Sustainable Built Environment National Research Centre AUSTRALIA

Resource circular economy: Opportunities to reduce waste disposal across the supply chain

Concrete

Research Report 5

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SBEnrc P1.65 A National Economic Approach to Improved Management of Construction and Demolition Waste

Date: March 2019

ACKNOWLEDGEMENTS

This research has been developed with funding and support provided by Australia's Sustainable Built Environment National Research Centre (SBEnrc) and its partners.

Core Members of SBEnrc include Aurecon, BGC Australia, New South Wales Roads and Maritime Services, Curtin University, Griffith University, RMIT University, Queensland Government and Government of Western Australia.

Core Partners: This research would not have been possible without the ongoing support of our core industry, government and research partners:

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Citation: Maqsood, T., Shooshtarian, S., Wong, P., Khalfan M., Yang R. (2019) Resource circular economy: opportunities to reduce waste disposal across the supply chain. SBEnrc 1.65 - A National Economic Approach to Improved Management of Construction and Demolition Waste. https://sbenrc.com.au/research-programs/1-65/

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EXECUTIVE SUMMARY

Concrete is one of the most widely used building materials with a global consumption rate approaching 25 gigatonnes per year. The key economic drivers for concrete product manufacturing in Australia include demand from residential building construction, demand from heavy industry and other non-building construction, demand from non-residential building construction, actual capital expenditure on mining, capital expenditure by the public sector, demand from road and bridge construction. The residential and non-residential building markets represent the principal source of demand for concrete products. The prime building contractors or project developers, including individual homeowners or property developers, generally fund the procurement of concrete products for building projects. Concrete makes up the greatest proportion of masonry material recycled in Australia, at around 60% of all masonry material recycled. The latest data for concrete waste recovery indicated that Australia recycled 6,007,156 tonnes of concrete waste, of which 71% was generated in the construction industry. The current report reviews the main strategies to reduce the volume of concrete waste going to landfill at different stages of construction and demolition activities. The following are a selection of recommendations for the improved management of concrete waste:

- Recognise that recycled aggregate, when produced to conform to the standard specification criteria, is a technically viable alternative that can be utilised in non-structural and structural concrete elements;
- Conduct a life cycle analysis to quantify potential saving from increased durability;
- Introduce RCA through precast panels as a quality that can be closely monitored;
- Change the industry attitudes towards sustainability-conscious material choices, as inertia towards traditional practices in construction is prevalent;
- Improve separation on-site to sort concrete waste material from other C&D waste; and
- Utilise advanced density separation techniques to grade crushed concrete fines to increase homogeneity and reduce the presence of foreign inclusions.

1 INTRODUCTION

Concrete has been used for construction since ancient times. The oldest concrete discovered dates from around 7000 BC. It was found in 1985 when a concrete floor was uncovered during the construction of a road at Yiftah El in Galilee, Israel. It consisted of lime concrete, made from burning limestone to produce quicklime, which when mixed with water and stone, hardened to form concrete[1].

Currently, concrete is the world's most widely used architectural medium, owing to its incredible versatility. In 2009, it was reported that the annual concrete global consumption rate is approaching 25 gigatonnes[2]. Concrete is a composite material composed of fine and coarse aggregate bonded together with a fluid cement (cement paste) that hardens over time. As a building material, it has a unique ability to be shaped and sculpted into anything from roads and footpaths to art sculptures, residential homes and skyscrapers. It is a relatively cheap material and has a relatively long life with few maintenance requirements. It is strong in compression, and before it hardens, it is a very pliable substance that can easily be shaped. It is also fire-resistance. The main advantages of concrete as a construction material are provided in Table 1:

Table 1. The main features of concrete as a construction material

Feature	Description
Vibration	For common spans, the relatively high mass of concrete floors leads to natural damping and low vibration. For more-stringent criteria, such as for laboratories or hospital operating theatres, the additional cost to meet vibration criteria is small compared to lightweight construction.
Weather protection	High-quality concrete, properly compacted and cured, effectively detailed and (in some cases) coated, can contribute to a durable weather-proof building envelope.
Fire resistance	Concrete does not burn and does not emit any toxic fumes when subjected to fire. It will not produce smoke or drip molten particles. For these reasons, in the majority of applications, concrete can be described as 'fireproof'. Concrete structures generally do not require fire protection if appropriately designed, because of their inherent fire resistance. This removes the time, cost, additional materials and labour required to provide separate fire protection measures.
Acoustic performance	Concrete offers a good barrier to airborne due to its thick mass. It improves the sound insulation of a room in walls and floor. Impact sound can be controlled with appropriate floor and ceiling finishes. Concrete can effectively act as a buffer between outdoor noise and the indoor environment; road noise and residential areas, via a sound barrier; and adjoining apartments or other spaces.
Reflectivity	Concrete minimises the effects that produce urban heat islands. Light-coloured concrete pavements and roofs absorb less heat and reflect more solar radiation than dark-coloured materials, such as asphalt, reducing air conditioning demands in the summer.
Construction costs	Concrete structures, especially those using post-tensioned floors and/or precast concrete, are the most economical structural solution for multi-storey buildings.

[1] Brown, Gordon E., Analysis and History of Cement, Gordon E. Brown Associates, Keswick, Ontario, 1996.

[2] IEA, WBCSD. Cement Technology Roadmap 2009 – Carbon emissions reductions up to 2050. Paris, France: International Energy Agency [IEA], World Business Council for Sustainable Development [WBCSD].

Whole-of-life value	Concrete's range of inherent benefits including thermal mass, fire resistance and durability means that concrete buildings tend to have lower operating costs and lower maintenance requirements
Construction duration	Construction of concrete framed buildings requires only short lead-in times; with modern formwork systems, floor-to-floor construction periods can be reduced
Durability[3]	When a structure is built with concrete, it is built to last. Concrete is a building material that gains strength over time. Concrete's 100-year service life conserves resources by reducing the need for reconstruction. Concrete is durable - it resists weathering, erosion and natural disasters, needs few repairs and little maintenance, adding up to a solid investment
Waste management	Concrete can be produced in the quantities needed for each project, reducing waste. Concrete waste can be recycled into aggregate for use in new pavements or as backfill or road base.

Source: Adapted from Cement Concrete & Aggregates Australia (2010)[4]

1.1 Types of concrete

This section provides information about various types of concrete that are currently used in the construction industry. These types are classified based on the constituents, their mix ratio and other properties such as strength, weight, density, porosity and time of setting. Furthermore, the main applications of these concerts are provided in Table 2. In total, 24 main concretes types that have the most frequent usage in Australia, and other developing nations are identified. The information tabulated in Table 2 is primarily sourced from The Constructor (2017)[5].

[3] Concrete Sask. 2016. Why is concrete better? http://www.concretesask.org/resources/why-is-concrete-better

[4]Cement Concrete & Aggregates Australia. 2010. Sustainable Concrete Buildings. https://www.ccaa.com.au/imisprod/documents/Library%20Documents/CCAA%20Technical%20Publications/CCAA%20Briefings/Briefing13.pdf

[5]The Constructor. 2017. 23 Types of Concrete Used in Construction and their Applications. https://theconstructor.org/concrete/types-concrete-applications/19779/

Table 2. Various types of concrete and their applications

Type	Characteristics	Main application
Normal Strength Concrete	The concrete that is obtained by mixing the basic ingredients cement, water and aggregate will give us normal strength concrete.	It is used in concrete mixing.
Ordinary Concrete	The plain concrete will have no reinforcement in it. The main constituents are cement, aggregates, and water.	It is used in pavements, kerbs and the buildings, especially in areas where there is less demand for high tensile strength.
Reinforced Concrete	A concrete to which reinforcement is introduced to bear the tensile strength. The steel reinforcement used in the concrete can be in the form of rods, bars or in the form of meshes. Recently, steel fibres are also developed as reinforcement.	It is used in slab, wall, beam, column, foundation, and frame construction.
Prestressed Concrete	This is a special technique in which the bars or the tendons used in the concrete is stressed before the actual service load application.	It is used in bridges, heavily loaded structures, and roof with longer spans.
Precast Concrete	The precast concrete units are made and cast in the factory as per the specifications and bought to the site at the time of assembly.	It is used in structural components such as; wall panels, beams, columns, floors, staircases, pipes, tunnels.
Light-weight Concrete	It has a density lesser than 1920 kg/m^3 will be categorised as lightweight concrete and are made of lightweight aggregates such as pumice, perlites, and scoria.	It is used in floor slabs, window panels and roofs.
High-density Concrete	Made up of heavy-weight aggregates such as crushed rocks and Barytes, this kind of concrete has densities between 3000-4000 kg/ m^3. The heavy-weight aggregate will help the structure to resist all possible type of radiations.	It is used in atomic power plants and for similar projects.
Air Entrained Concrete	A concrete into which air is intentionally entrained through foams or gas (i.e. foaming agents: resins, fatty acids and alcohols) for an amount of 3 to 6% of the concrete. These air pockets relieve internal pressure on the concrete by providing tiny chambers for water to expand into when it freezes.	It is used in parking structures, bridge decks, highway pavements, curbs, and sidewalks in cold regions. Also, it applies to structures that are exposed to moisture, freeze-thaw cycles and de-icing chemicals.
Ready Mix Concrete	A type of concrete that is mixed and bathed in a central mixing plant. The method of mixing will also be specified and are developed for the specialist application.	It is used in bridges, walls, piles, support walls, tunnel, covered trenches, retainment, bulkheads, tiles, columns, and girders.
Polymer Concrete	In this type of concrete, a polymer material is used to bind aggregates instead of cement. Using polymer helps with the reduction of volume of voids in the aggregates. There are	It is used in engineering structures, including aircraft, helicopters, offshore

	three categories that come under this type of concrete: polymer impregnated concrete, polymer cement concrete, and partially impregnated. Epoxy is the largest category of this concrete due to its increasing use in construction and its superior properties of high impact strength, high vibration resistance, good bonding with concrete and metal surfaces.	platforms, and others and also used in biomedical devices and civil structures.
High-Strength Concrete	This concert is yielded through the reduction in the water-cement ratio even lower than 0.35. This ratio gives a concrete strength greater than 40MPa.	It is used in high-rise structures such as columns (especially on lower floors where the loads will be greatest), shear walls, and foundation. It is also used in bridge applications such as highway bridges.
High-Performance Concrete	This type of concrete is made according to a particular standard, but they are not limited to strength. Some examples of standards include strength gain in early age, easy placement of the concrete, permeability and density factors, long life and durability and environmental concerns.	It is used in long-span bridges, high-rise buildings or structures, highway pavement[6].
Self- Consolidated Concrete	This concrete that is also known as flowing concrete is compacted by its own weight is regarded as self-consolidated concrete. No vibration must be provided for the same separately.	It is used in road and bridge projects.
Shotcrete Concrete	This type of concrete is shot into the frame or the prepared structural formwork with the help of a nozzle. As the shooting is carried out in higher air pressure, the placing and the compaction process will be occurring at the same time.	Concrete repairs or placement on bridges, dams, pools, and on other applications where forming is costly, or material handling and installation is difficult.
Pervious Concrete	A type concrete that is designed to allow the water to pass through it. These types of concrete will have 15 to 20% voids of the volume of the concrete when they are designed.	It is used in pavements and driveways where stormwater issues persist.
Vacuum Concrete	In this type of concrete, the material with water content more than the required quantity is poured into the formwork. The excess water is then removed out with the help of a vacuum pump without waiting for the concrete to undergo setting. As a result, the concrete structure will be ready to use earlier when compared with normal construction technique.	It is used in industrial floor sheds such as cold storages, hydropower plants, bridges ports and harbours, cooling towers.

[6] Rana, N., Tiwari, A. and Srivastava, A.K., 2016. High performance concrete and its applications in the field of civil engineering construction. *International Journal of Current Engineering and Technology*, 6(3), 982-985.

Pumped Concrete	This concrete is fluid in nature to be easily conveyed through a pipe. It has enough fine material as well as water to fill up the voids. The more the finer material used, the greater will be control achieved on the mix.	It is used in high rise buildings and large mega construction projects.
Stamped Concrete	It is an architectural concrete where realistic patterns similar to natural stones, granites, and tiles can be obtained by placing an impression of professional stamping pads. This stamping is carried out on the concrete when it is in its plastic condition.	It is used in parking lots, pavements, walkways.
Limecrete	In this concrete, cement is replaced by lime. Unlike cement-based concrete, these types of concrete have many environmental and health benefits. These products are renewable and easily cleaned.	It is used in floors, domes as well as vaults.
Asphalt Concrete	It is a composite material, mixture of aggregates and asphalt. This kind of concrete is also known as asphalt, blacktop, tarmac, bitumen macadam or rolled asphalt.	It is used to surface roads, parking lots, airports, as well as the core of embankment dams.
Roller Compacted Concrete	This concrete is placed and compacted with the help of earthmoving equipment like heavy rollers. It has cement content in a lesser amount and filled for the area necessary. After compaction, this concrete provides high density and finally cures into a strong monolithic block.	Excavation and filling needs.
Rapid Strength Concrete	A type of concrete that acquires strength with few hours after its manufacture.	It is mainly in road repair projects. Also, in the airport, building floor, dockyard, formed work, parking area, rail network, and road/bridge.
Glass Concrete	It is a type of concrete into which a recycled glass is used. The recycled glass increases the aesthetic appeal of the concrete and provides long-term strength and better thermal insulation.	It is used in exterior cladding panels.
Fly ash concrete	This concrete has fly ash as a substitute to fine aggregates or cement or partially both. Fly ash improves workability in the fresh concrete and durability and strength in hardened concrete.	It is used in brick manufacture and pavements.

Source: Adapted from 'The Constructor' (2017)[5]

1.2 Concrete applications

Due to the features outlined in Table 1, concrete has a wide range of applications in the construction industry as well as other relevant industries. Concrete is used in large quantities almost everywhere; mankind has a need for infrastructure. Figure 1 exhibits some of the most common applications of concrete as a construction material in various industries.

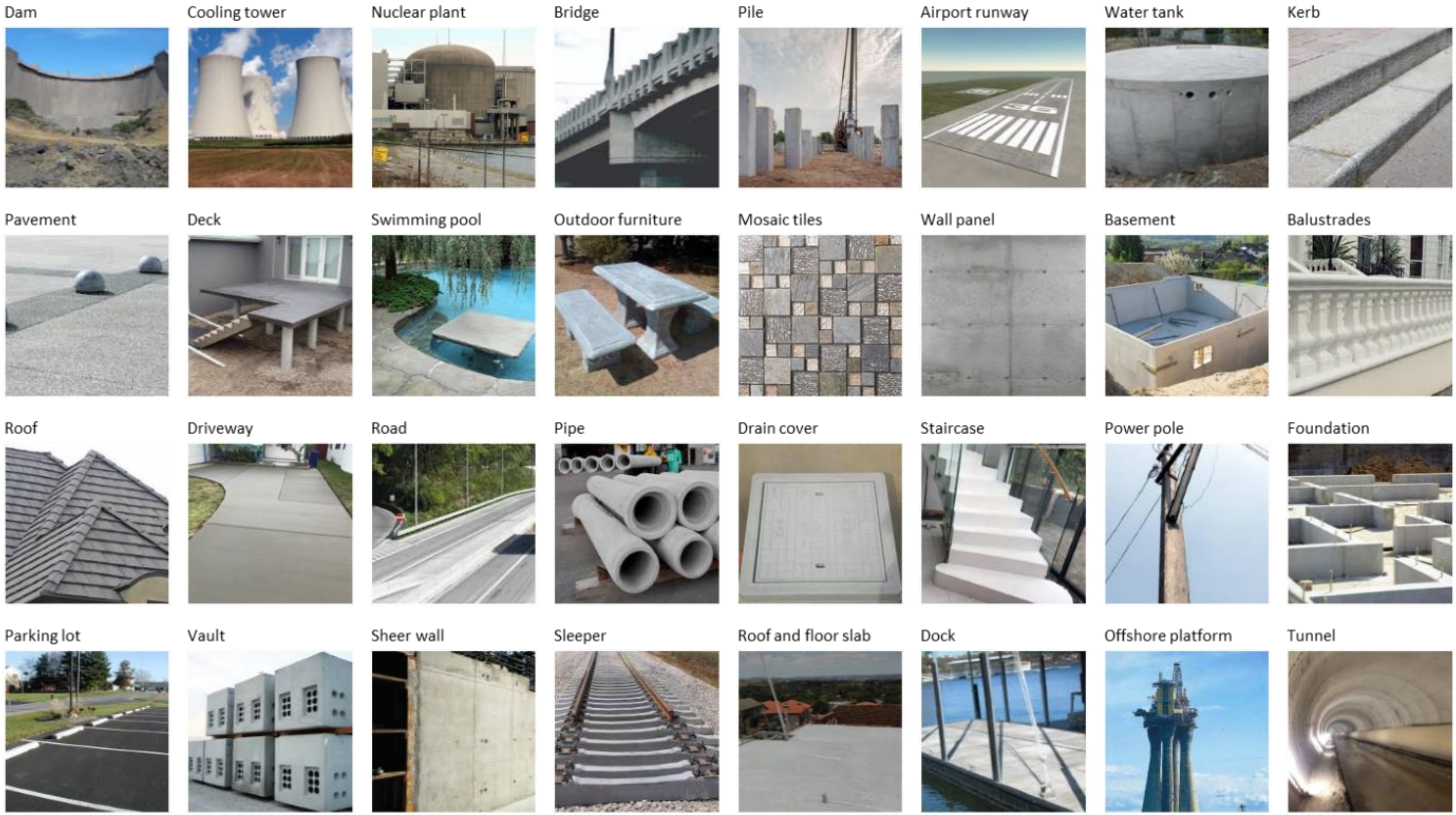

Figure 1. Different applications of concrete in the construction and relevant industries

2 CONCRETE MANUFACTURING INDUSTRY OVERVIEW

Operators in the Concrete Product Manufacturing (CPM) industry produce concrete products, including aerated and composite products. Downstream sectors use industry products for a range of construction and ornamental applications.

Table 3. Key drivers and the major industries dealing with the concrete product manufacturing industry (demand & supply)

Key economic drivers	Demand industries	Supply industries
Demand from residential building construction	Mining	Cement and Lime Manufacturing
Demand from heavy industry and other non-building construction	Water Supply	Electricity, Gas, Water and Waste Services
Demand from non-residential building construction	House Construction	Metal and Mineral Wholesaling
Actual capital expenditure on mining	Road and Bridge Construction	Rock, Limestone and Clay Mining
Capital expenditure by the public sector	Heavy Industry and Other Non-Building Construction	Cement and Lime Manufacturing
Demand from road and bridge construction	Commercial and Industrial Building Construction	

Source: IBISWorld 2019[7]

2.1.1 The domestic price and industry-current performance

The CPM industry produces a diverse range of products for use across many construction markets. Consequently, varying demand conditions across the downstream construction markets have influenced the industry's performance over the past five years. IBISWorld[7] reports that domestic demand for concrete products has increased due to strong growth in the commercial building and apartment construction markets.

IBISWorld[7] forecasts the domestic price of concrete, cement and sand to rise by 1.5% in 2019-20, to 111.3 index points. Growth is anticipated to slow compared to the previous year, due to falling demand from residential building construction. However, this is expected to be mitigated by road and bridge construction, which is anticipated to have high demand due to a large array of both state and federal government-funded infrastructure projects. Overall, there are four key external factors that impact the current industry performance:

- Demand from residential building construction
- Demand from heavy industry and other non-building construction
- Actual capital expenditure on mining
- Capital expenditure by the public sector
- Demand from road and bridge construction

[7] IBISWorld. 2019. Concrete Product Manufacturing in Australia: IBISWorld Industry Report C2034.

Demand from residential building construction

Residential building construction is the main source of demand for concrete products (i.e. concrete bricks and roof tiles, building boards and pavers). Demand from this sector is expected to decline over 2018-19, following the completion of several major apartment developments, which poses a threat to industry revenue growth.

Demand from heavy industry and other non-building construction

The decline in demand from infrastructure construction over the past five years[7] has limited the demand for a range of concrete products (i.e. sleepers, tensioning posts and concrete storage tanks) used in this sector. Demand from heavy industry and other non-building construction is expected to decline during 2018-19, which will likely reduce demand for precast concrete pipes, box culverts and other structural concrete products.

Actual capital expenditure on mining

Capital expenditure on mining development, which increases the demand for a range of heavy construction products (i.e. concrete pipes and box culverts, concrete beams, panels, tubes, poles and railway sleepers), has declined over the past five years and is expected to continue declining sharply during 2018-19, constraining the pace of industry expansion. Following a surge in investment in new mine development in 2012-13, the Mining division has now moved to the production phase as most of these development projects have been completed.

Capital expenditure by the public sector

The public sector manages a large number of construction projects (i.e. water, sewerage, drainage, telecommunications, power and energy, and road and bridge infrastructure) across Australia. Many of these projects use concrete products and, as a result, the CPM industry is sensitive to the fluctuations in the public sector capital expenditure. Public-sector capital expenditure is expected to grow significantly in 2018-19, which may provide an opportunity for industry operators to supply more concrete products to railway, telecommunication and road projects.

Demand from road and bridge construction

Road and bridge construction impact the demand for concrete products (i.e. beams, tensioning posts, traffic barriers, precast columns and light poles). This market has grown significantly since the mid-2000s, supporting demand for industry products. Several large-scale road developments, notably NorthConnex and WestConnex in NSW and the West Gate Tunnel in Vic, drove demand from road and bridge construction to a record peak in 2017-18. Demand from road and bridge construction is expected to decline marginally during 2018-19 but remain high.

2.1.2 Major markets

The residential and non-residential building markets represent the principal source of demand for concrete products. The prime building contractors or project developers, including individual homeowners or property developers, generally fund the procurement of concrete products for building projects[7].

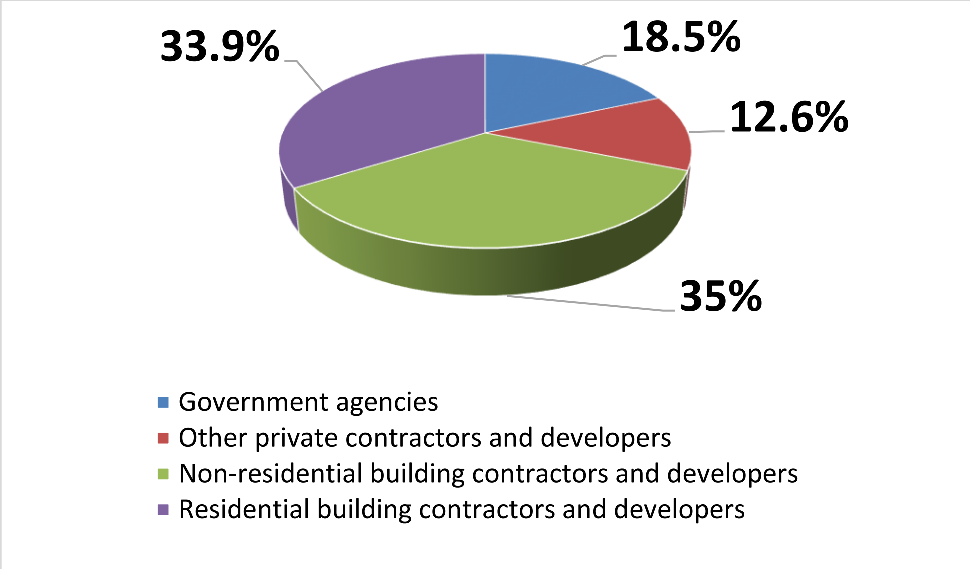

Figure 2. Major concrete markets identified in Australia
Source: IBISWorld[7]

2.1.3 Major producers in Australia

The major producers of concrete products in Australia include Fletcher Building Limited (19.1%), James Hardie Industries Public Limited Company (17.7%), CSR Limited (15.1%), Brickworks Ltd (10.80%), Holcim (Australia) Holdings Pty Ltd, Adelaide Brighton Ltd (5.1%), and others (23.6%).

3 CONCRETE MANUFACTURING

3.1 Constituents

The ingredients of concrete include a binding material (e.g. cement or lime), a fine aggregate (e.g. sand or other such materials), coarse aggregate (e.g. gravel, crushed rocks or other alike materials) and water. Other constituents such as admixtures, pigments, fibres, polymers and reinforcement can be incorporated to modify the properties of the plastic or hardened concrete.

3.1.1 Cement

The function of a Binding material (Cement or Lime) is to bind the coarse and fine aggregate particles together. Although "Portland Cement" is the most common binding material used as a binder in a mixture, much research has been done to prove that lime (especially Hydraulic Lime) can also be used successfully as a binding material in a common type of construction. Lime is economical as compared to cement and is also strong enough for the ordinary type of construction. In 2017-18, the Australian cement industry recorded a turnover of A$2.4 billion, employing more than 1,300 directly and more than 5,000 indirectly—many based in regional Australia[8].

3.1.2 Water

Water is the main component of the concrete mix. Water plays a vital role in the process of the chemical reaction of cement and aggregate.

3.1.3 Aggregate

The function of Fine aggregates serves the purpose of filling all the open spaces in between the coarse particles. In this way, the porosity of the final mass is decreased. The maximum particle size in fine aggregates is always less than 6.35 mm. However, sand is commonly and universally used as a fine aggregate, and its grain size is around 2 mm. The function of coarse aggregates is to act as the main load-bearing component of concrete. When a good number of coarse aggregate fragments (all more than 6.35 mm in diameter) are held together by a cementing material, their behaviour towards the imposed loads is just like a solid rock mass. Gravel and crushed stone are commonly used for this purpose.

3.2 Products overview

In this section, the concrete production process is outlined. Understanding the concrete manufacturing conditions can provide a basis for waste minimising opportunities during manufacturing.

3.3 Manufacturing process

The specification, production and delivery of concrete are achieved in different ways. Production of concrete requires meticulous care at every stage. Manufacturing of concrete that is based on Portland cement (Figure 3) includes the following stages[9]:

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[8] Cement Industry Federation. 2017. Australian Cement Industry Statistics. http://www.cement.org.au/Portals/0/ Documents/ Fast%20Facts/CIF%20Fast%20Facts%202018.pdf

[9] Made How platform. 2015. Volume 1. Concrete. http://www.madehow.com/Volume-1/Concrete.html

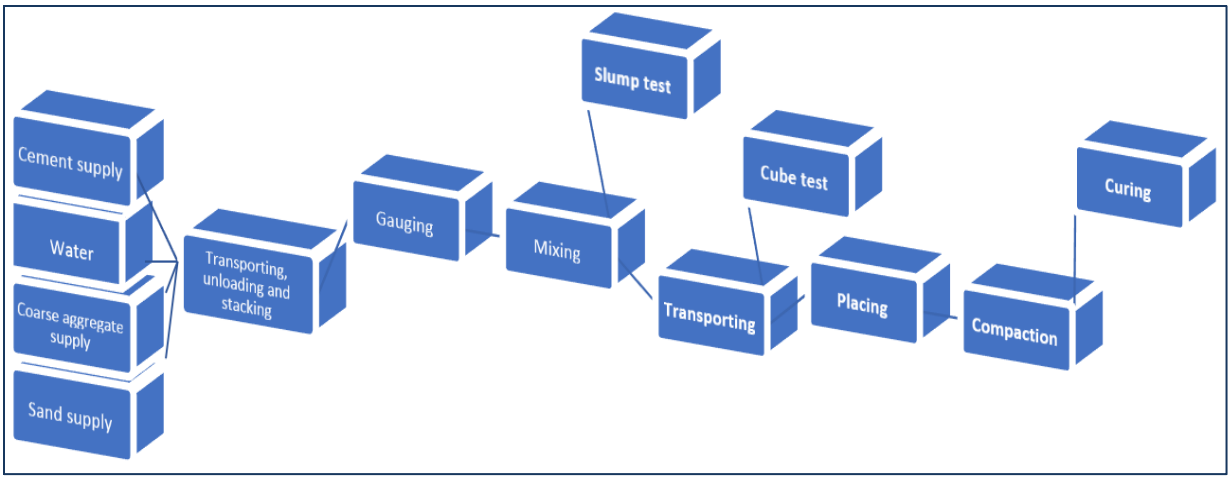

Figure 3. Schematic view of a typical concrete production process

Preparing Portland cement- The first step in making concrete is to prepare the cement. One type of cement, Portland cement, is considered superior to natural cement because it is stronger, more durable and of more consistent quality. The limestone, silica and alumina that make up Portland cement are dry ground into a very fine powder, mixed together in predetermined proportions, preheated and calcined (heated to a high temperature that will burn off impurities without fusing the ingredients). Next, the material is burned in a large rotary kiln at 1,400 °C. At this temperature, the material partially fuses into a substance known as clinker.

The clinker is then cooled and ground to a fine powder in a tube or ball mill. A ball mill is a rotating drum filled with steel balls of different sizes (depending on the desired fineness of the cement) that crush and grind the clinker. Gypsum is added during the grinding process. The final composition consists of several compounds: tricalcium silicate, dicalcium silicate, tricalcium aluminate and tetracalcium aluminoferrite.

Mixing- The cement is then mixed with the other ingredients: aggregates (sand, gravel or crushed stone), admixtures, fibres and water. Aggregates are pre-blended or added at the ready-mix concrete plant under normal operating conditions. The mixing operation uses rotation or stirring to coat the surface of the aggregate with cement paste and to blend the other ingredients uniformly. A variety of batch or continuous mixers is used. Fibres, if desired, can be added by a variety of methods including direct spraying, premixing, impregnating or hand laying-up. Silica fume is often used as a dispersing or densifying agent.

Transporting- Once the concrete mixture is ready, it is transported to the worksite. There are many methods of transporting concrete, including wheelbarrows, buckets, belt conveyors, special trucks and pumping. Pumping transports large quantities of concrete over large distances through pipelines using a system consisting of a hopper, a pump and the pipes. Pumps come in several types—the horizontal piston pump with semi-rotary valves and small portable pumps called squeeze pumps. A vacuum provides a continuous flow of concrete, with two rotating rollers squeezing a flexible pipe to move the concrete into the delivery pipe.

Placing and compacting- The next stage is to place and compact the concrete. These two operations are performed almost simultaneously. Placing must be done so that segregation of the various ingredients is avoided and full compaction—with all air bubbles eliminated—can be achieved. Whether chutes or buggies are used, the position is important in achieving these goals. The rates of placing and of compaction should be equal; the latter is usually accomplished using internal or external vibrators. An internal vibrator uses a poker housing a motor-driven shaft. When the poker is inserted into the concrete, controlled vibration occurs to compact the concrete. External vibrators are used for precast or thin in situ sections having a shape or thickness unsuitable for internal vibrators. These types of vibrators are rigidly clamped to the formwork, which rests on an elastic support. Both the form and the concrete are vibrated. Vibrating tables are also used, where a table produces vertical vibration by using two shafts rotating in opposite directions.

Curing- After placing and compacting, the concrete must be cured before it is finished to make sure that it doesn't dry too quickly. Concrete's strength is influenced by its moisture level during the hardening process: as the cement solidifies, the concrete shrinks. If site constraints prevent the concrete from contracting, tensile stresses will develop, weakening the concrete. To minimise this problem, concrete must be kept damp during the several days it requires to set and harden.

4 REGULATIONS, POLICIES AND GUIDELINES

The management of concrete waste is regulated at the state and territory level and can vary accordingly. A list of current jurisdictional C&D waste regulations and policies that apply to concrete waste is provided in Research No.2[10].

Due to the huge volume of concrete waste rubbles, health and safety issues during waste collection, particularly in demolition projects, is of importance. Furthermore, the presence of asbestos can present a serious threat to the labourers at a worksite. There are a number of policies and guidelines that provide best practice management or obligatory requirements in dealing with hazardous situations when concrete waste needs to be managed. However, these regulations are not consistent across Australia; while some states heavily regulate C&D waste, others have a more relaxed approach. Take Victoria and concrete waste as an example. The following regulations are in place:

- Occupational Health and Safety Act 2004 (Victorian Government)
- Occupational Health and Safety Regulations 2007 (Victorian Government)
- Guide to Best Practice at Resource Recovery Centres (Sustainability Victoria)
- Code of Practice for Manual Handling 2000 (Work Safe Victoria).
- The Occupational Health and Safety (Asbestos) Regulations 2003 (EPA Victoria).
- Industrial Waste Resource Guidelines Asbestos Transport and Disposal
- Recycling Construction and Demolition Material: Guidance On Complying with The Occupational Health and Safety (Asbestos) Regulations 2003 (WorkSafe Victoria) – Compliance Code: Managing asbestos in workplaces (WorkSafe Victoria).

Cement Concrete & Aggregates Australia (CCAA) has provided a number of industry guidelines that are relevant to the production and placement of concrete. The guidelines aim to assist concrete plants, truck manufacturers and drivers in operating safely, and to minimise the concrete waste during their operation. Table 4 provides a snapshot of these industry guidelines that have been published recently.

Table 4. CCAA's industry guidelines

Guideline	Description	Date of release
Environmental Management Guideline for Concrete Batch Plants	This risk-based guideline provides guidance to operators of concrete batch plants to help them comply with their general environmental duty.	2019
Guideline for End Tipper Unloading Exclusion Zones	This guideline has been developed to provide an industry-wide consistent approach for End Tipper Unloading Exclusion Zones to ensure that aggregate material is delivered safely to customer sites.	2019
Concrete Pump Delivery Guidelines	To reduce the unacceptable safety risks that may be involved in the delivery of concrete to on-site pumps, CCAA has developed a new industry guidelines document and checklist.	2019
Guideline for End Tipper Unloading Exclusion Zones	This guideline has been developed to provide an industry-wide consistent approach for End Tipper Unloading Exclusion Zones to ensure that aggregate material is delivered safely to customer sites.	2019

[10] Maqsood, T. P.SP Wong, M. Khalfan, R. Yang and S. Shooshtarian. 2019. Discrepancies in regulations governing C&D waste and recommendations for reforms. https://sbenrc.com.au/app/uploads/2019/09/Research-Report-1-OBJECTIVE-1.pdf

Guideline for Pedestrian and Traffic Management at Concrete Plants	To assist industry in considering pedestrian and traffic safety at concrete plants, CCAA has developed a Guideline for Pedestrian and Traffic Management at Concrete Plants. The guideline identifies the range of pedestrian and traffic movements at concrete plants.	2018
Guidelines for Delivery of Bulk Cementitious Products to Premixed Concrete Plants	This document is intended primarily to provide a standardised approach for the pneumatic transfer of bulk cementitious powders into silos used by the premixed concrete industry.	2018
New South Wales Concrete by-product Recycling and Disposal Industry Guidelines	NSW legislation and regulations require that all operators must minimise the number of new resources used in the production process, ensure that as much material as possible is re-used or recycled and that any waste that cannot be re-used is disposed of.	2014
Best Practice Guidelines For Concrete By-Product Re-Use At Concrete Batching Plants Queensland	This document provides the industry with best practice management guidelines for concrete by-product re-use management that meets legislative requirements.	2012

Source: Cement Concrete & Aggregates Australia[11]

Another set of regulations deals with the use of recycled concrete waste materials in construction projects such as roads and pavements. The Standard Specifications regulate and maintain the quality and provide producers as well as consumers an assurance of uniformity and consistency in quality of the recycled aggregate. For instance, in Victoria, Vicroads, which is a state authority managing the road and traffic, has provided a code of practice[12] that outlines the specifications of recycled crushed concrete for application in the state road and pavement bases/subbase. In NSW, Roads and Maritime Services (RMS) has set specifications for granular pavement base and subbase materials[13]. Later, EPA NSW published a guideline entitled "Specification for Supply of Recycled Material for Pavements, Earthworks and Drainage 2010 (Greenspec)"[14], which was set to encourage local government professionals and other key players within both the private and public works engineering sector to use recycled concrete, brick and asphalt materials. Other states also have their own version of code of practice for recycled concrete. However, similar to environmental regulations, the specifications provided in codes are not uniform[15].

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[11] CCAA. 2019. https://www.ccaa.com.au/iMIS_Prod/CCAA/Public_Content/LISTS/Industry_Guidelines.aspx

[12] Vicroads. 2017. Code of Practice RC 500.02. Registration of Crushed Rock Mixes. https://www.vicroads.vic.gov.au/-/media/files/technical-documents-new/codes-of-practice-rc500/code-of-practice-rc-50002--registration-of-crushed-rock-mix-designs-july-2017.ashx

[13]RMS. 2008. ROADS AND MARITIME SERVICES (RMS) . RT 3051 https://www.rms.nsw.gov.au/business-industry/partners-suppliers/documents/specifications/3051.pdf

[14]EPA NSW. 2011. IPWEA Roads & Transport Directorate https://www.epa.nsw.gov.au/~/media/EPA/Corporate%20Site/resources/waste/100004-supply-recycled-material.ashx

[15] Gabr, A.R., Cameron, D.A., Andrews, R. and Mitchell, P.W., 2011. Comparison of specifications for recycled concrete aggregate for pavement construction. *Journal of ASTM International*, 8(10), 1-15.

Table 5. The standards and specifications guiding the use of recycled concrete

State	Title
ACT	N/A
NSW	Specification for Supply of Recycled Material for Pavements, Earthworks and Drainage 2010 (Greenspec)
QLD	Transport and Main Roads Specifications MRTS35 Recycled Material Blends for Pavements
NT	Standard specification for roadworks
SA	The standard for the production and use of Waste Derived Fill Recycled Fill Materials for Transport Infrastructure - Operational Instruction 21.6 Policy Specification: Part 215 Supply of Pavement Materials
TAS	Unbound Flexible Pavement Construction
VIC	VicRoads Standard Specifications for Roadworks and Bridgeworks VicRoads Codes of Practice
WA	Main roads Western Australia specification 501—pavements

5 CONCRETE WASTE GENERATION

Concrete waste is a large contributor to C&D waste volume worldwide. There are several sources of concrete waste and, accordingly, there are multiple concrete waste types based on the origin of generation. These may include concrete pavement waste, building structures concrete waste and unwanted delivered concrete to construction sites. However, there is no widely accepted classification for concrete waste. EPA NSW[16] has categorised concrete waste into four groups: concrete washings, concrete effluent, concrete delivered to a site but not used for the development and any other waste material containing concrete. Rakhimova and Rakhimov (2014) listed four types of concrete waste, namely: concrete waste, concrete waste powder, hydrated mortar concrete waste and ground concrete waste.

5.1 How much concrete waste is generated

Previous studies have shown that brick and concrete waste can account for 75% of C&D waste from a construction site[17,18]. In the US, 23.1 million tonnes of concrete waste were produced in construction activities alone in 2015; buildings are the second-largest source of this waste after bridges and roads[19].

Furthermore, there are studies suggesting that some materials are the highest waste generators than others by their own nature[20,21,22]. These studies reported that concrete, together with concrete, mortar, bricks, steel and ceramics/tiles are among the materials with a high rate of waste generation[20]. Analysis of wastage in five housing projects in Hong Kong showed that, among the six study materials (i.e. concrete, plastic, timber, glass, metal and paper), concrete waste was the largest producer of waste[23]. In WA, the Waste Authority reported that concrete waste was the second contributor (24%) to their overall C&D waste generated in 2015-16 by weight[24]. The latest data for concrete waste was reported in 2018[25] and was prepared by Blue Environment Pty Ltd and Randel Environmental Consulting. The concrete waste data for the period of 2016-17 is presented in Table 6. The individual data for the waste generation was only available for three jurisdictions: ACT, NSW and SA. Analysis of the table below shows that, among these three jurisdictions, NSW had 1,191.4 kt, from which 91.3% belonged to the C&D waste stream.

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[16] NSW EPA. 2017. Concrete waste. https://www.epa.nsw.gov.au/licensing-and-regulation/licensing/environment-protection-licences/authorised-officers/resources-and-training/concrete-wastes

[17] Crowther, P. 2000. Building Deconstruction in Australia, Kibert, Charles J., Chini, Abdol, R., eds., "Overview of Deconstruction in Selected Countries" CIB Report No. 252, 18-19.

[18] Formoso, C.T., Soibelman, L., De Cesare, C. and E.L. Isatto, 2002. Material waste in building industry: main causes and prevention. *Journal of Construction Engineering and Management*, 128(4), 316-325.

[19] Environmental Protection Agency, 2018. Advancing Sustainable Materials Management: 2015 Fact Sheet Accessed on Sep. 6th, 2018. https://www.epa.gov/sites/production/files/2018-07/documents/2015_smmmswfactsheet07242018_fnl_508_002.pdf

[20] de Magalhães, R.F., Danilevicz, Â.D.M.F. and Saurin, T.A., 2017. Reducing construction waste: A study of urban infrastructure projects. *Waste Management*, 67, 265-277.

[21] Hassan, S.H., Aziz, H.A., Adlan, M.N. and Johari, I., 2015. The causes of waste generated in Malaysian housing construction sites using site observations and interviews. *International Journal of Environment and Waste Management*, 15(4), 295-308.

[22] Song, Y., Wang, Y., Liu, F. and Zhang, Y., 2017. Development of a hybrid model to predict construction and demolition waste: China as a case study. *Waste Management*, 59, 350-361.

[23] Tam, V.W., 2011. Rate of reusable and recyclable waste in construction. *Open Waste Management Journal*, 4(1), 28-32.

[24] ASK Waste Management Consultancy Services. 2018. Recycling Activity in Western Australia 2015-16. Project No. 1603. http://www.wasteauthority.wa.gov.au/media/files/documents/WA_Recycling_Activity_15_16-Amended.pdf

[25] Department of Environment and Energy. 2018. P863 National waste data and reporting cycle 2017-19. https://www.environment.gov.au/system/files/resources/7381c1de-31d0-429b-912c-91a6dbc83af7/files/national-waste-report-2018-data.xlsx

Table 6. Concrete waste in Australian states and territories

	Waste Generation				Waste Landfill				Waste Recycling			
State	**MSW**	**C&I**	**C&D**	**TOTAL**	**MSW**	**C&I**	**C&D**	**TOTAL**	**MSW**	**C&I**	**C&D**	**TOTAL**
ACT	0	766	1,160	1,925	0	766	1,160	1,925	-	-	-	86,602
NSW	12,907	90,600	1,087,881	1,191,388	-	-	-	-	12,907	90,600	1,087,881	1,191,388
NT	-	-	-	-	-	-	-	-	-	-	-	-
QLD	-	-	-	-	-	-	-	-	-	-	-	1,476,739
SA	7,500	22,500	734,860	765,300	-	441	14,859	15,030	7,500	22,500	720,000	750,000
TAS	-	-	-	-	-	-	-	-	-	-	-	-
VIC	-	-	-	-	-	-	-	-	30,000	5,909	2,227,056	2,262,965
WA									2,291	1,900	235,271	239,462
TOTAL									**52,698**	**120,909**	**4,270,208**	**6,007,156**

Source: Department of Environment and Energy. 2016-17

6 WASTE MANAGEMENT

6.1 Waste during manufacturing

There are a large number of studies suggesting the replacement of the traditional ingredients of concrete that are freshly extracted from nature with recycled C&D waste materials. The primary ingredient that is replaced is aggregate[26]. There is an excessive need for aggregates in the production of concrete and other construction materials due to the massive construction projects taking place all over the world. Therefore, there is a business case for encouraging recycling facilities as well as construction material manufacturers to source a part of their need for aggregate from recycled materials. In 2014, the results of the analysis[27] of the consumption of aggregates showed a huge consumption of aggregates in various regions.

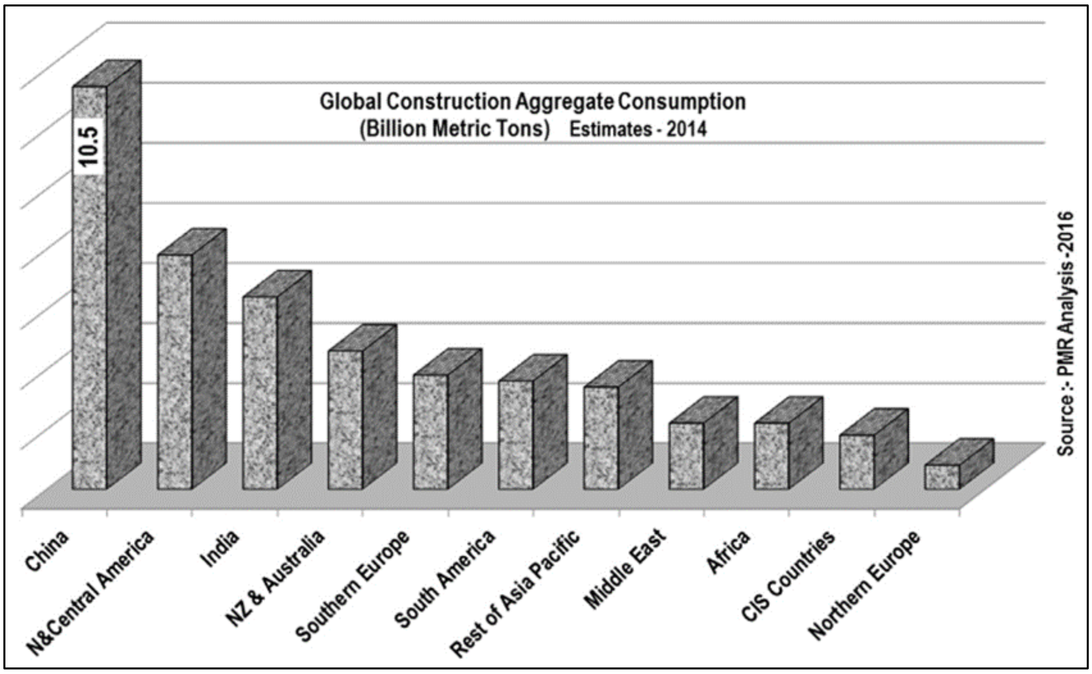


Figure 4. Worldwide consumption of recycled aggregate
Source: PMR Analysis (2016)

With some mechanical modifications, such as adding epoxy resin[28], crushed recycled concrete waste can also be used in the form of aggregate for brand new concrete if it is free of contaminants. The difference between natural aggregates and recycled concrete aggregates (RCA) include that RCA typically has higher water absorption and lower specific gravity[29]. The density of RCA is lower than the density of normal aggregates, and their porosity is also much higher than those of natural aggregates[30].

[26] Tam, V.W., Soomro, M. and Evangelista, A.C.J., 2018. A review of recycled aggregate in concrete applications (2000–2017). *Construction and Building Materials*, 172, 272-292.

[27] PMR Analysis. Global Market Study on Construction Aggregate. New York, USA, 2016

[28] Shahidan, S., Azmi, M.A.M., Kupusamy, K., Zuki, S.S.M. and Ali, N., 2017. Utilizing construction and demolition (C&D) waste as recycled aggregates (RA) in concrete. *Procedia Engineering*, 174, 1028-1035.

[29] Rao, A., Jha, K.N. and Misra, S., 2007. Use of aggregates from recycled construction and demolition waste in concrete. *Resources, Conservation and Recycling*, 50(1), 71-81.

[30] Marinković, S.B., Ignjatović, I.S., Radonjanin, V.S. and Malešev, M.M., 2012. Recycled aggregate concrete for structural use– an overview of technologies, properties and applications. In Innovative Materials and Techniques in Concrete Construction (pp. 115-130). Springer, Dordrecht.

A case study[31] in Australia commissioned by construction and demolition materials recycler, the Alex Fraser Group, found that recycled crushed concrete offers superior performance, compared with its virgin counterpart, is cheaper and is better from an environmental perspective. The findings from this case study are:

1. Crushed concrete has 65% less of a carbon footprint than equivalent quarried material;
2. It is softer, resulting in less energy to crush than relative virgin rock;
3. It is 20–25% less dense than crushed rock, so fewer trucks are required for delivery;
4. Since cost is calculated on a weight basis, it is cheaper than crushed rock;
5. It can offer better performance in wet weather; and
6. There is the reliability of supply and convenience of locations, leading to cheaper disposal of waste concrete.

Sustainability Victoria[32] reported that anecdotal evidence indicates that crushed concrete is quicker and easier to lay and to compact. It is thought that improved compaction is due to the product being made up of smoother and rounder particles, with better distribution and a larger percentage of fines and binder particles in the mix.

However, despite all the research performed in this area, recycled aggregates from waste concrete are mostly used in lower quality product applications such as backfills and road sub-base material[30]. A review study[33] on recycled concrete in structural applications compiled various methods to improve the quality of RAC based on the previous studies; these include the addition of limestone filler, additional cement, polymer additives, mineral admixture, water-reducing admixtures, two-stage and three-stage mixing approaches, and steel fibre. In addition to the aggregates, other components of concrete can be replaced with C&D waste materials such as filler, cement and freshwater. The main C&D wastes that are found to offer benefits after being replaced are glass, brick, stone and timber. Table 7 provides a summary of some of the studies that investigate the use of recycled C&D waste in the production of concrete.

Table 7. Summary of studies investigating the use of C&D waste in the production of concrete.

Material	Summary of findings	Reference
Use of glass waste in the production of various cement-based concrete products	The findings of this investigation show encouraging results and opened up several outlets for recycling waste glass in the production of various concrete products, including architectural cement mortars, concrete paving blocks and self-compacting concrete.	Lu and Poon (2019)
Use of recycled concrete aggregates	The evaluation of recycled aggregate concrete in pavement construction under heavy traffic loads showed satisfactory performance.	Nassar and Soroushian (2016)
Use of recycled ceramic waste as fine and coarse aggregate for concrete production	The study proved that use of up to 50 % of crushed ceramics, as fine and coarse aggregates, could be used for concrete production exposed to high temperature.	Canbaz (2016)

[31]Environment Protection and Heritage Council. 2010. National Waste Report. https://www.environment.gov.au /system/files/ resources/af649966-5c11-4993-8390-ab300b081f65/files/national-waste-report-2010.pdf

[32] Sustainability Victoria. 2015. Market summary – recycled brick, stone and concrete. https://www.sustainability.vic.gov.au/-/media/SV/Publications/Government/Waste-and-resource-recovery/Recycled-materials-in-pavement/Market-Analysis-Bricks-Stone-Concrete-Sept-2014-PDF.pdf?la=en

[33] Senaratne, S., Lambrousis, G., Mirza, O., Tam, V.W. and Kang, W.H., 2017. Recycled concrete in structural applications for sustainable construction practices in Australia. *Procedia Engineering*, 180, 751-758.

Crushed brick as a coarse aggregate in concrete	The results demonstrated the durability of crushed bricks as a natural aggregate replacement at 25 and 50% and recommended to use the bricks in unreinforced concrete.	Adamson et al. (2015)
Use of granite industry waste in the production of concrete	The obtained test results were indicated that the replacement of natural sand by granite powder waste up to 15% of any formulation is favourable for the concrete making without adversely affecting the strength and durability criteria.	Vijayalakshmi et al. (2013)
Use of wood ash as a cement in concrete mix	Blended cement with wood ash as a partial Ordinary Portland Cement (OPC) replacement material has a higher standard consistency, initial and final setting time. Concrete and mortar mixtures containing wood ash increase magnitudes of water absorption in concrete mixtures. Inclusion of wood ash at low levels of cement replacement actually contributed towards the enhancement of compressive strength in concrete mixtures produced.	Cheah and Ramli (2011)
Use of waste marble aggregates in concrete	The results obtained show that the mechanical properties of concrete specimens produced using the marble wastes were found to conform with the concrete production standards and the substitution of natural aggregates by waste marble aggregates up to 75% of any formulation is beneficial for the concrete resistance.	Hebhoub et al. (2011)
Use of recycled brick waste powder as a mineral filler in asphalt concrete mixture	The results show that the mixtures prepared with recycled brick powder have better mechanical properties than the mixtures with limestone filler. Thus, it is promising to use recycled brick powder as a mineral filler in asphalt mixture.	Chen et al. (2011)
Use of ceramic waste in concrete production	Results show that concrete with 20% cement replacement, although it has a minor strength loss, possess increase durability performance. Results also show that concrete mixtures with ceramic aggregates perform better than the control concrete mixtures concerning compressive strength, capillary water absorption, oxygen permeability and chloride diffusion, thus leading to more durable concrete structures.	Pacheco-Torgal and Jalali (2010)
Use of timber waste as aggregate for special lightweight concrete	The aggregate is made from a recycled small wood chunk that undertakes blast furnace deoxidisation.	Tam and Tam (2006)

6.2 Waste reduction opportunities during the design, planning and contract

Errors during the design stage, rework and unexpected changes continue to contribute to concrete waste generation in construction activities around the world[34]. The rate of occurrence of design errors in the building sector is higher as a building consists of components that are designed by different project participants and are corrected only after the construction work has started on site, which can

[34] Won, J., Cheng, J.C. and Lee, G., 2016. Quantification of construction waste prevented by BIM-based design validation: Case studies in South Korea. *Waste Management*, 49, 170-180.

lead to rework and construction waste[35]. Recently utilisation of the Building Information Technology (BIM) has come to the assistance of designers to reduce concrete waste in the construction industry. By definition, BIM is a parametric component-based, three-dimensional reference structure modelling system created using file formats that allow all disciplines involved in the project life cycle to exchange their data. In the broader context, BIM is a new approach to design and construction beyond modelling[36]. BIM, at the design stage, can be beneficial in minimising waste in different ways. For instance, Won et al. (2017)[34] indicated that the use of BIM could reduce improper design, residues of raw materials and unexpected changes in building design and improve procurement, site planning and material handling in construction management. The following table provides some information on how BIM can benefit the construction industry in minimising the waste that might be generated at a construction site.

Table 8. Various BIM-based methods that prevent the generation of concrete waste at the design stage

Method	Case study	Results	Reference
Analysing reinforced concrete structures to reduce reinforcement waste by selecting proper lengths of rebars and considering available cut-off lengths	N/a	BIM was utilised to simulate architectural and structural design requirements and to compare results in order to make the necessary changes in the design to reduce and reuse rebar waste.	Hewage and Porwal (2011)
BIM-based design validation was conducted to improve the design quality. Practitioners found 381 and 136 design errors by conducting BIM-based design validation in the first case.	Two case projects in South Korea included two residential buildings, which are reinforced concrete structures with a total floor area of about 120,000 m^2 and a sports complex with a total floor area of 9995 m^2	Concrete waste comprised the largest portion of construction waste prevented by BIM-based design validation in the two cases (98.3% and 95.6%)	Won et al. (2016)

6.3 Reducing waste during the procurement

In a study in the UK[37], prefabrication and procurement management were identified as the most recommended methods for minimising concrete waste. Tam (2011) indicated that accurate calculation and ordering the quantity of concrete needs to be practised to reduce potential waste. This researcher reported that the interviewed quantity surveyors explained that projects could not order concrete as the same calculation from bills of quantity without considering wastage. His observation showed that on-site practices tend to order 5-10% additional concrete to the construction site. One of the main problems is that organisations cannot afford to have not enough concrete for on-site concreting activities; otherwise, whole building structures will change. One possible strategy to tackle this

[35] Gavilan, R.M., Bemold, L.E., 1994. Source evaluation of solid waste in building construction. *Journal of Construction Engineering, and Management*. 120 (3), 536-555.
[36] Crotty, R. 2012. The Impact of Building Information Modelling: Transforming Construction, Spon Press, London, UK.
[37] Meibodi, A.B., Kew, H., Haroglu, H., 2014. Most popular methods for minimizing insitu concrete waste in the UK. New York Sci. J. 7 (12), 111–116.

problem is to use on-site mobile crushers that minimise the waste by crushing it as recycled aggregate for concrete production.

6.4 Reducing waste during transportation and delivery

Wilson and Kosmatka[38] summarised 15 methods and equipment for transporting and handling concrete. Depending on the construction site situations, some of these methods may have advantage in reducing the likelihood of concrete waste generation over the others. On any large construction sites requiring multiple deliveries, a washout area needs to be designated to let the water soak into the ground and not run over the land into the stormwater system or into streams[39].

6.5 Reducing waste during construction

Construction technology is proven to have a fundamental impact on the generation of construction waste. The adoption of prefabrication technology in the construction industry dates back to 1980s, when concrete was the first construction material that was prefabricated. Precast concrete was used to build a casino by François Coignet in Biarritz in 1891[40]. In 2002, a study[41] estimated a reduction of 70% in concrete waste by using prefabrication. Drawing on a set of interviews with construction practitioners, Tam (2011) suggested that the best way to reduce concrete waste is to use prefabrication instead of in situ concreting.

Another strategy to reduce waste during construction is to use structural steel. It is reported that steel caused a reduction in concrete and rebar waste.

One strategy that can reduce the concrete waste is providing education for labours who are indirectly involved in applying concrete into the construction project. In Australia, under the Continuing Professional Development (CPD) system, PointBuild[42], in partnership with the Concrete Masonry Association of Australia (CMAA) provides online training courses for construction professionals including work with concrete materials. The following table (Table 9) shows the courses relevant to the concrete industry and contributing to improving concrete waste management:

Table 9. The online courses provided by Pointsbuild®[42]

Course	Objectives
CMAA Introduction to Concrete Masonry and Pavers	This course provides a background on the benefits and advantages of concrete masonry and paving, and includes key industry concepts and terms to build your knowledge.
Designing Robust Concrete Structures	This learning module brings together two of Australia's leading experts in the design and understanding of robust concrete structures.
The durability of Concrete Structures	This Concrete Institute of Australia webinar provides an update on the work of the Institute Durability Committee and provides guidance on durability design processes and practice that satisfy requirements

[38] Wilson M.L and SH Kosmatka. 2011. Design and Control of Concrete Mixtures. Chapter 10: Batching, Mixing, Transporting, and Handling Concrete. https://scetcivil.weebly.com/uploads/5/3/9/5/5395830/batching_mixing_transporting_ handling_ concrete.pdf

[39] Taranaki Regional Council. 2013. Concrete washings and concrete cutting waste water. https://www.trc.govt.nz/assets/Documents/Guidelines/Industry-infosheets/BIinfo-concrete+washings.pdf

[40] Staib, G., A. Dörrhöfer, and M.J. Rosenthal, Components and Systems : Modular Construction : Design, Structure, New Technologies. 1st ed. 2008, Basel, Switzerland: Birkhäuser Verlag AG. 239.

[41] Lawton, T., Moore, P., Cox, K., Clark, J., 2002. The gammon skanska construction system. In: Proceedings of the International Conference Advances in Building Technology, Hong Kong, China, 1073–1080.

[42] PointsBuild®. https://www.pointsbuild.com.au/

Prefabricated Concrete Elements (Changes to AS 3850)	This seminar looks at the reforms made to the prefabricated concrete elements industry and to the Australian Standards documents, formally known as AS3850 Tilt-up Concrete Construction.

6.6 Reducing waste during demolition

If space permits, on-site mobile crushers are an excellent choice for concrete waste management through crushing the waste to aggregate that is usable in concrete production. Figure 5 shows the typical recycling process in stationary recycling plants, which are suitable as recycling centres in urban areas.

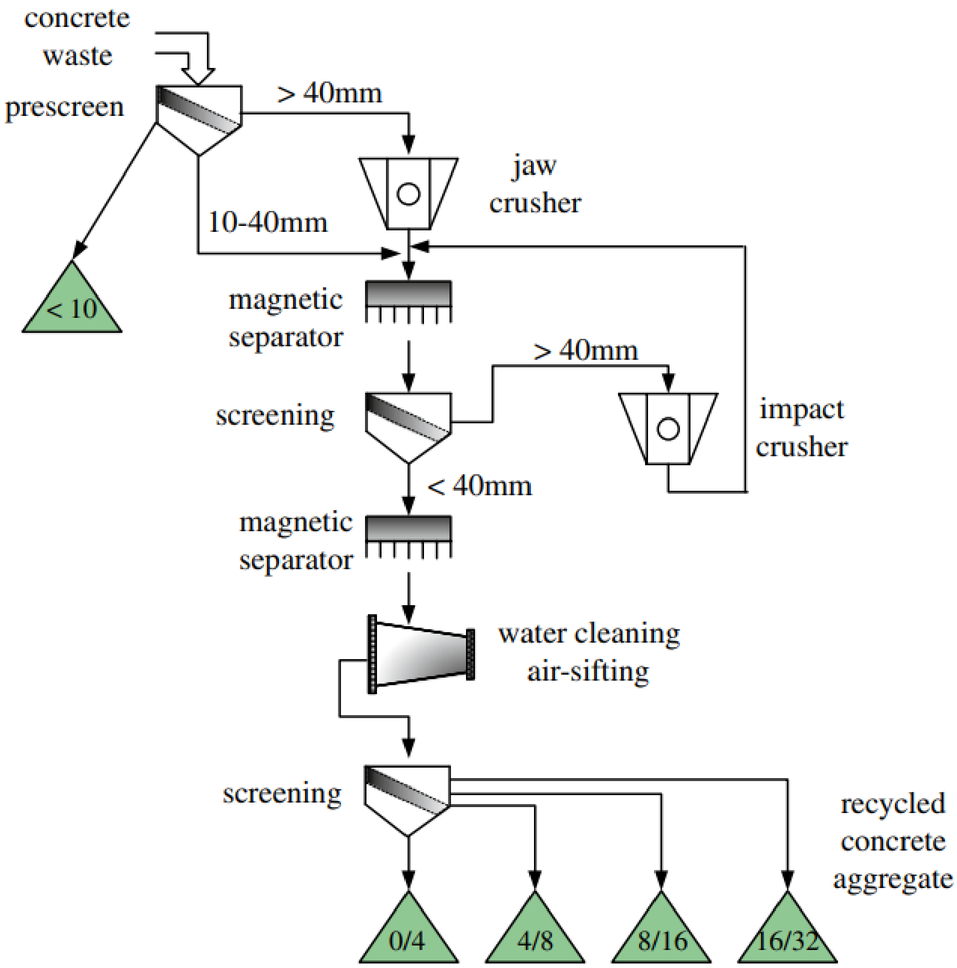


Figure 5. Concrete waste recycling process using an on-site recycle crusher
Source: Marinković et al (2012)[30]

In mobile recycling plants, the processing is limited to one-stage crushing, magnetic separation and screening. When demolished concrete is crushed, a certain amount of mortar and cement paste from original concrete remains attached to stone particles in recycled aggregate.

6.7 Reducing waste through reusing

Reusing concrete waste provided that it has an acceptable level of contamination is a typical practice in the construction industry. However, there are limitations in the level of reusing concrete waste. For instance, in NSW, Hardened Returned Concrete cannot be utilised for dams, mine, quarry and sand dredge rehabilitations, as backfill for voids, or utilised in reshaping land for agricultural purposes. However, this material can be applied to road construction on private land if the following conditions are met[43]:

- The relevant waste is applied to land to the minimum extent necessary for the construction of a road.
- Development consent for the development has been granted under the relevant Environmental Planning Instrument. It is to provide access (temporary or permanent) to a development approved by a local government.
- The works undertaken are either exempt or are a complying development. The material is applied to the land must be sampled and tested, as detailed in the general exemptions, to ensure that it will pose minimal risk of harm to the environment.

One study in Hong Kong[44] showed that the actual average rate of reusable and recycled concrete waste in five housing projects was 48%. This percentage for metal, timber, glass and paper was 64%, 58.5%, 29.6% and 83%, respectively.

There are some examples of construction with significant usage of RAC, including an office building with an open multi-storey garage, Vilbeler Weg, built in Darmstadt (**Error! Reference source not found.**). The complete reinforced concrete structure was constructed using RAC. Approximately 480 m^3 of RAC was built in, and RAC was applied for all in-door structural elements, as well as for the foundation slab in a residential building in Darmstadt, Germany (1998, **Error! Reference source not found.**).

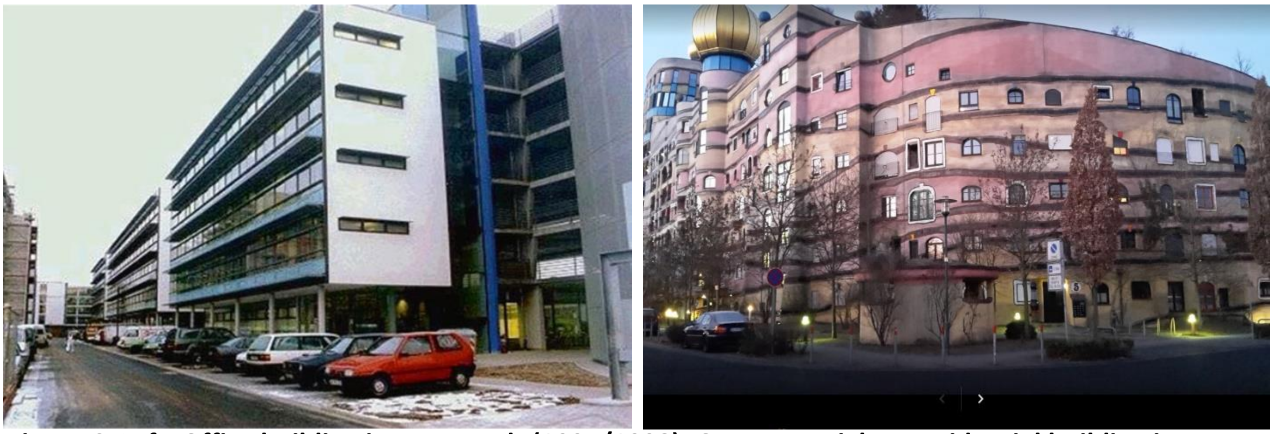


Figure 6. Left: Office building in Darmstadt (1997/1998), Germany, Right: Residential building in Darmstadt Germany.
Source: BIM (2010)[45]

[43] CCAA. 2014. New South Wales Concrete by-product Recycling and Disposal Industry Guidelines. https://www.ccaa.com.au/imis_prod/documents/Library%20Documents/CCAA%20Industry%20Guidelines/CCAA_Concrete%20Waste%20Guideline%20-%20FINAL%20(1).pdf

[44] Tam, V.W., 2011. Rate of reusable and recyclable waste in construction. *Open Waste Management Journal*, 4(1), 28-32.

[45] BIM. 2010. Projekte-Hinweise zur Bedienung. http://www.b-i-m.de/projekte/projframe.htm

Cement Concrete & Aggregates Australia has provided a guideline[46] on RCA specifications that reviews the various types of aggregates and their potential for use in concrete and/or road construction materials.

Crushed concrete can be reused in the landscape industry. It is possible to create a short planter or garden wall with broken pieces of concrete that are about the same height. Brief instruction for such an application is provided by All Round Soil and Stone blog[47]:

- Dig down 25cm to build a base for the wall.
- Add 8 cm of sand in the trench.
- Stack the broken concrete pieces to form an even wall.
- Check regularly with a level to make sure it is even.

6.8 Waste recovery (recycling and upcycling)

Recycling is a typical practice for concrete waste management, and it offers multiple benefits, including reduced costs of removing and hauling, elimination of high landfill fees and contribution to the production of lower-cost recycled aggregate products. Japan is a leading country in recycling concrete waste, with a recycling rate of 98% recycling; the recycled materials are used in structural concrete applications[48]. Also, in Denmark, only 2% of concrete and bricks generated are landfilled, with the remainder reused and recycled[49]. In Australia, it is common to mix recycled concrete aggregate with small amounts of crushed bricks and soil to obtain a recycled product considered suitable for use in pavements[50]. There are three main types of concrete waste-based aggregates: Recycled Concrete Aggregate (RCA), Recycled Concrete and Masonry (RCM), and Reclaimed Aggregate (RA). The performance of these materials is compared to Natural Aggregates (NA).

Table 10. Summary of studies investigating the applications of recycled concrete waste

	Application	Summary of findings	Reference
Upcycling	Oyster bed	In the USA, a novel application for recycled concrete aggregates was found in the construction of an artificial reef. Since the recycled material is being placed in a marine environment, concrete, particularly with high chloride content, is acceptable.	Presented in Tam et al. (2018)
	Use of Autoclaved Aerated Concrete (AAC) as lighting material in the structure of a green roof	The results showed some similarities between the study AAC and natural green roof characteristics. Based on the results, the authors indicated that the introduction of granular waste AAC within the structure of a green roof could help to reduce industrial wastes.	Bisceglie et al. (2014)

[46] Cement Concrete & Aggregates Australia. 2008. Use of Recycled Aggregates in Construction. https://www.ccaa.com.au/imis_prod/documents/Library%20Documents/CCAA%20Reports/RecycledAggregates.pdf

[47] All Around Soil and Stone. 2018. Uses for Recycling Concrete in Landscaping. https://www.soilandstone.com/recycling-concrete-landscaping/

[48] Tam, V.W., Tam, L. and Le, K.N., 2010. Cross-cultural comparison of concrete recycling decision-making and implementation in construction industry. *Waste Management*, 30(2), 291-297.

[49] Residua. 1999. Construction and Demolition Waste", Information Sheet in Warmer Bulletin, Issue 67, July 1999.

[50] Bakoss, S.L., Ravindrarajah, R.S., 1999. Recycled Construction and Demolition Materials for Use in Road Works and Other Local Government Activities: Scoping Report. University of Technology, Centre for Built Infrastructure Research, Sydney, 136.

	Use of recycled concrete as a gardening mulch	The resulting concrete mulch is an aesthetically pleasing landscaping ground cover that effectively and productively disposes of post-consumer waste.	Flynn (2010)
Recycling	Use of recycled concrete as alternative granular infills in hollow segmental block systems	RCAs are an alternative infill material for used for segmental retaining walls. The interface shear capacity (peak) of blocks infilled with RCA is almost equal to that of those with NA, and the grade of concrete has little or no effect on the frictional performance of the recycled concrete aggregate used in facing units.	Bhuiyan et al. (2015)
	Use of RCA in structural members such as beams, columns, slabs and walls	A C40 grade concrete, with up to 100% RCA, was used for all structural members (i.e. beams, columns, slabs and walls). The good experience acquired in the construction of this building enabled alterations in the building code requirements of Singapore to allow the use of RCA in all buildings.	Ho et al. (2015)

The Australian states have already started taking advantages of these materials in the construction industry. The following are some example of such applications:

Case Study 1 - Rehabilitation of existing pavement in a residential street: Fairfield City Council-Delgarno Road, Bonnyrigg Heights[14].

In this project, which used recycled concrete, the contractor engaged replaced 175m^2 of the failed pavement material with 150 m^2 of crushed concrete in 2002. Inspection after seven years shows that the pavement is still in excellent condition, with no defects being observed. Figure 7 shows the conditions of the rehabilitated residential road before and 7 years after improvement using crushed concrete.

Figure 7. Road conditions before and 7 years after reclimination with crushed concrete
Source: IPWEA NSW (2010)[14]

In the ACT, in 2018-2019 a program called Sustainable Roads[51] was launched whereby the roads in Canberra were rehabilitated using various waste materials including old car tyres, printer toner powder, recycled road surface, recycled road base, recycled concrete and fly ash from power generation. Recycled concrete was incorporated in roadbase and paths. In WA, upon successful application of crushed recycled concrete in several state projects, in 2018 a large infrastructure

[51] ACT Transport Canberra and City Services. 2019. Sustainable Roads. https://www.tccs.act.gov.au/roads-paths/Road_Infrastucture_and_Maintenance/road-resurfacing/sustainable-roads

project[52] (Kwinana Freeway Northbound Widening) has set out to maximise the use of recycled concrete. This eight km project is planned to consume 25 kt of recycled concrete as roadbase.

Case Study 2 - Samwoh Eco-Green Building in Singapore

The Samwoh Eco-Green Building (Figure 8) was the result of a demonstration project envisaging the construction of the first structure in Singapore using concrete with up to 100% RCA[53]. The objective of this project was to evaluate the feasibility of using RCA produced from C&D waste in structural concrete. This project involved two stages, including the extensive evaluation of the performance of concrete containing RCA, and construction and structural monitoring of a three-storey building containing the material. A C40 grade concrete, with up to 100% RCA, was used for all structural members (i.e. beams, columns, slabs and walls) of the building in the second stage of the project. In situ performance monitoring of the RAC was based on fibre-optic sensors installed to measure the columns' deformation. The good experience acquired in the construction of this building enabled alterations in the building code requirements of Singapore to allow the use of RCA in all buildings.

Figure 8. Using recycled concrete aggregate for building construction
Source: SAMWOH (2019)[54]

Metals coming from the C&D sector are also sourced from concrete reinforced with steel. In the demolition phase there can be a ratio of 80% concrete to 20% steel. Demolition companies recover and reprocess the concrete. However, a report in the context of Australia estimated that even after this processing of the steel, it generally has about 10% concrete (contamination) remaining with the steel[55].

[52] WA Main Roads. Kwinana Freeway Northbound Widening. 2019. https://project.mainroads.wa.gov.au/home/current/kwinanafreewayrusselltoroe/Pages/default.aspx

[53] Ho, N.Y., Lee, Y.P.K., Lim, W.F., Chew, K.C., Low, G.L. and Ting, S.K., 2015. Evaluation of RCA concrete for the construction of Samwoh Eco-Green Building. *Magazine of Concrete Research*, 67(12), 633-644.

[54] SAMWOH. 2019. Innovative solutions. https://www.samwoh.com.sg/careers/16-what-we-do/innovative-solutions.html

[55] Hyder Consulting and EnCycle Consulting & Sustainable Resource Solutions. 2011. Construction and Demolition Waste Status Report: Management of Construction and Demolition Waste in Australia, Department of Sustainability, Environment, Water, Population and Communities and Queensland Department of Environment and Resource Management.

6.9 Illegal dumping and stockpiling

There is a limited documented data about illegal dumping of concrete waste in Australia. As stipulated in Research Report No. 1, while there are hefty penalties for illegal dumping and stockpiling of C&D waste in some jurisdictions (e.g. NSW and Vic), in other jurisdictions there are no (or more relaxed) regulations against dumping activities. The inconsistencies are believed to be a source of inter-state waste transfer. Another issue that has created confusion or opportunity for wrongdoing by developers and the waste recovery industry is an unclear definition of waste and resource. This uncertainty could lead to a commitment of the offence of illegal dumping and stockpiling.

Case Study: Darwin water park site[56] In 2019, NT EPA lay charges against DWD Project Pty Ltd, a construction company accused of illegally dumping thousands of cubic metres of construction waste on Darwin harbour's foreshore, including some that was allegedly dumped on neighbouring government land—the proposed site of the water theme park (Figure 9). NT EPA reported that the disposal and burial of these wastes raised the levels of the land, covered foreshore habitat and filled a large area of Darwin Harbour with wastes and contaminants.

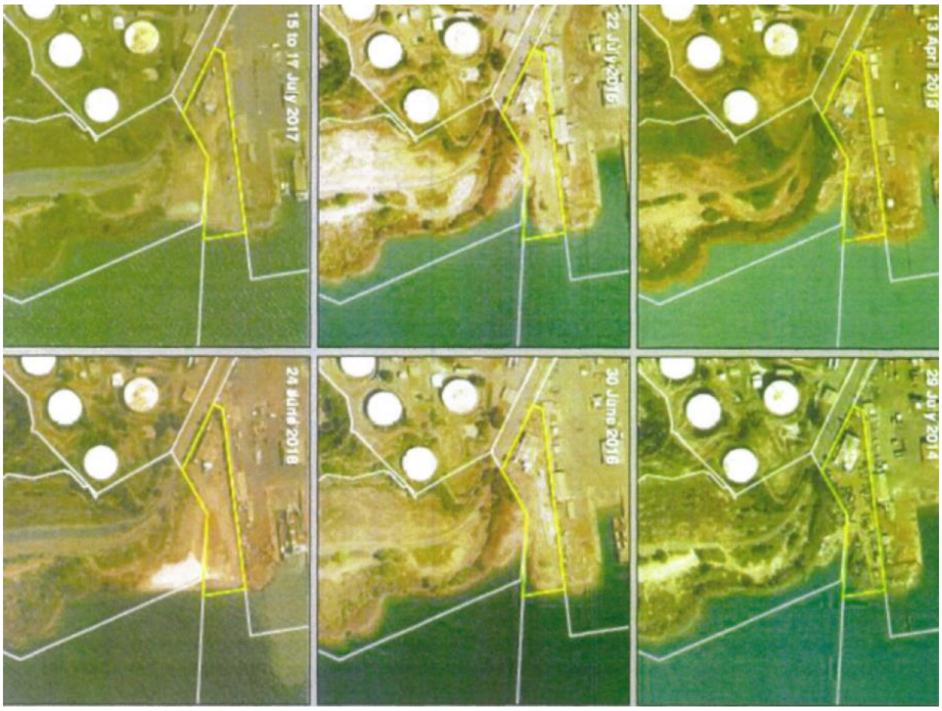


Figure 9. Satellite pictures of the water park site
Source: Ashton (2019)[56], supplied by NT EPA.

Figure 8 shows how construction waste was allegedly used to change the shoreline of the DWD Project Pty Ltd's property (yellow) and the adjacent proposed water park site. However, the director of this company indicated that the alleged pollution is, in fact, part of another program of recycling; all the debris, according to the director, is recycled concrete from building sites.

6.10 Landfill the waste

There is a lack of accurate data registered for concrete waste landfilling in various Australian jurisdictions. In the financial year of 2008-2009, concrete waste disposal including landfilling in the

[56] Ashton, K. 2019. ABC News: Illegal waste allegedly dumped on proposed Darwin water park site, NT EPA claims. https://www.abc.net.au/news/2019-05-22/illegal-waste-allegedly-dumped-darwin-water-park-site-nt-epa/11135666

three states of NSW, WA and SA was 2,063.6 kt[57]. According to the latest available data that is presented in Table 6, SA and ACT landfilled 16.96 kt of concrete waste in 2016-17. From this number, 94.5% was from C&D waste stream.

[57] DSEWPaC (2011) Waste and Recycling in Australia 2011, prepared by Hyder Consulting.

7 CONCRETE WASTE MARKET, BARRIERS AND STRATEGIES

Concrete makes up the greatest proportion of masonry material recycled in Australia, at around 60% of all masonry material recycled[55]. According to market analysis conducted by Sustainability Victoria[58], the markets for recycled concrete are generally mature and strong, particularly in metropolitan areas. The C&D recovery sector is dominated by private companies where basic economic principles apply; that is, when there is sufficient market demand and the product is the right price, the supply side of the equation will, to a large extent, look after itself. This analysis also estimated that the value of concrete waste recovery and end product is at about 167m and 40m, respectively. However, the market faces a number of challenges that need to Brief in the interest of sustainable operation of the market.

In 2017, a review study[59] identified the main barriers to the wider usage of recycled aggregates including recycled concrete aggregates, which include limiting standards/specifications, low-quality materials, insufficient financial incentives, customer perception, low supply and demand, and long distances from C&D waste recycling. Specifically, in Australia, the three factors that are having a negative impact and are regarded as a barrier are:

1. The need for separation of concrete waste from other waste that is sometimes next to impossible; the price of management of contaminated concrete waste is more than five times that of clean waste;
2. Inconsistent jurisdictional standard specifications limiting an operation of a nationwide market; and
3. Long distances between construction sites and C&D waste recycling facilities.

Another study[60] in the context of Australia investigated the main barriers among Australian designers, builders and engineers. The barriers include:

1. Builders: a. cost related to using additives to improve RCA durability and b. reluctance to change the resultant concrete specification;
2. Designers and architects: a. lack of cost-saving associated with the use of RCA and b. presence of the risk of structural failure ;
3. Engineers: a. uncertainty about the consistency of recycled concrete, b. lack of standard specifying the specifications of RCA and c. potential higher costs of RCA.

In keeping with the above-mentioned barriers, anecdotal evidence acquired by Sustainability Victoria[58] suggests there is less likelihood that product with recycled content will be used for higher performance applications where traditional ”proven” products are available. However, evidence and case studies supporting the application of recycled products is gradually emerging in the market place. Table 11 provides a summary of strategies identified to overcome barriers in the development of the market for concrete waste.

[58] Sustainability Victoria. 2015. Market summary – recycled brick, stone and concrete.

[59] Silva, R.V., De Brito, J. and Dhir, R.K., 2017. Availability and processing of recycled aggregates within the construction and demolition supply chain: A review. *Journal of Cleaner Production*, 143, 598-614.

[60] Senaratne, S., Lambrousis, G., Mirza, O., Tam, V.W. and Kang, W.H., 2017. Recycled concrete in structural applications for sustainable construction practices in Australia. *Procedia Engineering*, 180, 751-758.

Table 11. Strategies to remove barriers to market development for concrete waste

Reference	Barrier	Strategy to remove the barrier(s)
Senaratne et al. (2017)	Costs associated with additives to RCA for a better durability	▪ Conduct a life cycle analysis to quantify potential saving from increased durability; ▪ Introduce RCA through precast panels as a quality that can be closely monitored; and ▪ Change the industry attitudes towards sustainability-conscious material choices, as inertia towards traditional practices in construction is prevalent.
Sustainability Victoria[58]	Labour costs, changes in building technology and low demand	▪ Improve separation on site to sort concrete waste material from other C&D waste; ▪ Develop educational materials for designers and builders about material choice and waste management; and ▪ Increase promotion of the use of recycled in pavement construction.

7.1 Integrated supply chain

According to Sustainability Victoria,[61] costs associated with transport are major factors in determining whether the material will be recycled or landfilled. Similarly, the generally low value of end product (per cubic metre or by tonnage) means that transportation of products to end-users is similarly impacted by the relative distance that the recycled product must be transported vs. a substitute product. As such, the location of facilities for reprocessing is of particular importance, as they are the determinant of the total haulage distance from collection to recycled product end-user. Currently, there are companies across Australia that specialise in the removal and collection of brick waste generated from demolition, construction or renovation projects. The following table summarises some of these companies management practice. These companies operate in different jurisdictions and the business information is extracted through direct contact with their sale and technical teams.

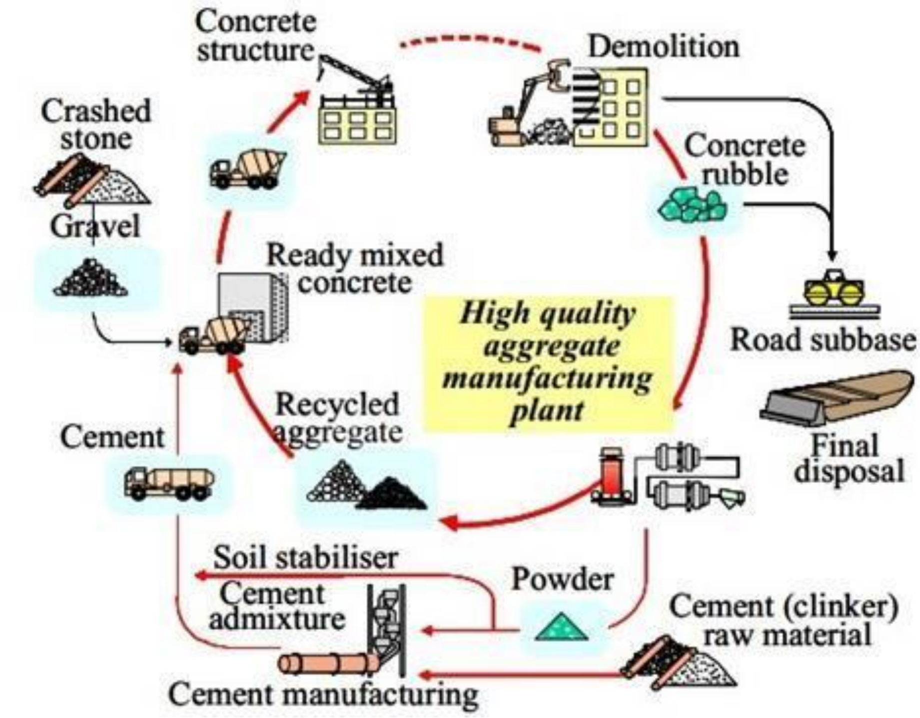
Table 12. Supply chain characteristics of the waste collector

Business name	State	Pricing mechanism	Others
Cleanway Environmental Services	Vic	$250 per load of 6 m skip bin that can get 8 tonnes of waste. The clean waste costs $ 31/tonnes. If it is contaminated, the price will be $250 for transport and $145 per tonne.	Concrete waste will be sent to a recycling facility.
Bingo	Vic	$420 per load of 6 tonnes of concrete waste, the price includes drop off, pick up and renting a skip bin for seven days $125/tonnes clean concrete waste $150/tonnes mixed concrete waste	The waste received at the yard will be recycled, un-recyclables will be sent to landfill

Note: the prices tabulated above are current as of November 2019.

7.2 Concrete lifecycle models

Figure 10 shows the supply chain of concrete waste in various applications[62]. This diagram illustrates how a concrete waste can explore various possible avenues including upcycling in road base or solid



stabiliser, recycling into as aggregates in preparation of ready mixed concrete or cement, or disposal.

Figure 10. Supply chain or concrete waste recycling
Source: ASTM C136[62]

[62] ASTM C 136 – 95a, 2009. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregate, Annual Book of ASTM, International Standard Worldwide.

In this model, there are 11 points at which concrete waste can be efficiently managed. Figure 11 depicts these opportunities and the relationships between them.

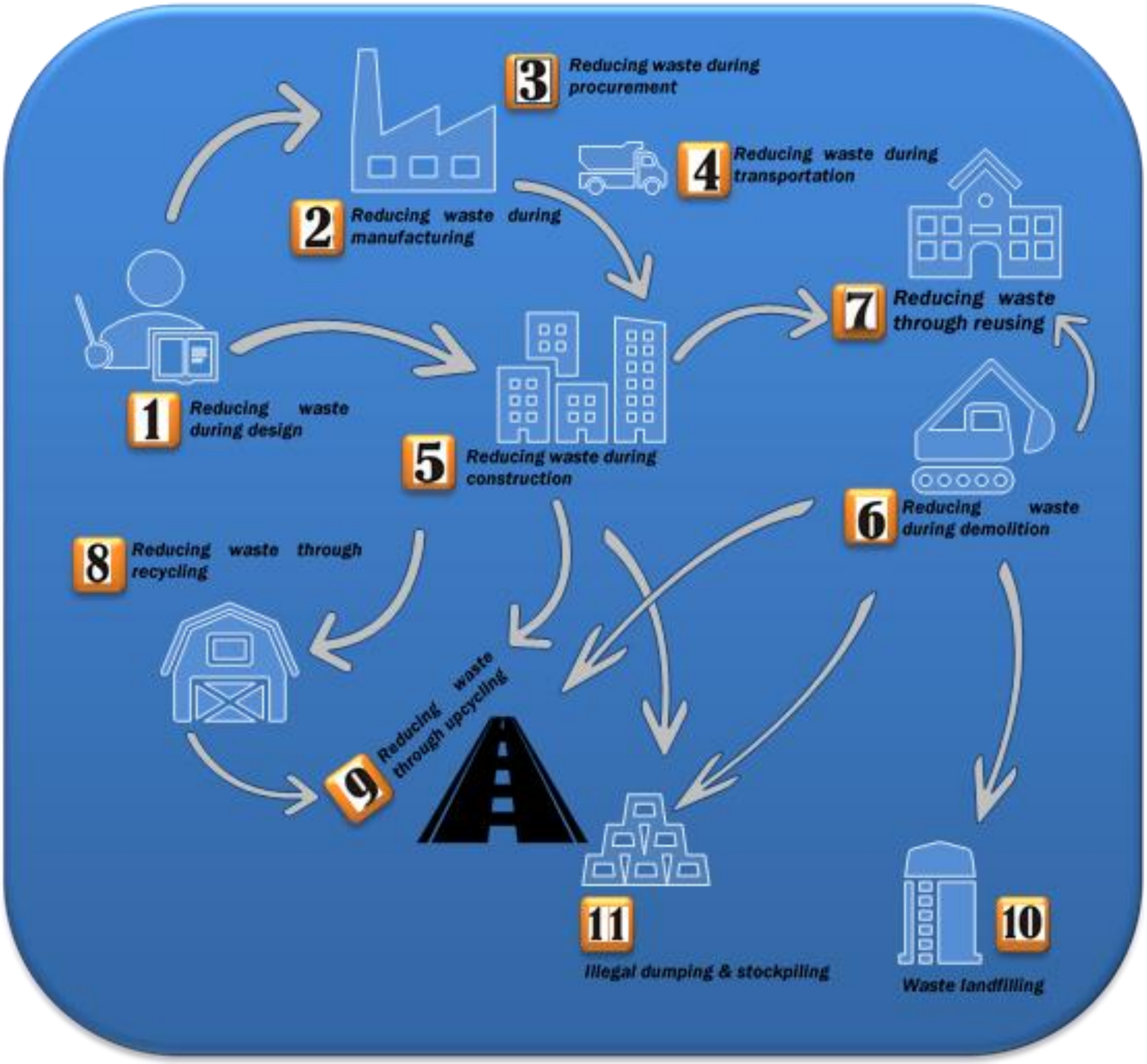


Figure 11. The integrated supply chain lifecycle model for concrete waste

Table 13 shows the role of the main players in the management of concrete waste corresponding to the developed integrated supply chain. The key players identified below are believed to have a major contribution to the effective management of concrete waste. Their contribution could be translated into waste minimisation or reduced waste landfilling, directly or indirectly.

Table 13. The role of various stakeholders in the effective management of concrete waste

No.	Stage	Stakeholder(s)	Contributions
1	Design	Designers, construction firms, clients	• Reuse an existing building instead of a new one; • Design a new building to facilitate its re-use in the future; • Consider precast concrete panels in the designs; and • Consider building standardisation to improve buildability and reduce the number of offcuts.
2	Manufacturer	Manufacturers, recyclers, suppliers	• Develop an agreement where a contractor "sells back" the recycled waste from the original material supplier; and • Participate in the extended producer responsibility and product stewardship schemes.
3	Procurement and contract	Construction firms, quantity surveyors, government	• Construction firms to order concrete more accurately using the best take-off practice; • Suppliers to provide more flexible "last pack" sizes, i.e. a "fractional" pallet instead of a full pallet; and • Alter public contracts (purchasing) for crushed concrete usage in public projects.
4	Transportation & delivery	Construction firms, transporters, recycling companies	• Just-in-time delivery of materials to construction to avoid damage taking place due to insufficient space for proper storage and adverse weather conditions; and • Do due diligence and exercise standard work practices.
5	Construction	Construction firms, waste collectors, recyclers	• Adopting prefabrication technologies • Providing cost-efficient recycled aggregates for constructions • Separating clean concrete waste with other waste materials
6	Demolition	Demolition contractors, waste collectors, recyclers	• Consider selective de-construction to maximising the reuse potential of its components.
7	Reusing	Construction firms, state and territory governments, EPAs and other equivalent organisations, waste collectors	• Facilitate market development; an • Adjust specifications in favour of more usage of brick waste-based materials in new constructions project.
8	Recycling	Recyclers, construction firms, state and territory governments, EPAs and other equivalent organisations	• Facilitate market development; • Fund the development of waste recovery infrastructure; and • Adjust specifications in favour of more usage of concrete waste-based materials in new constructions project.
9	Upcycling	Recyclers, construction firms, state and territory	• Facilitate market development;

		governments, EPAs and other equivalent organisations	• Adjust specifications in favour of more usage of concrete waste-based materials in new constructions project; and • Fund the development of waste recovery infrastructure.
10	Stopping illegal dumping and stockpiling	State and territory governments, EPAs and other equivalent organisations	• Reinforce activities that stop illegal dumping and stockpiling; • Set stricter regulations with a higher rate of penalty fees to discourage illegal dumping and stockpiling; and • Strengthen controls over licensed landfill sites.
11	Landfill	State and territory governments, EPAs and other equivalent organisations	• Design appropriate landfill levy schemes to discourage concrete waste landfilling.

7.3 Relevant industry associations

In addition to the key players identified above, the industry associations and training foundations are reported to have a meaningful impact on sustainable concrete waste management. In this section, the relevant industry associations that specifically work towards better management of concrete and the waste associated with concrete are identified. These associations are to collaborate with the public sector towards recognising opportunities for further reducing, reusing and recycling the concrete waste in Australia. Table 14 summarises the main industry associations with a focus on clay brick in Australia.

Table 14. Industry associations relevant to the management of concrete waste

Associations	Vision	Website
Concrete Pipe Association of Australasia (CPAA)	As the principal source of technical knowledge and education covering all aspects of pipe and related products, the aim of CPAA is to promote and develop excellence in the steel-reinforced concrete pipe industry, ensuring that reinforced concrete pipe is the benchmark product for stormwater drainage, large diameter sewer, low pressure and irrigation pipe applications in Australasia.	www.cpaa.asn.au
Cement, Concrete & Aggregates Australia (CCAA)	CCAA is the peak body for the heavy construction materials industry in Australia. The members include cement manufacturing and distribution facilities, concrete batching plants, hard rock quarries and sand and gravel extraction operations throughout the nation.	www.concrete.net.au
Cement Industry Federation (CIF)	CIF is the national body representing the Australian cement industry. Its membership is made up of the three major Australian cement producers: Adelaide Brighton Ltd, Boral Cement Ltd and Cement Australia Pty Ltd.	www.cement.org.au
Concrete Masonry Association of	CMAA represents concrete masonry and segmental paving manufacturers of Australia. CMAA's aim is to inspire contemporary masonry architecture and building design in all	www.cmaa.com.au

Australia (CMAA)	areas of the built environment: commercial, residential and landscape.	
Concrete Institute of Australia (CIA)	CIA is an independent, not for profit organisation made up of many members who share a common interest in staying at the forefront of concrete technology, design and construction in this country.	https://www.concreteinstitute.com.au/Home
National Precast Concrete Association Australia (NPCAA)	Since 1990, NPCAA has grown to become the peak body for the Australian precast concrete industry. Membership comprises precast manufacturers of all capabilities, across all states, as well as product and service suppliers, industry professionals, tertiary institutions and allied organisation.	www.nationalprecast.com.au
National Concrete Solution (NCS)	National Concrete Solutions (NCS) is a specialist, contracting organisation that has been incorporated since 1991, which, through continued investment, assists in lessening the effects on the community. An investment that not only addresses global factors, it further provides technical education and development of people.	https://ncsaustralia.com.au/
Concrete Pumping Association of Australia Inc (CPAA)	CPAA is the national body representing the interests of the Concrete Pumping industry within Australia. The CPAA provides a strong, unified and respected voice for the concrete pumping industry across Australia whilst working to improve the professionalism, safety, standards and performance of the industry it represents.	http://www.cpassoc.com.au/

8 RECOMMENDATIONS

- Recognise that recycled aggregate, when produced to conform to the standard specification criteria, is a technically viable alternative that can be utilised in non-structural and structural concrete elements;
- Conduct a life cycle analysis to quantify potential saving from increase durability;
- Introduce RCA through precast panels as a quality that can be closely monitored;
- Change the industry attitudes towards sustainability-conscious material choices, as inertia towards traditional practices in construction is prevalent;
- Improve separation on site to sort concrete waste material from other C&D waste, and
- Utilise advanced density separation techniques to grade crushed concrete fines to increase homogeneity and reduce the presence of foreign inclusions.

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