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Briefing

Sustainable Concrete Materials

Concrete is the most commonly used construction material in the world today. Concrete's constituent materials occur naturally in all parts of the world. In Australia it is manufactured from local materials using local skills and expertise. Concrete has been used in the construction of durable bridges, roads, water-supply structures, medical facilities, housing and commercial buildings to give people a social foundation, a thriving economy and serviceable facilities for many years.

INTRODUCTION

Throughout history, the use of concrete as a building material has contributed significantly to the built environment. Enduring examples of various forms of concrete can be found as far back as the early Egyptian civilisation. Significant building remnants still exist from the Roman civilisation, which used concretes made from naturally occurring volcanic ash pozzolans, mixed with water, sand and stone. Then, as now, concrete has been used in the construction of durable bridges, roads, water supply, hospitals, churches,

houses and commercial buildings, to give people a social foundation, a thriving economy, and serviceable facilities for many years.

In the modern era, the properties of concrete were refined in the late 1800s, with the introduction of a patented manufacturing process for portland cement. While it has ancient roots, concrete, as we know it today, is a modern and highly advanced building material. In the last 150 years, concrete has become one of the most widely used building materials on earth.



Such a ubiquitous form of construction has a significant impact on sustainability – a concept that needs to be clearly understood. Environmental responsibility is certainly part of it, but any form of construction must also be socially beneficial and economically viable. A building material, to be truly sustainable, must address all three of these criteria.

When considered within this framework, it becomes clear that concrete construction delivers a very strong sustainability performance. A more in-depth discussion of these concepts is provided in *Concrete – the responsible choice*¹.

To strive for an even higher level of sustainability, the supply sector has been working for many years on a range of measures aimed at reducing the environmental impact of concrete production. This Briefing provides designers, builders and owners with information on the sustainable performance of concrete materials, demonstrating that concrete is truly the responsible choice for sustainable development.

CONCRETE CONSTITUENTS

Concrete is the most commonly used construction material in the world today. In Australia, a large proportion of concrete is produced in premixed concrete batching plants and delivered in a plastic state to construction sites. A 'just-in-time' product, premixed concrete is mixed and delivered locally to order, using locally sourced materials, labour and other resources. The resulting social and economic impacts are felt in large cities and industrial hubs, as well as in small rural communities.

In its simplest form, three basic ingredients are required to make concrete – cement (the binder), aggregates (ranging in size from fine to coarse) and water. Cement reacts with water to form hardened silicate compounds that bind all of the individual aggregate components together into one homogenous material – concrete. This reaction is known as hydration.

In recent decades, intense technological development has seen the development and addition of various other constituents, such as chemical admixtures and supplementary cementitious materials. Where once such additions were used only for highly specialised concrete, now they are used in most concretes.

Portland Cement

Raw materials

Portland cement consists of a mixture of calcium carbonate, silica, iron oxide and alumina. The primary raw material used in the production process is limestone, which is the source of calcium. Other raw materials include clay, shale, sand and ironstone.

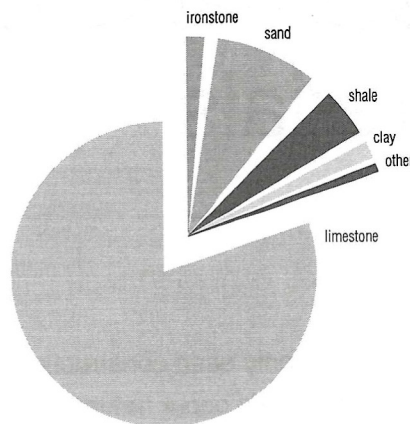


Figure 1 Raw materials used in the production of portland cement

Production Process

The raw materials are mixed and placed in a high-temperature kiln (fuelled by coal, natural gas or other fuels) and heated to around 1450° C, transforming them chemically and physically into a grey pebble-like material called clinker. Clinker is a chemically stable material, which can be readily stored and transported. In the final process, clinker is ground into a very fine powder and mixed with a small amount of ground gypsum to make portland cement.

During the heating phase, significant energy is consumed, which accounts for most of the embodied energy contained in cement. Apart from the energy-related CO₂ (carbon dioxide) emissions, a further amount of CO₂ is emitted by the chemical

Australia leads the industrialised world in cement production efficiency. The manufacture of cement in Australia leads to approximately 700 kg of CO₂ being emitted per tonne of cement produced². However, cement makes up only approximately 10% of concrete; water and aggregates make up the other 90% of the mass of concrete. This is why concrete has a relatively low embodied energy, even though it contains cement, which has a relatively significant embodied energy.

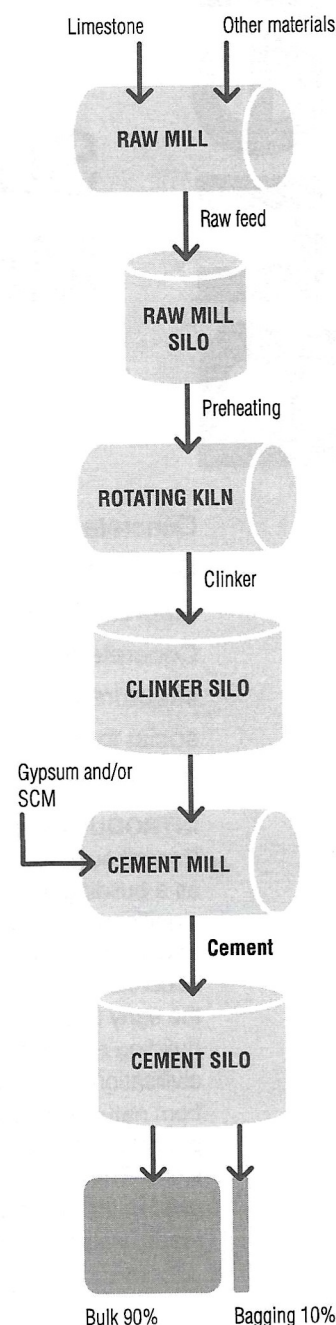


Figure 2 Cement manufacture

Premixed Concrete Production

Process

Premixed concrete is manufactured at batching plants that are typically located strategically within a radius of 45 minute travelling time from major development areas. The most common type of batching process used in Australia is shown diagrammatically in **Figure 6**. The cementitious material, aggregate and water are delivered to the plant and stored. These materials are accurately weighed and placed in a premixed concrete truck (agitator), where the materials are then thoroughly mixed together using the rotating agitator apparatus on the truck.

Over many years the premixed concrete industry has continually striven to achieve a high environmental performance in the operation of these facilities. This is well demonstrated by the industry's annual environmental awards that reward outstanding environmental performances across a range of criteria.

Recycled water

The use of water in concrete production has been a source of debate and research over many years. Recent water shortages and drought conditions around Australia have brought about a number of process innovations to reduce the demand on municipal water supplies by the concrete batching process.

The acceptability of recycled water for use in concrete is governed by its effect on workability, strength and durability of the concrete.

One of the most common methods of recycling water in the concrete batching process is to use water run-off or slurry from concrete production operations. These are collected in settling ponds on the concrete plant site. Highly alkaline slurry, containing cement, admixtures, dust and other materials commonly found on site, is channelled into settling ponds to prevent it from reaching storm water drains. The cement sludge settles to the bottom, and the light 'grey water' is progressively decanted into adjacent ponds until it is suitable for use. The solids content, cementitious properties and a range of other properties are carefully monitored to ensure the properties of the finished concrete are not adversely affected.

In order to conserve water and reduce the demand on town water supply, most concrete batching plants try to improve their process efficiency by using as much grey water as possible. For more detailed information on the use of recycled water refer to *Use of Recycled Water in Concrete Production*⁵.

A related measure is the on-site capture of rain-water. Concrete plant sites which have a suitable location, topography and catchment area, have installed reservoirs and/or tanks to maximise their storage capacity.

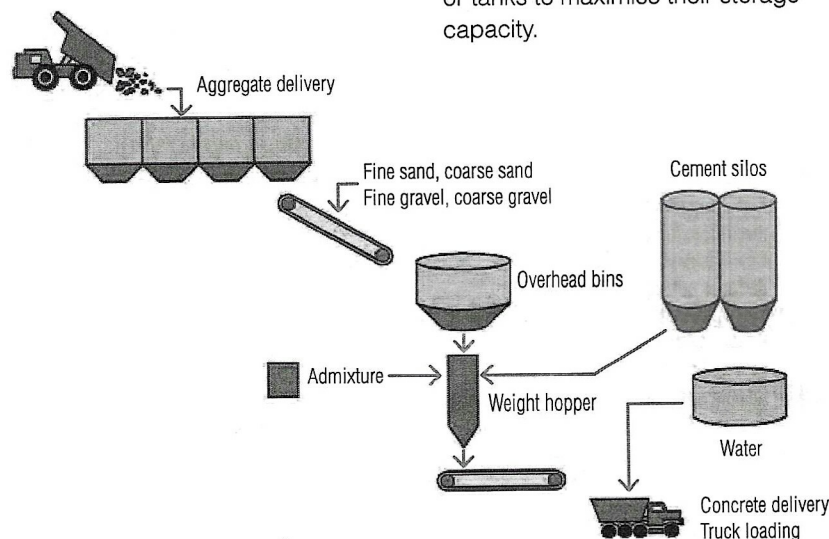


Figure 6 Concrete manufacture

Reclaimed aggregates

If the batching plant has a reclaiming facility, aggregates can be reclaimed from returned concrete. Unused concrete which is returned to a plant in a plastic state goes through a separation process washing cement slurry from the aggregates

Figure 7. The aggregates are then re-graded, and are available for use in freshly batched concrete. The materials reclaimed from this process, however, are limited by unpredictable supply, as it relies on returned, unused concrete.

Admixtures

A large range of chemical admixtures are used in premixed concrete production to enhance certain properties of the concrete, mostly its plastic-state properties such as workability, pumpability and setting time. Admixtures, unlike cement, aggregate and water, are not essential components of the concrete mix. However, they are an important and increasingly-used component. In many situations, a mix that contains no admixtures is now an exception, rather than the rule.

The reason for the large growth in the use of admixtures is that they are capable of imparting desirable properties as well as economic benefits. Admixtures support the sustainability of concrete by extending its range of economic and useful applications.

Water reduction

The most common admixture used in concrete mixes is a water-reducing admixture (commonly known as 'plasticiser'). By aiding dispersion of cement particles within the concrete mix, the water-reducing admixtures improve workability, reducing the water required for a concrete mix by up to 20%.

This ability also leads to the production of high-strength concrete mixes that still have a high degree of workability. The strength of concrete is inversely proportional to the water-cement ratio of the concrete mix; ie low water-cement ratios lead to higher strength. Water-reducing admixtures allow very low water-cement ratios to be achieved, while maintaining the

Currently, most concrete producers utilise aggregates sourced from the nearest quarry, and design their concrete mixes to suit. This leads to a lower overall cost, lower environmental impact due to minimising transportation, and often underpins the local economy, especially in rural areas.

Social responsibility

As an industry dealing with heavy materials, the extractive industry takes its responsibility to the local economy and environment very seriously. Although the average life of a quarry is 50 years, a progressive rehabilitation plan is often introduced during the operation phase. Feasibility studies indicate how the site is to be used when production ceases (eg artificial lakes) and how to restore the site through native vegetation.

Manufactured sands

When rock is extracted, crushed and sized in a quarry, the main aim has traditionally been to produce coarse aggregates for use in concrete production, asphalt production, road construction and civil works. The waste from this process is an excess fine aggregate, generally finer than 5 mm, and with variable properties. The extractive and concrete industries have tried, for some time, to find ways to use this material as a controlled replacement for natural sand. Manufactured sand is defined as a purpose-made crushed fine aggregate, produced from a suitable source material. Production generally involves crushing, screening and possibly washing. Extensive research by the concrete and extractive industries has concluded that, provided the material is appropriately processed and selected from suitable materials, a significant proportion of naturally-extracted sand can be replaced by manufactured sand, while still meeting the highest quality concrete specifications.

This means that natural sand, which is being rapidly depleted in some areas, can now be replaced by a material that was previously a quarry waste. Extensive research³ into the use and properties of

manufactured sand has shown that it is suitable for blending with natural sands without adversely affecting the plastic properties of concrete, such as workability, cohesiveness, bleed and setting time.

Recycled aggregates

In many countries, including Australia, recycled concrete aggregates have been proven to be practical for low-strength concretes, and, to a limited extent, for some structural-grade concrete. Positive benefits include:

- The amount of material going to land fill is reduced.
- Aggregates from selected materials and industrial by-products may be used economically in concrete and as road construction materials.

Considerations include the cost of:

- recovery and processing;
- additional quality control; and
- mix design adjustment to achieve the same strength grade as concrete with natural aggregates.

A number of manufactured and recycled aggregates are readily available in certain Australian localities. Air-cooled blast furnace slag and manufactured sand are two good examples of concrete coarse and fine aggregates that are currently in use.

Comprehensive performance data are available for air-cooled blast furnace slag, while work is continuing to provide performance data and appropriate specifications for manufactured sands. For other construction applications, such as pavements, road-bases and sub-bases, there is some information on the performance of each material. Assessment is based on field trials, especially those by road authorities.

In all cases, the availability and consistency of supply are prerequisites for the use of manufactured and recycled aggregates in the various applications⁴.

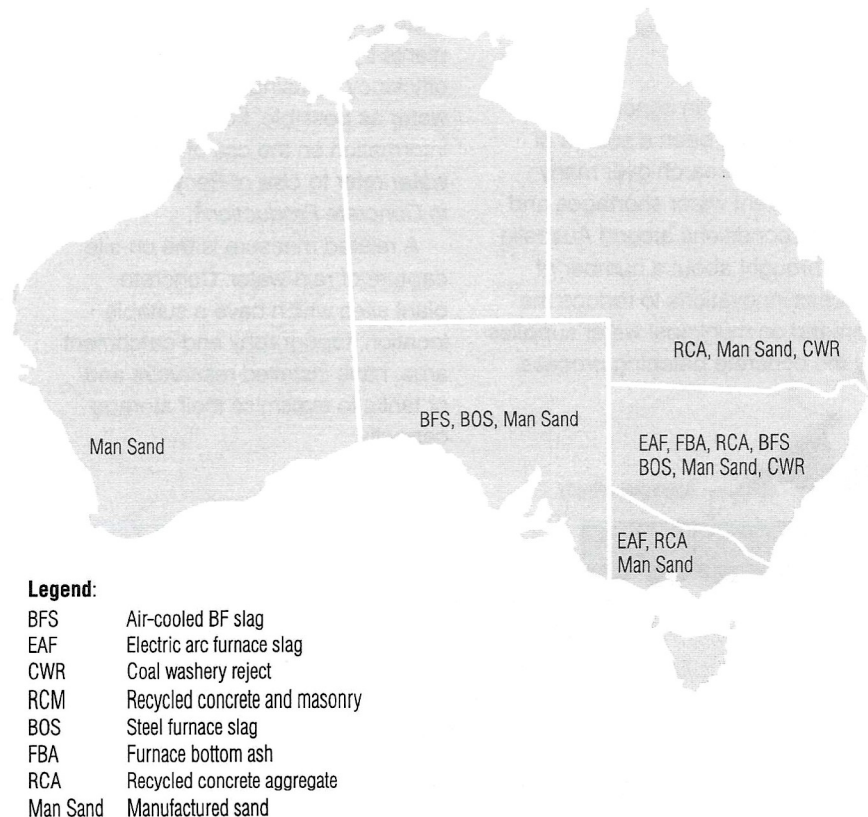


Figure 5 Availability of recycled aggregates and manufactured sand⁴

Ground granulated iron blast furnace slag (slag)

Slag is a by-product of the manufacture of steel in a blast furnace. It is formed simultaneously with iron; when cooled rapidly it produces a non-metallic product that can be ground and used as an SCM in concrete. Slag has a coarse texture in comparison to that of portland cement, and a much slower hydration reaction. However, in the presence of activators, such as portland cement, it will behave as a hydraulic cement with characteristics similar to portland cement.

The slower hydration reaction of slag means that concrete made from slag-based cements exhibit lower heat of hydration than concretes made from portland cements. This property can be used to good effect to control thermal cracking in large-element concrete pours, such as in raft footings, dam spillways and retaining structures. Slag also has many other beneficial properties in the hardened concrete, including enhanced durability.

In Australia, slag has been used in quantities of up to 65% of the mass of the total cement.

Fly ash

Fly ash is one of the residues generated in the combustion of coal. Fly ash suitable for use as an SCM in concrete is recovered from the precipitators before the chimneys in coal-fired power stations. In the past, fly ash may have been released into the atmosphere, but pollution control regulations introduced in recent decades require that it be retained and disposed of responsibly. The resulting power station by-product is now being effectively captured and reused, yielding a significant reduction in environmental impact.

The desire to recycle fly ash, combined with its natural pozzolanic properties, has led to its widespread use in concrete. Fly ash is an effective SCM due to its pozzolanic nature, spherical shape, and relative uniformity. When used as a supplement to portland cement, it delivers improved workability, later-age strength, and enhanced durability.

Fly ash will not react with water to form cementitious products. It does, however, exhibit a slow reaction with calcium hydroxide, in the presence of water, to form a hardened binder. Calcium hydroxide is a by-product of the portland cement hydration reaction. Therefore, if enough portland cement is available, the pozzolanic effect of fly ash can be fully utilised in a concrete mix. The slower reaction rates of fly ash also mean that large quantities in the cement, or in the concrete mix, will inhibit the early-age strength of concrete. This should be taken into account when designing concrete mixes for building projects with specific requirements for early-age strength.

In Australia, fly ash is typically used in quantities of up to 30% of the mass of the total cement.

Amorphous silica

Amorphous silica covers a range of products, from a naturally-occurring material to by-products of the silicon and ferrosilicon production processes. The latter is sometimes referred to as silica dust, silica powder, silica flour or microsilica. The name most commonly used in Australia is silica fume.

Silica fume consists of extremely fine spherical particles of amorphous silicon dioxide, and possesses an exceedingly high specific surface area (surface area divided by mass or volume), which gives it an active pozzolanic characteristic.

It is used as a component of blended cement, or as a separate material, added to the concrete batch. The high surface area of silica fume makes it an excellent addition to concrete mixes requiring a high level of durability, such as for maritime structures. It is also used in the production of high-strength concretes, typically achieving up to 100 MPa characteristic compressive strength.

The use of silica fume in concrete alters many of the fresh concrete (plastic state) characteristics, notably water demand and workability. In Australia, silica fume is typically used in quantities of up to 10% of the mass of the total cement for specific applications,

Aggregates

Both coarse aggregates (stone fractions) and fine aggregates (sand fractions) are quarried and/or dredged for use in concrete. This use makes up only a small portion of the total extractive industry output, most of which is used in asphalt, road base, civil works and site works.

Aggregates are obtained by a variety of means, including ripping, blasting and dredging. The raw materials are processed by crushing, screening, washing, blending and grading. Since aggregates are a naturally-occurring resource that requires only simple extraction techniques and no fundamental alteration, the quarrying operation has an extremely low environmental impact.

The three fundamentals for the aggregate extraction industry are:

- Suitable aggregates are site specific, limited in occurrence by geological conditions.
- The supply of suitable aggregates is finite.
- Because aggregates are high-volume, low-cost materials, it is efficient and sustainable to extract them close to the communities and industries where they are to be used.

Local materials

It takes, on average, 7 to 10 years to identify, obtain the necessary planning approvals and construct a 'greenfields' quarry site, which will often have an economic operating life of approximately 50 years.

Security of resources and the ability to predict the regulatory environment over the operating life of a quarry are, therefore, imperative if the industry is to invest with confidence in new sites and meet the nation's future demands for cost-effective aggregates.

Restrictions on the expansion of existing quarry sites have a major impact on the reliable and cost-effective supply of aggregates. The current location of most quarrying sites around Australia is a key factor in maintaining the fine balance of social, environmental and economic viability.

Energy use – efficiencies from 1990 to 2009

Due to the significant amount of heating energy consumed in manufacturing cement, and its associated cost, the cement industry has been keenly focused over a long period on increasing plant efficiency and reducing energy consumption. This not only makes good business sense, but also lowers the environmental impact of cement manufacture.

The strong investment in cement plant technology, made by the Australian cement industry, is evident from the 23% decrease in CO₂ emissions from 1990 to 2009. This has been brought about by industry-wide fuel and power efficiency improvements **Figure 3**.

Alternative energy sources

A range of non-traditional or alternative fuels can be used to produce heat energy in cement kilns, resulting in a benefit for both the environment and the market. Alternative fuels may be sourced from the by-products of other manufacturing processes, or from end-of-life products. Some Australian cement plants are using up to 40% alternative fuels in clinker manufacture; including the use of waste tyres, oils, tallow and spent pot linings. Currently, all Australian cement manufacturers are involved in the investigation of alternative fuels, and the economic and environmental benefits that flow from their use.

Supplementary Cementitious Materials

A significant proportion of concrete produced today contains Supplementary Cementitious Materials (SCMs) as part of the total cementitious component or binder. The three types of SCMs commonly used in Australia are ground granulated blast-furnace slag (slag), fly ash and amorphous silica. Fly ash and amorphous silica are pozzolanic materials that harden by reacting with the calcium hydroxide released during the hydration of portland cement. Slag has latent hydraulicity, ie in the presence of alkaline materials such as portland

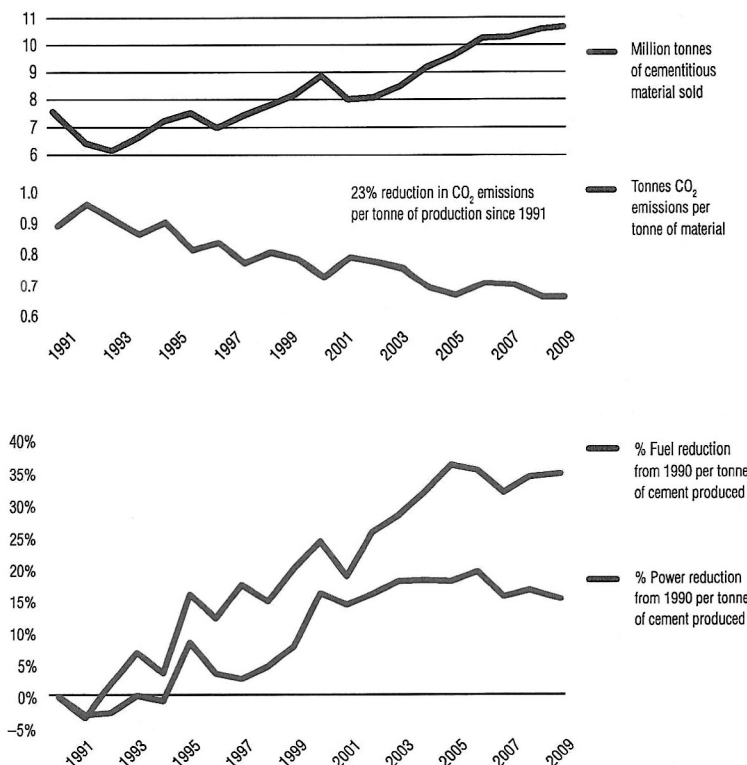


Figure 3 CO₂ emission and fuel and power efficiency gains²

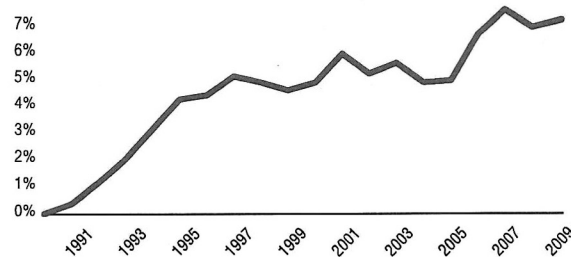


Figure 4 Alternative fuel use²

cement, it will react with water to form hardened binder.

SCMs are often thought of as new materials, but that is not strictly the case. The early Romans were the first to use naturally-occurring pozzolans, found in volcanic ash. Their use predates that of portland cement by several centuries. 'Modern' SCMs are by-products of other industries; when blended with portland cement in certain proportions, they impart many beneficial properties to concrete. By reducing the amount of manufactured cement required in a given concrete mix, the use of SCMs further reduces concrete's

environmental impact. SCMs also lead to better economic outcomes for concrete construction – being an industrial by-product, they can be procured at a lower cost than that of manufactured cement.

There is large body of research world-wide on the use and benefits of SCMs in concrete including enhanced durability.

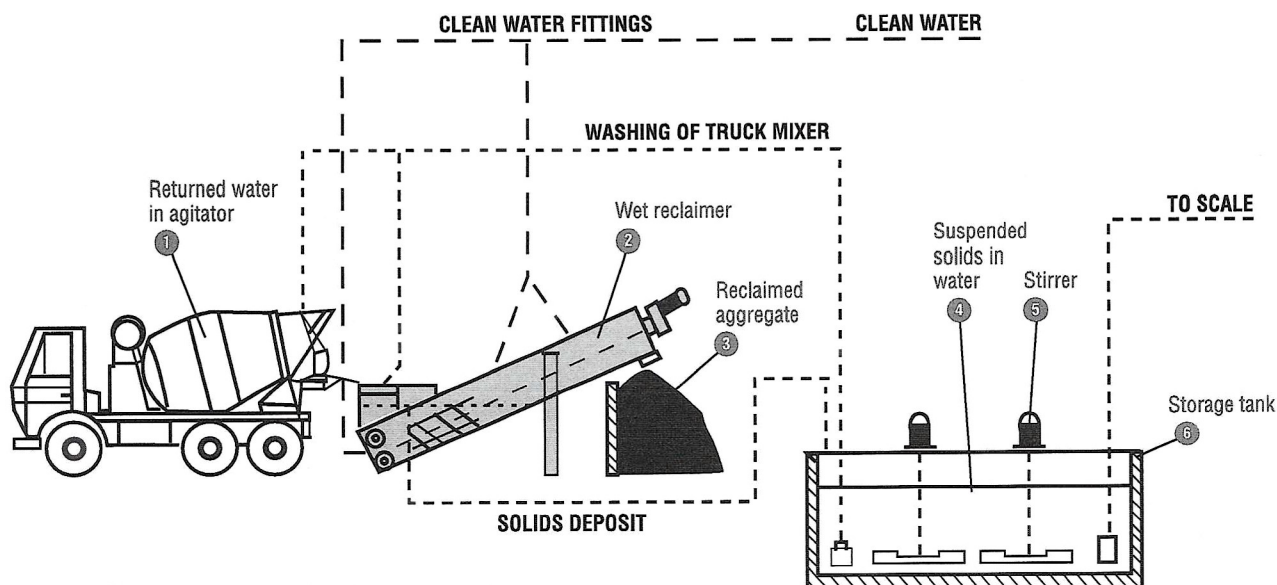


Figure 7 The process of reclaiming aggregates

required workability necessary for the concrete to be transported to site and pumped into position.

Dispersing the cement particles evenly and efficiently throughout the mix makes the cement hydration process more efficient, increasing the strength gain overall. As a result, with the use of admixtures, a lesser quantity of cement is required to achieve the same strength as for a mix without admixtures.

Other properties

Purpose-specific admixtures also impart beneficial properties to concrete containing SCMs. These materials, being very fine, may be difficult to disperse and work into the concrete mix. However, it is their fineness that is desirable for many applications requiring increased strength and/or enhanced durability.

There are also various other types of admixtures used to enhance corrosion inhibition and limit shrinkage, leading to the construction of more durable and fit-for-purpose structures.

Concrete – the responsible choice

Social impact

Concrete construction has had, and will continue to have, a great social impact on the world. Without durable infrastructure such as roads, highways, rail networks, wharf and port facilities, the world's economies would grind to a halt. Concrete enables these facilities to be built economically, which has an inherent social equity dimension as well. Concrete is essentially a simple, naturally resourced product available in practically all parts of the world. Poorer countries can be empowered by building social infrastructure that is affordable and produced from locally-sourced materials, thus providing employment in the process.

Concrete buildings are safe, easy to maintain and commonly have a design life of 50 years or more. The foundation upon which most of our homes and lives are built is the unwavering durability of concrete.

Environmental impact

The only true method of assessing a building system's environmental impact is via a life-cycle assessment. The methodology is well established with a rigorous scientific platform that has an international standard⁶ which sets out the process. In the case of a building, a life cycle includes extraction of raw materials, manufacture, construction,

operation (commonly 50–100 years) and re-use or recycle phases. A life-cycle assessment of a range of concrete buildings commissioned by CCAA can be found on the website⁷, showing that concrete buildings perform very strongly across all environmental indicators, including energy use and CO₂ emissions.

At the material production level, the three major industries that provide concrete – cement, premixed concrete and extractive, are all continuing to make further reductions in their environmental impacts, through plant efficiencies, technology uptake and embracing an environmental awareness culture.

Economic impact

The construction industry has impacted on economies for thousands of years. At the macro-economic level, the construction industry in Australia represents approximately 10% of Gross Domestic Product. It employs over 250,000 people directly and millions indirectly. It generates billions in taxation revenue, and is a primary vehicle for wealth generation. In Australia, as in industrialised nations, concrete is the most widely used material for construction and without it the construction industry would come to halt. Concrete plays a pivotal role in overall economic growth, both locally and globally.

At the micro-economic level, concrete offers the lowest cost of construction in most cases. Recent independent studies have conclusively demonstrated this to be so in Australia^{8,9}. This means that for a given investment, concrete enables more hospitals, schools, bridges, houses, etc to be built than would be the case if less cost competitive building materials were used.

Returning to the central premise of sustainable development – the three pillars of social, economic and environmental, it can be seen that concrete is truly the responsible choice.

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CCAA OFFICES

SYDNEY OFFICE:

Level 6, 504 Pacific Highway
St Leonards NSW Australia 2065

POSTAL ADDRESS:

Locked Bag 2010
St Leonards NSW 1590
TELEPHONE: (61 2) 9437 9711
FACSIMILE: (61 2) 9437 9470

BRISBANE OFFICE:

Suite 2, Level 2, 485 Ipswich Road
Annerley QLD 4103
TELEPHONE: (61 7) 3227 5200
FACSIMILE: (61 7) 3892 5655

MELBOURNE OFFICE:

2nd Floor, 1 Hobson Street
South Yarra VIC 3141
TELEPHONE: (61 3) 9825 0200
FACSIMILE: (61 3) 9825 0222

PERTH OFFICE:

45 Ventnor Avenue
West Perth WA 6005
TELEPHONE: (61 8) 9389 4452
FACSIMILE: (61 8) 9389 4451

ADELAIDE OFFICE:

PO Box 229
Fullarton SA 5063
TELEPHONE: (61 8) 8274 3758

PREMIXED CONCRETE AND
EXTRACTIVE INDUSTRIES OFFICE
PO Box 243
Henley Beach SA 5022
TELEPHONE: (61 8) 8353 8151
FACSIMILE: (61 8) 8125 5822

TASMANIAN OFFICE:

PO Box 246
Sheffield TAS 7306
TELEPHONE: (61 3) 6491 1509
FACSIMILE: (61 3) 6491 2529

WEBSITE: www.ccaa.com.au

EMAIL: info@ccaa.com.au

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