete and/or Nat. aggregate >94% + Crushed bricks <5.0% Non-minerals* <1.0% Organic materials <0.1% (by vol.) Crushed asphalt <1.0%	[87,21,103–106]
	RMA (Mix Materials)	≥1500	≤20					Crushed concrete + Crushed bricks >90% Non-minerals* <2.5% Organic materials <0.5% (by vol.) Crushed asphalt <1.0% *(wood, paper, metal, plastics, glass, rubber and others)	
Portugal (LNEC- E471)	RCA 1	≥2200	≤7	SO4 (≤0.8%) (acid soluble)		25%	Class C 35/45 (28 days Comp. Str.)	Masonry ≤10%, Light weight + ≤1.0% Non-mineral components* <0.2%	[87,96,88,107,21]
	RCA 2	≥2200	≤7	SO4 (≤0.8%) (acid soluble)		20%	Class C 40/50 (28 days Comp. Str.) and also meet requirements of Environmental Classes	Masonry ≤30%, Light weight + ≤1.0% Non-mineral components* <0.5%	
	RMA	≥2000	≤7	SO4 (≤0.8%) (acid soluble)		–	–	Light weight + ≤1.0% Non-mineral components* <1.0% + (Material with density <1000 kg/m3) * (Glass, Clay, Plastics, Rubber, Metals etc.)	
RILEM	RCA 1	≥2000	≤10	SO4 (≤1.0%) (water soluble)	ARS testing needed as per ENV 206 when used in Exposure Classes 2a & 4a	≤100% (Coarse ≥4 mm)	Class C 50/50, (50 MPa) Concrete strength class	Aggregates from concrete rubble	[87,82,108,88,85,109,110,21]

(*continued on next page*)

Table 3 (*continued*)

National standard	Recycled aggregate type	Dry density (kg/m3)	Water absorption (%)	Cl & SO4 content	Limitations	Percentage of recycled aggregate allowed	Conditions of application	Notes	References
	RCA 2	≥1500	≤20	SO4 (≤1.0%) (water soluble)	ARS testing needed as per ENV 206 when used in Exposure Classes 2a & 4a	≤100% (Coarse ≥4 mm)	Class C 16/20, Concrete strength	Aggregates from demolished masonry	
	RMA	≥2400	≤3	SO4 (≤1.0%) (water soluble)	ARS testing needed as per ENV 206 when used in Exposure Classes 2a & 4a	≤20% (Coarse ≥4 mm)	No limit	Mix of natural (min 80%) + Type 1 (max 20%) aggregate	
Spain (EHE 08-2000) (UNE EN 12620:2003)	RCA	≥2000	≤5	Cl (≤0.05%) (water soluble) SO4 (≤0.08%) (acid soluble)	Not allowed in Pre-stressed concrete	≤20%	(40 MPa) Concrete strength Class	Non minerals* ≤1.0% Lightweight particles ≤1.0% sand content ≤5% *(metals, glass, soft materials, asphalt)	[87,80,111,21,112,85,113,114]
Switzerland(IT 70085: 2006) (SIA 430:1994) (SN EN 12620:2003)	RCA	n.a	n.a	Cl (≤0.03%) in reinforced & (≤0.12%) in non-reinforced concrete SO4 (≤1.0%)	Reinforced concrete, pre-stressed concrete only with additional tests Not allowed in Reinforced concrete	Coarse up to (100%) but must comply with SIA 162/4 Fine (100%)	Concrete strength Indoor C 30/37 & C 20/30 Outdoor ≥C25/30 Minor C 15/20 Cement content: 150–230 kg/m3 (100% concrete aggregate) Cement content: <150 kg/m3 (100% mixed aggregates)	Contaminants* (≤1.0% vol.) Mixed material (≤3.0%) Bituminous material (Zero%)	[87,88,21,85,115–117]
	RMA	n.a n.a = not available	n.a	SO4 (≤1.0%)		n.a		Contaminants* (≤1.0% vol.) Mixed material (No Limitation) Bituminous material (≤7.0%)	
U.K (BS 8500-2) (BS EN 12620:2013) (BS EN 206:2013)	RCA	–	–	SO3 <1%	Can be used in non-reinforced, internal, external not exposed to Cl^- or de-icing salts	≤20%	(20–40 MPa) Concrete strength class C 40/50, and class C 20/25	Masonry <5%, Fines <5%, non-minerals* <0.5%,	[87,82,88,85,21,118,119]
	RA	–	–	Appropriate limit needs to be determined	Use of Fine RA excluded in the concrete production	~100%	Used only in concrete strength class C 16/20	Masonry <100%, Fines <3%, non-minerals* <1.0%	
AMERICAS									
American Concrete Institute (ACI) (ACI E-701. 2007)	RCA (Coarse)					100%	Not specified	Content of foreign materials <2 kg/m3	[82,120,121]

Table 3 (*continued*)

National standard	Recycled aggregate type	Dry density (kg/m3)	Water absorption (%)	Cl & SO4 content	Limitations	Percentage of recycled aggregate allowed	Conditions of application	Notes	References
Brazil (NBR 15.116)	RCA (Fine)					20%	Not Specified		
	RCA (Class A-Coarse)	n.a	≤7	Cl (<1.0%) (water soluble), SO4 (<1.0%)	Use of both, coarse & Fine RA allowed in non-structural concrete.			Contaminants – non-minerals <2.0%, Clay lumps <2.0%, Sieve 75 µm passing ≤10% *(wood, plastic, bitumen, carbonized material, glass, ceramic tiles, gypsum)	[87,21,88,122,123]
	RCA (Class A-Fine)	n.a	≤12					Sieve 75 µm passing ≤15%	
	RMA (Class A-Coarse)	n.a	≤12	Cl (<1.0%) (water soluble), SO4 (<1.0%)				Sieve 75 µm passing ≤10%	
	RMA (Class A – Fine)	n.a	≤17					Sieve 75 µm passing ≤20%	

environmental conditions. A maximum of 20% of aggregates with the particle size 0–4 mm must come from recycled concrete while the remaining 80% shall be natural sand.

9.2.3.3. Finland. In Finland, the crushed concrete aggregate (CCA) was classified into four categories based on the origin of the raw material and their technical properties. The CCA to be used in road construction should have Confirmite Europeenne (CE) certificate.

Category 1: Raw materials from concrete elements which come as spoil.

Categories 2–4: Demolition of old concrete structures, categories 2–4 differ from each other based on grain size distribution, self-hardening properties, frost resistance etc.

9.2.3.4. Germany. For non-conforming aggregates, the German norm specify that if recycled aggregate does not conform to the requirements, they shall be: re-processed or assigned to another application for which it may be suitable or rejected and marked as non-conforming. For the application and mechanical requirements of recycled aggregate, the "Guideline of the German Committee for Reinforced Concrete (DAfStb, 2010) [28] specifies that only aggregates >2 mm belonging to Type 1(RCA-concrete waste) or Type 2 (RCA-demolition waste) can be used in the production of structural concrete. DAfStb allows the production of concrete up to the strength class B35 (35 MPa) with a maximum 25% (in volume) of recycled aggregate, while higher percentage of replacement, 35% can be employed for the production of concrete with strength class less than B25 (25 MPa).

9.2.3.5. Italy

See Table 4.

Table 4
Limitations of recycled concrete aggregates as per (NTC 2008).

Source of Recycled Material	Concrete Grade	Percentage of Utilisation (%)
Demolition of buildings (waste)	C 8/10	Up to 100%
Demolition of concrete & reinforced concrete	≤C 30/37 ≤C 20/25	Up to 30% Up to 60%
From concrete ≥C 45/55	≤C 45/55 Parent concrete	Up to 15% Up to 5%

9.2.3.6. Norway. For clarification, the Type 2 "Mixed Materials" are allowed to contain ≥90% of crushed concrete, crushed bricks and natural aggregate, however, for applications with material property requirements other than material constituents, it is recommended to keep the percentage of concrete and/or natural aggregate at minimum of 80%.

9.2.3.7. Portugal. As per the Portuguese National Laboratory of Civil Engineering (LNEC – 2006), though RCA1 and RCA2 have the same requirements for density and water absorption, the RCA2 may contain significant quantity of mortar/masonry and therefore may have difficulty in meeting the specified requirements of E 471 "Guidelines for the use of recycled concrete aggregate in hydraulic binder concrete". The requirement for maximum level of water absorption for RCA1 and RCA2 as well as RMA is the same, but the density requirement of RMA is 2000 kg/m3, since the density and water absorption are inter-related, hence for RMA it is more difficult to meet the requirements of water absorption. The recycled concrete aggregate RCAI and RCA2 should also meet the requirements of Environmental Classes (Xo, XC1, XC2, XC3, XC4, XS1 and in foundations XA1).

9.2.3.8. RILEM. The RILEM (*Reunion Internationale des Laboratoires et Experts des Materiaux, systems de construction et ouvrages*) Technical Committee – 121 and the recent Technical Committee – 217, suggest a classification system based on material composition and indicates the scope of application for concrete incorporating these recycled fractions in terms of acceptable environmental exposure classes and concrete strength classes. The replacement of natural coarse aggregates with recycled coarse aggregates can be up to 100% and the maximum strength class is C 50/50 for the RCA1 aggregate.

9.2.3.9. Spain. For the replacement ratio of 20% of natural aggregates, the allowed maximum water absorption is ≤7.0% for recycled aggregate (RA) and 4.5% for virgin aggregate (NA). For higher replacement ratios of NA, the combined NA and RA must have water absorption of ≤5.0%.

9.2.3.10. Switzerland. The Swiss Standard OT 70,085 in combination with "SIA 162/4 – 1994" "Beton de recyclage", specifies that recycled materials should be utilised on priority & preferable basis, even if the cost is 5–10% higher for secondary materials, they should still be considered as economically viable. The Standard differentiates between two types of concrete made with recycled aggregate (1) Classified concrete (2) Unclassified concrete.

Classified concrete: recycled concrete aggregates can replace up to 100% of virgin aggregate in this concrete type and its quality requirements must comply with the requirements of Standard "SIA 162 Ouverages in Beton".

Unclassified concrete: recycled concrete aggregates and/or masonry can replace up to 100% of virgin aggregate, but the application is limited to plain concrete. Recycled concrete aggregate are intended for concrete with cement content higher than 150 kg/m3 and masonry aggregate can also be used in screed concrete and concrete with low cement content.

9.2.5.1. United Kingdom. In the U.K B.S. 8500-2 "Concrete", complementary British Standard to BS EN 206-1 Part-2: "Specifications for constituent materials and concrete", provides general requirements for the use of coarse recycled aggregate, while provisions for the use of fine recycled aggregate are not given in BS 8500-2. Moreover, it is specified that the concrete made from recycled aggregate can have applications in un-reinforced concrete, internal concrete and external concrete not exposed to the chlorides or de-icing salts and also cannot be used in foundations or paving. Provisions for the use of fine recycled aggregate are not given in BS 8500-2.

9.2.5.2. ACI. Section 5 of ACI 555 Technical Committee Report provides no acceptance criteria and procedures for RCA evaluation but serves only as an overview. It discusses the aggregate production, aggregate properties, its effects on concrete properties, guidelines on the mix proportioning and recommends pre-soaking of RCA before making the batch.

9.2.5.3. Brazil. As per the Brazil Standards NBR 15.116 [123] for recycled concrete aggregate, Class A out of the four classes (A–D) of C&D waste can be considered as aggregate which can be used in concrete. Class A is further sub-divided into 2 sub-classes (a) RCA (recycled concrete aggregate) which are composed of >90% concrete and natural resources and (b) RMA (recycled mixed aggregate) which is composed of <90% concrete and natural resources. The sub-classes RCA and RMA are further separated into 4 groups based according to their composition.

Group 1: C&D waste consisting 50% by volume of hardened cement paste.

Group 2: C&D waste consisting 50% by volume of rock particles.

Group 3: C&D waste consisting of red clay tiles and white ceramics with polished surfaces not>50% by volume.

Group 4: C&D waste containing non-minerals such as wood, plastic, bitumen, glass, ceramics, gypsum, carbonized material.

This standard (compared to all the EU standards) does not impose requirements on the minimum density of the aggregates, but the requirements on water absorption are quite strict and demanding and limit the use of masonry rubble.

10. Some barriers and issues for acceptability and re-use of recycled aggregate

Acceptability of recycled aggregate is hampered due to a poor image associated with recycling activity and lack of confidence, by consumers in the finished product made from recycled material. Even though recycled aggregate is being utilised in substantial quantities in civil engineering construction, it is still difficult to overcome the barriers that prevent the wider use of recycled aggregate in construction are depicted in Fig. 3.

The advantages both economic and environmental, of using recycled aggregate as an alternative to natural aggregate, are greatly affected by economic reasons, for example:

(i) The choice between recycled and virgin material depends upon price and quality. The quality of concrete with recycled aggregate can be the same as that of concrete with virgin aggregate, but recycled aggregate is regarded with suspicion. Hence, recycled concrete material will only be preferred where the price for such aggregate is considerably lower than that of the natural material, even when the recycled aggregate meet given specifications [125].

(ii) An important barrier is the variation in quality of recycled aggregate, this type of barrier can be overcome easily by the C&D processing plants.

(iii) Another barrier to increased reuse of recycled aggregate in construction is the lack of a well-developed collection and processing facilities/infrastructure (See Fig. 7).

(iv) Recycled aggregate must be available in sufficient quantity which can be utilised. This becomes the primary concern in encouraging the reuse of recycled aggregate for constructors and builders, shortages of potentially useable material will have a considerable impact on their decision making [127].

(v) The concrete debris of higher quality should be used as a recycled aggregate, and that of lower quality should be used as a road base aggregate. When making a ready-mixed recycled concrete, the factory should be located close to the recycled aggregate factory to save on the cost for haulage distances for transportation which may significantly increase the cost of recycled aggregate. As a result, the incentives of using recycled aggregate to concrete manufacturers and contractors will be low [128].

(vi) In most cases, distrust concerning the recycle aggregate's technical feasibility is claimed by clients, concrete producers and contractors. If the product complies with high-quality standards, the use of recycled aggregate in structural concrete manufacture will then be accepted as a realistic alternative to virgin aggregate [129].

(vii) The trust of purchaser or user is thin to recycled products, and there is tendency of disliking the recycled products.

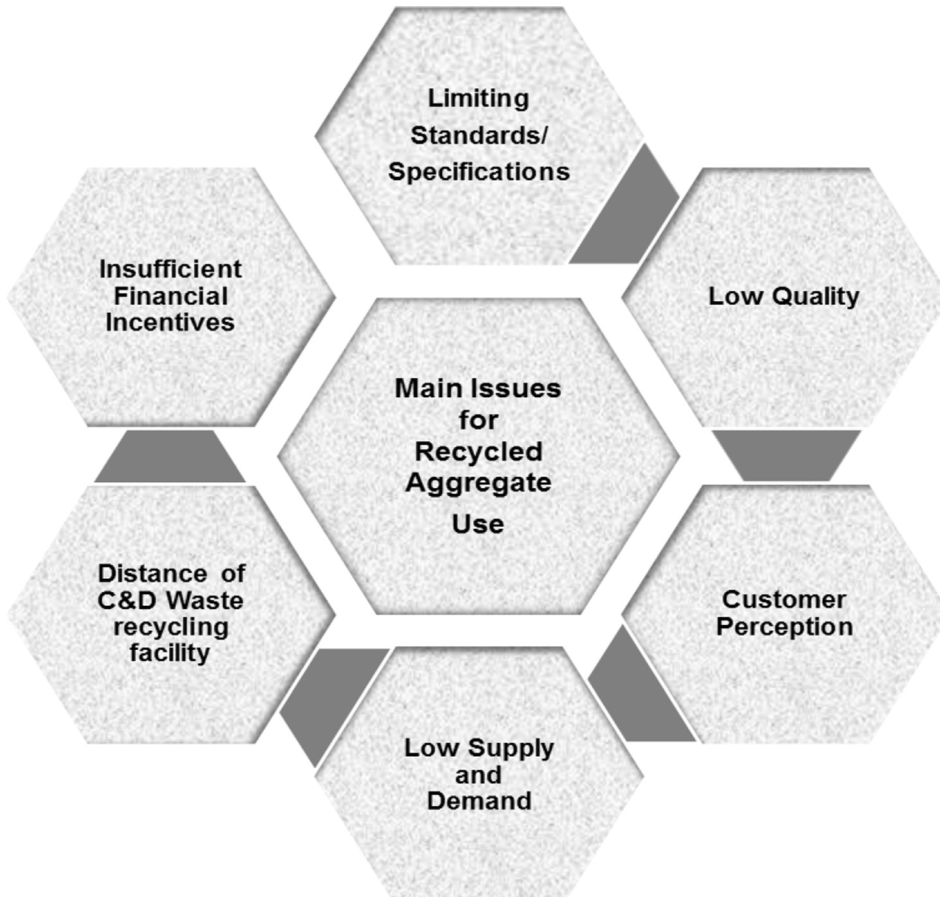

Fig. 7. Barriers that prevent a wider use of recycled aggregate in construction [126].

10.1. Recycled aggregate market

Different factors influence the recycled aggregate market, the primary factors could be;

- Taxation in mining activity of virgin aggregate
- Taxation on landfills
- Availability and cost of recycled and virgin aggregate
- Misconception and bias against the performance of recycled materials

10.2. Certification

The majority of the output of recycling plants in several countries is currently non-certified aggregate, but due to stricter demands from consumers, who would like to use recycled aggregate conforming to specifications and guaranteed quality, certification has become of prime importance.

The marketable recycled aggregate currently produced can be divided in two categories, non-certified and certified aggregate. The majority of the output of recycling plants is currently non-certified aggregate, however due to stricter demands from consumers, who would like to use specifiable and guaranteed quality, the certification of recycled aggregate is of prime importance [130].

All recycled product has to meet the quality requirements, before their use can be encouraged. However, low quality recycled aggregate can be considered for low grade applications. Due to traditions and acceptance barriers in constructors, builders and public at large, the general attitude towards recycling in the building and construction industry is largely inhibitive to the utilisation of recycled material. Therefore, it is of great importance that recycled materials are officially certified and accepted by the building and construction industry. Considerable emphasis must be placed on specifying the areas of utilisation and quality standards for recycled materials. These must be in accordance with the local demand in order to improve confidence in the recycled material and solve problems regarding the responsibility of using recycled material [128].

Silva et al. [131] developed a performance-based classification system, based on the predictable relationship of basic physical properties of recycled aggregate, regardless of their size and composition, which allows accurate prediction of the material's performance and is easily understandable by all professionals in the industry. This classification system showing high reliability and reproducibility of results can help facilitate certification of the final product.

10.3. Lack of government support

A lack of government support and commitment towards development of recycling industry is also an impediment. Developing appropriate policy supported by proper regulatory framework can provide necessary impetus. It will also help in data compilation, documentation, education of consumers on its use and control over disposal of waste material [132].

Lauritzen [128] recommended that long-term strategies, e.g., for a decade or two decades, with respect to achieving goals for recycling of C&D waste should be adopted. These must then be continuously revised in accordance with the political situation, and followed up by adequate legislation and regulation at all levels, national, regional and local.

11. Conclusion

Use of recycled aggregate in concrete provides a promising solution to the problem of construction and demolishing waste. The major quantity of recycled aggregate at present is used in lower end applications, however in some developed economies; it is also used in structural concrete, due to its quality which is certified and bears Confirmite Europeenne (CE) Certificate. The standards (normative documents) regulate and maintain the quality and provide producers as well as the users, an assurance of the consistent quality of the recycled aggregate. China and India at present are the major consumers of construction aggregate and hence have high potential for recycling and re-use of C&D waste, however, despite its potential, there is huge variation in the level of recycling and material recovery in various countries around the world e.g. Brazil (6.14%), Denmark (94%), Netherland (98%). This variation is due to vast differences in construction traditions, the legislation on landfills and due to the perception and acceptance level of constructors and builders. Comparison in tabulation form of the Standards (normative documents) from various countries have been presented to provide producers, consumers as well as researchers a wider outlook on the characteristics of recycled aggregate which are desired and specified in legislation of those countries. To alleviate the concerns of consumers related to durability performance of concrete produced from recycled aggregate, it is suggested that with further research and development, improvement in legislation and by inclusion of durability factors, such as deformation (shrinkage and creep) and permeability (carbonation, air and water penetration and chloride ingress) in the legislation, will help in improving the acceptance level and usage of recycled concrete applications and assist in turning recycling as one of the important components for sustainable development.

Conflict of interest

There is no conflict of interest.

References

[1] K. Slattery, Global developments in the aggregate industry: global aggregates information, Network (2016).
[2] The Freedonia Group. Global Demands for Construction Aggregates to Exceed 48 Billion Metric Tons in 2015 2012:1.
[3] PMR Analysis. Global Market Study on Construction Aggregate. New York, USA, 2016.
[4] M. Marzouk, S. Azab, Environmental and economic impact assessment of construction and demolition waste disposal using system dynamics, Resour. Conserv. Recycl. 82 (2014) 41–49, https://doi.org/10.1016/j.resconrec.2013.10.015.
[5] C.G. da Rocha, M.A. Sattler, A discussion on the reuse of building components in Brazil: an analysis of major social, economical and legal factors, Resour. Conserv. Recycl. 54 (2009) 104–112, https://doi.org/10.1016/j.resconrec.2009.07.004.
[6] European Union. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives. 2008. doi:2008/98/EC. 32008L0098.
[7] R. Oliveira Neto, P. Gastineau, B.G. Cazacliu, L. Le Guen, R.S. Paranhos, C.O. Petter, An economic analysis of the processing technologies in CDW recycling platforms, Waste Manage. 60 (2017) 277–289, https://doi.org/10.1016/j.wasman.2016.08.011.
[8] UEPG, European Aggregates Association – Annual Review (2015–2016), 2016. doi: 10.1016/0038-092X(81)90058-X.
[9] S.A. Dea, National Waste Information Baseline, Department of Environment Affairs, South Africa, 2012.
[10] H. Yang, J. Xia, J.R. Thompson, R.J. Flower, Urban construction and demolition waste and landfill failure in Shenzhen, China, Waste Manage. 63 (2017) 393–396, https://doi.org/10.1016/j.wasman.2017.01.026.
[11] Energy Protection Department. Monitoring of Solid Waste in Hong Kong, Waste Statics for 2015. 2016.
[12] V.W.Y. Tam, C.M. Tam, Evaluations of existing waste recycling methods: a Hong Kong study, Build. Environ. 41 (2006) 1649–1660, https://doi.org/10.1016/j.buildenv.2005.06.017.
[13] X. Duran, H. Lenihan, B. O'Regan, A model for assessing the economic viability of construction and demolition waste recycling—the case of Ireland, Resour. Conserv. Recycl. 46 (2006) 302–320, https://doi.org/10.1016/j.resconrec.2005.08.003.
[14] N. Dantata, A. Touran, J. Wang, An analysis of cost and duration for deconstruction and demolition of residential buildings in Massachusetts, Resour. Conserv. Recycl. 44 (2005) 1–15, https://doi.org/10.1016/j.resconrec.2004.09.001.
[16] P. Söderholm, Taxing virgin natural resources: lessons from aggregates taxation in Europe, Resour. Conserv. Recycl. 55 (2011) 911–922, https://doi.org/10.1016/j.resconrec.2011.05.011.
[17] V.W.Y. Tam, L. Tam, K.N. Le, Cross-cultural comparison of concrete recycling decision-making and implementation in construction industry, Waste Manage. 30 (2010) 291–297, https://doi.org/10.1016/j.wasman.2009.09.044.
[18] M. Malešev, V. Radonjanin, S. Marinković, Recycled concrete as aggregate for structural concrete production, Sustainability 2 (2010) 1204–1225, https://doi.org/10.3390/su2051204.
[19] M. Thomas, T. Bremner, Performance of lightweight aggregate concrete containing slag after 25years in a harsh marine environment, Cem. Concr. Res. 42 (2012) 358–364, https://doi.org/10.1016/j.cemconres.2011.10.009.
[20] C. Pellegrino, F. Faleschini, Sustainability and the Concrete Industry, 2016. doi: 10.1007/978-3-319-28540-5.
[21] J. de Brito, N. Saikia, Concrete with recycled aggregates in international codes, Recycl. Aggregates Concr. (2013), https://doi.org/10.1007/978-1-4471-4540-0.
[22] Cement Concrete, Aggregates Australia, Use of recycled aggregates, Construction 25 (2008).
[23] UEPG. European Aggregates Association – Annual Review (2013–2014). 2014.
[24] CSI. The Cement Sustainability Initiative. Recycling Concrete: Executive summary, 2009, 42.
[25] MPA. MPA Aggregates Information Sheet, 2009, 3.
[26] K. Obla, H. Kim, C. Lobo. Crushed Returned Concrete as Aggregates for New Concrete. RMC Res Educ Found 2007:51.
[27] WRAP, NRW. Aggregates from Inert Waste: End of Waste Briteria for the Production of Aggregates from Inert Waste 2013, pp. 1–24.
[28] DAfStb. DAfStb 2010, Concrete in accordance with DIN EN 206- 1 and DIN 1045-2 with recycled aggregates in accordance with DIN EN 12620, Deutscher Ausschuss für Stahlbeton e. V., Berlin, Germany. 2010.
[29] Fisher & Werge, EU as a Recycling Society. Present recycling levels of Municipal Waste and Construction & Demolition Waste in the EU, 2009.
[30] J. Staunton, C.D. Williams, L. Morrison, T. Henry, G.T.A. Fleming, M.J. Gormally, Spatio-temporal distribution of construction and demolition (C&D) waste disposal on wetlands: a case study, Land Use Policy 49 (2015) 43–52, https://doi.org/10.1016/j.landusepol.2015.06.023.
[31] ADEME, National Recycling Report (2005-2014), Agence de l'Environment et de la Maitrise de l'Energie, France. 2017.
[32] Williams, Turner, Waste management practices in the small-scale construction industry. Thirteen Int Waste Manag Landfill Symp, 2011.
[33] USEPA, Advancing sustainable materials management: 2014 fact sheet, United States Environmental Protection Agency, Office of Land and Emergency Management, Washington, DC 20460, 2016.
[34] I. Unep, Global Waste Management Outlook, International Environmental Technology Centre, Osaka, Japan, 2015. 10.1177/0734242X15616055.
[35] Chris Reardon EF. Waste minimisation, 2015.
[36] C.S. Poon, Sustainable management of construction waste for Hong Kong, 2009.
[37] Randell P& G. Waste generation and resource recovery in Australia- Reporting Period 2010/11, 2014.
[38] V.M. Tam, C.M. Tam, Re-use of Construction and Demolition Waste in Housing Developments, 2008, 247.
[39] V.W.Y. Tam, W. Lu, Construction waste management profiles, practices, and performance: a cross-jurisdictional analysis in four countries, Sustain 8 (2016) 1–16, https://doi.org/10.3390/su8020190.
[40] F.M. Khalaf, A.S. DeVenny, Recycling of demolished masonry rubble as coarse aggregate in concrete: review, J. Mater. Civ. Eng. 16 (2004) 331–340, https://doi.org/10.1061/(ASCE)0899-1561(2004) 16:4(331).
[41] Directive (2008/98/EC), Directive 2008/98/EC of the European Parliament, Off J Eur Union 2008, pp. 3–30. doi: 2008/98/EC.; 32008L0098.
[42] V. Corinaldesi, V. Moriconi, Reusing and recycling C&D waste in Europe, in: Proc Int Conf Concr Mason Res Gr, 2004, 405, doi: 10727732854.
[43] J. Pickin, P. Randell, Australian National Waste Report 2016, 2017.
[44] EPA. Zero Waste and Resource Recycling Promotion (Taiwan), 2017, pp. 1–2.
[45] J. Barritt, An overview on recycling and waste in construction, Proc, ICE – Constr. Mater, 169 (2015) 1–5, https://doi.org/10.1680/coma.15.00006.
[46] National Statistical Office, Solid waste and Hazardous waste in Thailand, 2012.
[47] European Union. Waste Statistics, Eurostat, 2017.
[48] European Commission (DG ENV), Service contract on management of construction and demolition waste – SR1. Final Report Task 2. Bio Intell Serv, 2011,33, pp. 1–240. doi: ENV.G.4/FRA/2008/0112.
[49] ADEME. National Recycling Report (2005-2014), Agence de l'Environment et de la Maitrise de l'Energie, France, 2014.
[50] E. Vazquez. Present situation in Spain of the use of waste materials to obtain building materials, in: Proceedings Eco-Serve Semin. "Challenges Sustain. Constr. "concrete" approach," 2006, pp. 1–341.

[51] Abrecon. Abrecon- Relatorio Pesquisa Setorial (2014–2015), Associacao Brasileira Para Reciclagem de Residuos da Construcao Civil e Demolicoes, Brazil, 2015.
[52] Giroux Environmental Consulting, State of Waste Management in Canada, Can. Counc. Minist. Environ, 2014, 155.
[53] UEPG, European Aggregate Association-Annual Review-2010-2011, 2011.
[54] UEPG, European Aggregate Association Annual Review- 2011-2012, 2012.
[55] UEPG, European Aggregates Association – Annual Review (2012-2013), 2013.
[56] UEPG, European Aggregates Association – Annual Review (2014-2015), 2015.
[57] S.L. Bakoss, R.S. Ravindrarajah, Recycled construction and demolition materials for use in roadworks and other local government activities, 1999, 72.
[58] R. Herrador, P. Pérez, L. Garach, J. Ordóñez, Use of recycled construction and demolition waste aggregate for road course surfacing, J. Transp. Eng. 138 (2012) 182–190, https://doi.org/10.1061/(ASCE)TE.1943-5436.0000320.
[59] Arisha and Gabr, Performance evaluation of construction and demolition and other waste materials for pavement construction in Egypt, J. Mater. Civ. Eng. 30 (2018) 1–14, https://doi.org/10.1061/(ASCE)MT.1943-5533.0002127.
[60] I. Haider, B. Cetin, Z. Kaya, M. Hatipoglu, A. Cetin, H.A. Ahmet, Evaluation of the Mechanical Performance of Recycled Concrete Aggregates Used in Highway Base Layers, Geo-Congress 2014, Tech Pap, 2014, 3686–2594, doi: 10.1061/9780784413272.357.
[61] P.K. Kolay, M. Akentuna, Characterization and utilization of recycled concrete aggregate from illinois as a construction material, Geo-Congress 2014 Tech Pap, 2014, 3570–3561, doi: 10.1061/9780784413272.345.
[62] M. Diagne, J.M. Tinjum, K. Nokkaew, The effects of recycled clay brick content on the engineering properties, weathering durability, and resilient modulus of recycled concrete aggregate, Transp. Geotech. 3 (2015) 15–23, https://doi.org/10.1016/j.trgeo.2014.12.003.
[63] X. Jia, F. Ye, B. Huang, Utilization of construction and demolition wastes in low-volume roads for rural areas in China, Transp. Res. Rec. J. Transp. Res. Board. 2474 (2015) 39–47, https://doi.org/10.3141/2474-05.
[64] J. Neves, A.C. Freire, A. Roque, I. Martins, M. Antunes, G. Faria, Utilization of Recycled Materials in Unbound Granular Layers Validated by Experimental Test Sections, 2013, Railw Airfields Ninth Int Conf Bear Capacit Roads, pp. 1–8.
[65] A.M. Azam, D.A. Cameron, Laboratory evaluation of recycled concrete aggregate and recycled clay masonry blends in pavement applications, Adv. Civ. Eng. Mater. 2 (2013) 20120016, https://doi.org/10.1520/ACEM20120016.
[66] A. Arulrajah, J. Piratheepan, Geotechnical and geoenvironmental properties of recycled construction and demolition materials in pavement subbase applications, J. Mater. Civ. Eng. 25 (2013) 1077–1088, https://doi.org/10.1061/(ASCE)MT.1943-5533.0000652.
[67] A. Barbudo, F. Agrela, J. Ayuso, J.R. Jiménez, C.S. Poon, Statistical analysis of recycled aggregates derived from different sources for sub-base applications, Constr. Build. Mater. 28 (2012) 129–138, https://doi.org/10.1016/j.conbuildmat.2011.07.035.
[68] M. Soomro, USE OF SELECTIVE RECYCLED MATERIALS IN CIVIL ENGINEERING CONSTRUCTION HANDb. Environ. Waste Manag 1st 2014 World Scientific Singapore, pp. 635–684.
[69] R. Nassar, P. Soroushian, Use of recycled aggregate concrete in pavement construction, J. Solid Waste Technol. Manage. 42 (2016) 137–144, https://doi.org/10.5276/JSWTM.2016.137.
[70] C.-S. Poon, S.C. Kou, L. Lam, Use of recycled aggregates in moulded concrete bricks and blocks, 16, 2002, pp. 281–289.
[71] ARRB. Recycled aggregates bring carbon reduction benefits, 2009.
[72] A.Y. Nayana, S. Kavitha, Evaluation of c02 emissions for green concrete with high volume slag, recycled aggregate, recycled water, Int. J. Civ. Eng. Technol. 8 (2017) 703–708.
[73] A. Korre, S. Durucan. Life Cycle Assessment of Aggregates – EVA025 Final Report, 2009, pp. 1–41.
[74] ARRB Group. Sustainable Aggregates-C02 Emission Factor Study, 2010.
[75] Mcrobert, Jencie RC. Recycled aggregates – environmental considerations, 2008.
[76] Interactive P. Energy and Road Construction-What's the Mileage of Roadway/? 2012, 0–4.
[77] M.U. Hossain, C.S. Poon, I.M.C. Lo, J.C.P. Cheng, Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA, Resour. Conserv. Recycl. 109 (2016) 67–77, https://doi.org/10.1016/J.RESCONREC.2016.02.009.
[78] N. Serres, S. Braymand, F. Feugeas, Environmental evaluation of concrete made from recycled concrete aggregate implementing life cycle assessment, J. Build. Eng. 5 (2016), https://doi.org/10.1016/j.jobe.2015.11.004.
[79] M. Wijayasundara, R.H. Crawford, P. Mendis, Comparative assessment of embodied energy of recycled aggregate concrete, J. Clean. Prod. 152 (2017) 2–4, https://doi.org/10.1016/j.jclepro.2017.03.118.
[80] K. McNeil, T.H.K. Kang, Recycled concrete aggregates: a review, Int. J .Concr. Struct. Mater. 7 (2013) 61–69, https://doi.org/10.1007/s40069-013-0032-5.
[81] CSIRO-HB 155. Guide to the use of recycled concrete and masonry materials, 2002.
[82] E. Martinelli, A. Eduardus, M. Pepe, Recent Advances on Green Concrete for Structural Purposes, 2017, doi: 10.1007/978-3-319-56797-6
[83] K. Kim, M. Shin, S. Cha, Combined effects of recycled aggregate and fly ash towards concrete sustainability, Constr. Build. Mater. 48 (2013) 499–507, https://doi.org/10.1016/j.conbuildmat.2013.07.014.
[84] Standards Australia. AS 1141.6.2—1996. Methods for sampling and testing aggregates Method 6. 2: Particle density and water absorption of coarse aggregate — Pycnometer method, vol. i, 1996.
[85] M. Martín-Morales, M. Zamorano, I. Valverde-Palacios, G.M. Cuenca-Moyano, Z. Sánchez-Roldán. Quality control of recycled aggregates (RAs) from construction and demolition waste (CDW), Handb. Recycl. Concr. Demolition Waste, 2013, p. 270–303, doi: 10.1533/9780857096906.2.270.
[86] R. Bodet. Standards and regulations Present status in France vs, Europe and other countries, 2014.
[87] P. Gonçalves, J.D. Brito, Recycled aggregate concrete (RAC) – comparative analysis of existing specifications, Mag. Concr. Res. 62 (2010) 339–346, https://doi.org/10.1680/macr.2008.62.5.339.
[88] M. Gonçalves, Concrete With Recycled Aggregates: Commented Analysis of Exististing Legislation, 2007.
[89] HK Govt. CS 3-2013, Aggregates for concrete. Construction Standards, Hong Kong Government, vol. 3, 2013, doi: 10.4324/9780203478981.ch16.
[90] DIN. DIN 4226-100, Aggregates for mortar and concrete, Part-100 "Recycled Aggregate, Deutsches Institut für Normung, Germany, 2002. DIN; 2002.
[91] C. Neno, J. de Brito, R. Veiga, Using fine recycled concrete aggregate for mortar production, Mater. Res. 17 (2014) 168–177, https://doi.org/10.1590/S1516-14392013005000164.
[92] European Standard, EN 933-2: Tests for geometrical properties of aggregates, 1999.
[93] COPRO. PTV-406, Classification of Recycled Aggregate, Belgium, 2016.
[94] European Standard. NEN EN 12620.2013 " Aggregates for concrete " the Netherlands. 2013.
[95] F. Debieb, L. Courard, S. Kenai, R. Degeimbre, Mechanical and durability properties of concrete using contaminated recycled aggregates, Cem. Concr. Compos. 32 (2010) 421–426, https://doi.org/10.1016/j.cemconcomp.2010.03.004.
[96] A.R. Gabr, D.A. Cameron, R. Andrews, P.W. Mitchell, T. Edil, S.W. Dean, Comparison of specifications for recycled concrete aggregate for pavement construction, J. ASTM Int. 8 (2011) 103646, https://doi.org/10.1520/JAI103646.
[97] Dansk Standard, DS-EN 12620 + a1:Aggregates for concrete, 2008, 2008, pp. 1–3.
[98] Dansk Standard, DS 2426-EN206-1 Concrete – Materials – Rules for application of EN 206-1 in Denmark, 2013.
[99] DIN. DIN EN 12620:2015, Aggregates for Concrete. German Institute for Standardisation, Berlin, Germany. Draft Stand, 2015.
[100] Italian Ministry of Infrastructure and Transport. NTC 2008 – Italian Building Code. D.M. 14/01/2008, 2008, 428. doi: 10.1515/9783110247190.153.
[101] I. Standards, UNI EN 12620.2013. Aggregate for Concrete. Italian Standards. n.d.
[102] H.S. Pietersen, A.L. Fraay, Performance of concrete with recycled aggregates, Int. Conf. Sustain. Concr. Constr. (2002) 187–198.
[103] J. Mehus, G. Petkovic, C.J. Engelsen, J. Karlsen, B. Lillestøl, Recycled aggregates a viable alternative for the norwegian building and construction industry, 2005.
[104] J. Karlsen, E. Manager. A Norwegian Certification Scheme for Recycled Aggregate (RCA), in: 3rd Int. Conf. Sustain. Build. (CD), Oslo, Norway, 2002.
[105] J. Mehus, O. Lahus. The use of recycled concrete aggregates in the Norwegian building and construction industry, 2005.
[106] Norwegian Standards, NS EN 12620.2013, Aggregates for Concrete. Norwegian Standards (Norges Standardiseringsforbund). n.d.
[107] LNEC. E 471-2009, Guia para a utilização de agregados reciclados grossos em betões de ligantes hidráulicos, 2009, 8.
[108] L. Butler, S.L. Tighe, J.S. West, Guidelines for the Selection and Use of Coarse Recycled Concrete Aggregates in Structural Concrete. TRB Annu Meet 2013:20. doi: 10.3141/2335-01.
[109] RILEM, Rilem Recommendation-Specifications for concrete with recycled aggregates, Mater. Struct. 27 (1994) 557–559.
[110] E.K. Lauritzen, S DCEA. Bulletin de la RILEM- Third International RILEM Symposium on Demolition and Reuse of Concrete and Masonry, Odense, Denmark, 24-27 October 1993 1994, 307–310.
[111] P. Alaejos, M. Sánches, E. Dapena, E. Vásquez, M. Barra, M. Etxeberria, et al., Draft of Spanish regulations for the use of recycled aggregate in the production of structural concrete, Int. RILEM Conf. Use Recycl. Mater. Build. Struct. (2004) 511–525, https://doi.org/10.1617/2912143756.057.
[112] E. Vazquez, Overview Regarding Construction & Demolition Waste in Several Countries, Prog. Recycl. Built Environ. (2013) 37–173, https://doi.org/10.1007/978-94-007-4908-5.
[113] Fomento M. Instrucción de Hormigón Estructural (EHE-08), 2008, doi: 10.1017/CBO9781107415324.004.
[114] AENOR. UNE EN 12620-2003, Aggregates for Concrete, Asociacion Espanola de Normalizacion, Spain, 2003.
[115] SNV, SN EN 12620.2003, Aggregates for Concrete, Swiss Standards, Switzerland. 2003.
[116] SN, SIA-430, Site Waste Management during construction work, transformation and demolition (Gestion des déchets de chantier), Schweizer Norm 1993.
[117] Schweize Eidgenossenschaft. Instruction technique (tV)-70085. Utilisation de matériaux de construction mi- néraux secondaires dans la construction d ' abris. Switzerland, 2006. 2006.
[118] BSI, BS EN 12620:2013, Aggregates for Concrete, British Standards Institution. 2013, pp. 2–6.
[119] BS EN 206. BSI Standards Publication Concrete — Specification, performance, production and conformity. Br Stand 2013:30.
[120] ACI, Aggregates for concrete – E-701. 2007. doi: 10.4324/9780203478981.ch16.

[121] ACI Committee-201, Guide to durable concrete, Vol. 79, 2005.
[122] M.J.E.C.S. Oliveira, J. De AssisDe Tavares, Recycled aggregate standardization in Brazil, Int. RILEM Conf Use Recycl. Mater. Build. Struct. (2004) 156–165.
[123] ABNT N. NBR-15116 "Recycled aggregate of solid residue of building constructions-Requirements and methodologies." 2004.
[124] CC&AA, Use of Recycled Aggregates in Construction, Cement Concrete & Aggregates Australia, 2008.
[125] M. Head, M. Lamb, The Use of Waste Materials in Construction – Progress Made and Challenges for the Future, in: 5th ICEG Environ. Geotech. Oppor. Challenges Responsib. Environ. Geotech, 2006.
[126] R.V. Silva, J. de Brito, R.K. Dhir, Availability and processing of recycled aggregates within the construction and demolition supply chain: a review, J. Clean Prod. 143 (2017) 598–614, https://doi.org/10.1016/j.jclepro.2016.12.070.
[127] Y. Kasai, By-Products and the Use of Recycled Aggregate in Concrete in Japan, Sustain. Constr. Use Recycl. Concr. Aggreg., 1998.
[128] E.K. Lauritzen, The Global Challenge of Recycled Concrete. Sustain Constr Use Recycl Concr Aggreg – Proc Int Symp Held Dep Trade Ind Conf Centre, London, Uk, pp. 11–12, November 1998, 1998.
[129] D. Pedro, J. De Brito, L. Evangelista, Influence of the use of recycled concrete aggregates from different sources on structural concrete, Constr. Build. Mater. 71 (2014) 141–151, https://doi.org/10.1016/j.conbuildmat.2014.08.030.
[130] A. Trevorrow, T.J. Lyne, Recycled Aggregate Markets: Where to start 1998.
[131] R.V. Silva, J. de Brito, R.K. Dhir, The influence of the use of recycled aggregates on the compressive strength of concrete: a review, Eur. J. Environ. Civ. Eng. 19 (2015) 825–849, https://doi.org/10.1080/19648189.2014.974831.
[132] A. Rao, K.N. Jha, S. Misra, Use of aggregates from recycled construction and demolition waste in concrete, Resour. Conserv. Recycl. 50 (2007) 71–81, https://doi.org/10.1016/j.resconrec.2006.05.010.