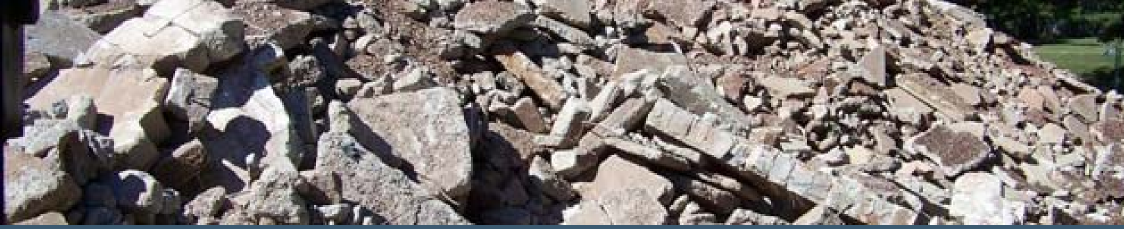
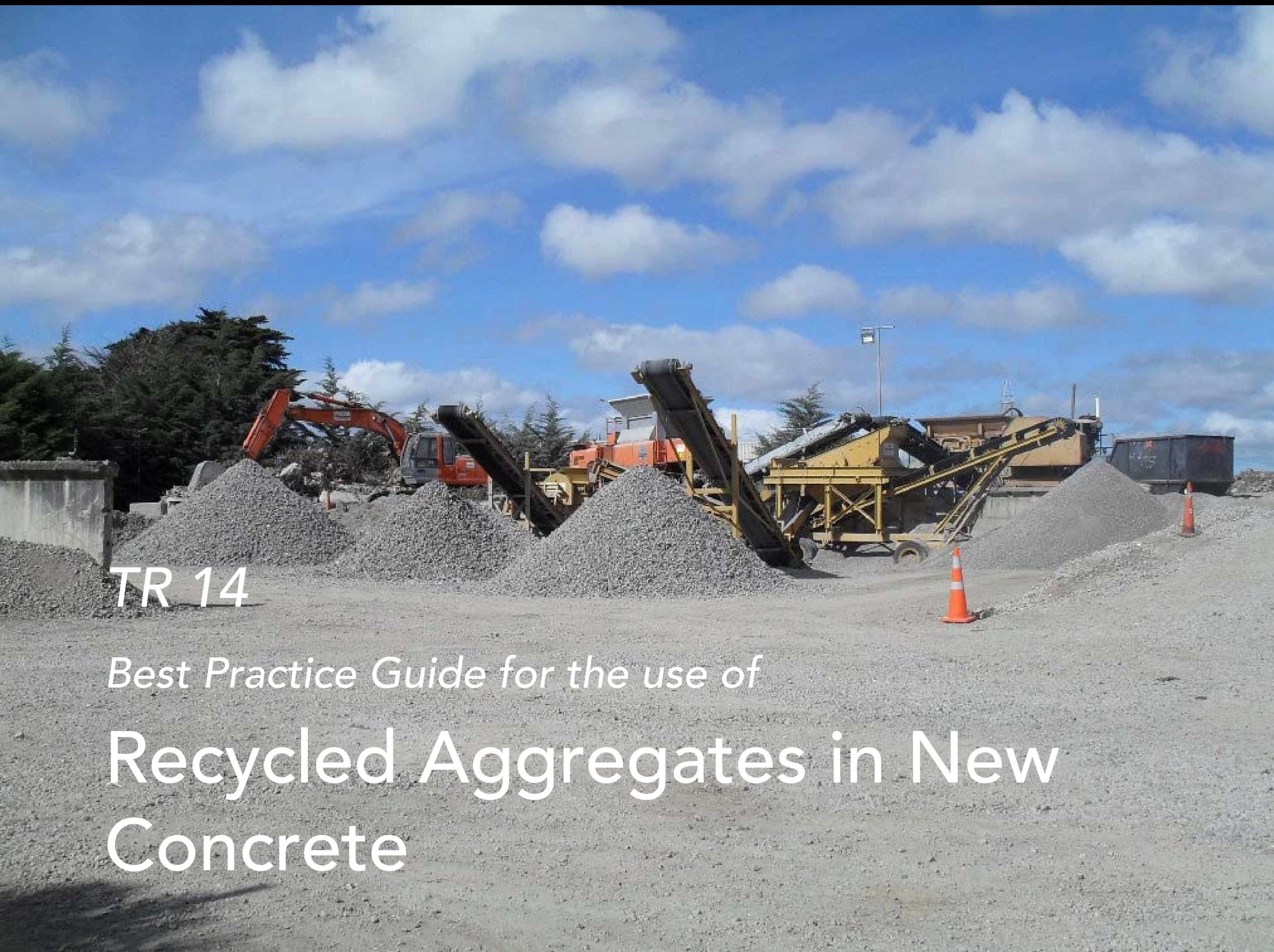


CCANZ concrete answers

CCANZ TECHNICAL REPORT



TR 14

Best Practice Guide for the use of

Recycled Aggregates in New Concrete

The use of processed crushed hardened concrete and leftover fresh concrete as recycled aggregate in new concrete.

Funded by BRANZ from the Building Research Levy

Best Practice Guide for the use of

Recycled Aggregates in New Concrete

This technical report is published by the Cement & Concrete Association of New Zealand (CCANZ) in the interests of actively promoting industry understanding of:

- The crushing and processing of hardened concrete as recycled aggregate in new concrete.
- The recovery of leftover fresh concrete for use as recycled slurry and as aggregate in new concrete.
- The use of secondary recycled material as aggregate for concrete.

Acknowledgements

CCANZ wishes to thank the following Working Party members for their contribution to this publication:

Derek Chisholm (Author)	Solid Concrete Solutions
Alan Kirby (Chair)	Cement & Concrete Association of New Zealand (CCANZ)
Jon Hambling	New Zealand Ready Mixed Concrete Association (NZRMCA)
David Barnard	NZRMCA Plant Audit Committee Chairman
Jason Lowe	Aggregate & Quarry Association of New Zealand (AQA)
Stuart Park	BRANZ
Allan Scott	University of Canterbury
Greg Slaughter	New Zealand Portland Cement Association (PCA)

CCANZ also wishes to thank:

- Sue Freitag, Opus International Consultants Limited, for her valuable review comments and input.
- the Aggregate and Quarry Association of New Zealand (AQA) for its financial contribution.

TR 14

ISSN: 1171-4204

ISBN: 978-0-908956-23-4 (online)

Table of Contents

List of Tables

List of Figures

Preface

Concrete is the world's second most consumed material after water, and its widespread use is the basis for urban development. It is estimated that 25 billion tonnes of concrete are manufactured each year. Twice as much concrete is used in construction around the world when compared to the total of all other building materials combined. In New Zealand 27% of the total waste generated is construction and demolition waste (C&DW), and of this concrete represents 25%, i.e. 7% of the total waste[1]. Many countries have recycling schemes for C&DW to avoid dumping to landfill, as suitable landfill sites are becoming scarce particularly in heavily populated countries. In New Zealand a $10/tonne landfill levy was introduced in 2008, and this will inevitably increase in the future as landfill sites become scarcer. Charges or levies on landfill dumping often make recycling concrete aggregate a preferred option.

The reuse of hardened concrete as aggregate is a proven technology - it can be crushed and reused as a partial replacement for natural aggregate in new concrete construction. The hardened concrete can be sourced either from the demolition of concrete structures at the end of their life – *recycled concrete aggregate*, or from leftover fresh concrete which is purposefully left to harden – *leftover concrete aggregate*. Alternatively fresh concrete which is leftover or surplus to site requirements can be recovered by separating out the wet fines fraction and the coarse aggregate for reuse in concrete manufacture – *recovered concrete aggregate*. Additionally, waste materials from other industries such as crushed glass can be used as *secondary aggregates* in concrete. All these processes avoid dumping to landfill whilst conserving natural aggregate resources, and are a better environmental option.

Recycling or recovering concrete materials has two main advantages - it conserves the use of natural aggregate and the associated environmental costs of exploitation and transportation, and it preserves the use of landfill for materials which cannot be recycled. Whilst crushed concrete can be used as a sub-base material for pavements and civil engineering projects[2], this Best Practice Guide outlines its use as a higher grade resource - as aggregate in new concrete. However, recycled concrete aggregate that is significantly contaminated may not be economical to decontaminate for use as concrete aggregate, whereas it may be suitable 'as is' for use as sub-base material. Green building schemes such as Green Star New Zealand[3] recognise C&DW reuse and provide credits for the use of recycled materials including recycled concrete aggregate.

Because waste minimisation and reducing the burden on landfills is a global issue, extensive research has been carried out worldwide on the use of recycled aggregate in concrete. This includes substantial research reports by WRAP[4], NRMCA[5] and RILEM[6]. Globally the concrete construction industry has taken a responsible attitude to ensuring its natural resources are not overexploited. In some cases the preservation of dwindling natural aggregate sources is a significant issue driving the use of recycled aggregates. Reduction in the impact of aggregate cartage on cost and environmental issues is also a factor where material processed from the demolition phase of a project, using a portable aggregate processing plant, can be reused in concrete for the construction phase of the project. This is a better option than transporting natural aggregates from quarries which through urbanisation are located at an ever increasing distance from city areas. In some cases in Auckland for instance, quarried aggregate is transported over 100 km from source to construction project.

In general the awareness of concrete recycling as an issue in New Zealand is not high. However overseas, landfill levies, waste dumping taxes and imported aggregate taxes have made it viable to recycle concrete generally into a 'low-grade' road-base material. The greatest users of recycled aggregate in new concrete are the United Kingdom, the Netherlands, Belgium, Switzerland and Germany. In these countries recycling rates are higher as a result of a longer period of awareness of concrete recycling, and the preservation of dwindling aggregate resources. Other countries are likely to follow this trend with time.

1.0 Introduction

The key to local materials recovery and the recycling industry sector is to achieve a balance between economic pressures and ecologically sound practices. This balance is critical not only to ensure a sustainable future for the industry, but also to secure essential quality improvements and development of markets for value-added products, which are required to make recycled materials more attractive and economical[7].

Several market constraints and technical challenges exist when developing markets for secondary products. Notable among these barriers is consumer uncertainty about the quality and consistency of products. In addition, there can be a lack of practical performance and engineering data on recycled materials. Such data is necessary to assist with the development of appropriate design codes to guide product specification and performance information on recycled materials. This Best Practice Guide and its references are intended to provide such information particularly for the New Zealand market.

The need to develop and adopt performance requirements specifically for secondary and recycled products will not only promote secondary and recycled materials specification, but will also ensure that externally verified quality certification and compliance systems covering both materials and recycling plants are adopted. This will inevitably create further market opportunities for using recycled materials as aggregate in concrete, which constitutes a step forward in providing contractors and clients with confidence when specifying recycled products. Nevertheless primary materials will continue to meet the bulk of the demand for construction materials.

The New Zealand cement and concrete industry sources its cement feedstock, water and aggregates locally and it is in its interest to use these resources efficiently and in a manner which can be sustained in the long term. Significant steps have been made by the industry as a whole in recent years in the efficiency of the cement manufacturing operation itself, with use of waste material to fuel the cement kilns – used car tyres, sewage sludge, used oil and wood waste; and in the use of supplementary industrial waste materials such as fly-ash and blast furnace slag as partial substitution for cement. The use of recycled materials has become accepted throughout the ready mixed concrete industry in response to increasing environmental focus, including product stewardship, and the increasing cost of disposing of waste material.

1.1 Scope and Application of TR 14

This Best Practice Guide outlines the processes involved in the use of recycled materials as aggregate in concrete and the effects of these materials on the fresh and hardened properties of concrete made from them. It is based on experience gained from the use of recycled materials in concrete construction projects and research projects both overseas and in New Zealand. It is intended to act as a resource on the practical performance and engineering properties of recycled materials as aggregate in concrete supplied in accordance with NZS 3104:2003[8].

This Best Practice Guide is intended to raise the awareness of the need for concrete recycling in New Zealand and to present the technical guidelines to specifiers, contractors, aggregate suppliers, and concrete manufacturers on the use of recycled aggregate in concrete, and on the recovery of concrete aggregate and fines from leftover fresh concrete. By providing a general overview of recycled concrete in construction, it will also be of interest to regulatory bodies providing relevant information for determining the suitability of recycled material for use in building and civil engineering projects.

1.2 Terminology

Terms used in this Guide are defined in Table 1. It is emphasised that other references may use different terms and/or definitions.

Table 1: Definition of Terms

Name	Description
Natural (or virgin) aggregate	Aggregate produced from alluvium or quarried rock
Recycled aggregate (RA)	Aggregate typically processed from demolition waste including concrete, masonry and asphalt
Recycled concrete aggregate (RCA)	Aggregate typically processed from demolition waste concrete
Leftover concrete aggregate (LCAgg)	Aggregate processed from leftover concrete that has been left to harden
Recovered concrete aggregate	Coarse aggregate recovered from leftover fresh concrete by separating it from the mortar fraction
Secondary aggregate	Aggregate derived from industrial waste or by-products from other industries
Adhered mortar	Mortar adhering to the recycled aggregate after processing
Parent concrete	The concrete from which the recycled aggregate is derived
Natural aggregate concrete	Concrete made from entirely natural aggregate
Recycled aggregate concrete (RAC)	Concrete made using recycled aggregate, recycled concrete aggregate or leftover concrete aggregate as a partial or complete replacement for natural aggregate, i.e. it excludes concrete made with recovered and secondary aggregates.

In this document 'recycled aggregate' and 'recycled concrete aggregate' are used interchangeably as generic terms for recycled materials. In contrast, the terms 'recycled aggregate (RA)', 'recycled concrete aggregate (RCA)' and 'leftover concrete aggregate (LCAgg)' refer to the specific types of recycled aggregate as defined in Table 1. Similarly, 'recycled aggregate concrete' can include concrete made from secondary aggregate, but 'recycled aggregate concrete (RAC)' does not. These distinctions are mostly made in Sections 7.0 and 8.0.

Recovered concrete aggregate is described in Section 2.0. However, because it is considered equivalent to natural aggregate it is not deemed to be a 'recycled aggregate'.

Furthermore, in this document, percentage replacement levels are quoted as percentage by mass of the total coarse aggregate fraction, unless specifically stated otherwise. Some other publications use percentage replacement of total aggregate (coarse + fine aggregate), or of coarse aggregate only; however this is not always stated and can cause confusion.

1.3 Sustainability in the Concrete Industry

Recycling concrete is not an end in itself[9]. A full Life Cycle Assessment of the concrete structure, including the recycling phase at the end of its life, is required to assess the overall sustainable credentials of the structure. It is useful to place concrete in the context of the environmental impact of other construction materials. As regards the concrete manufacturing phase, much effort has gone into reducing the environmental footprint of cement manufacture. Cement manufacture is the target area for carbon emissions reduction efforts as it is this stage of production where the most greenhouse gas impact occurs. Transportation and delivery at all stages of concrete production is the second greatest source of impact. Any savings in transport by using recycled aggregate as compared to using natural aggregate reduce both the cost and the environmental burden. Also recycling concrete into aggregate tends to produce environmental benefit by preserving natural aggregate, a finite resource. Nevertheless the environmental impact of concrete manufacture is a small part of the Life Cycle Assessment, which is dominated by the operational phase of a product (e.g. a structure).

The importance of recycling waste concrete gained impetus with the publication of overseas research[10] which found that a significant quantity of the CO_2 released during the calcination process in cement manufacture has the potential to be chemically reabsorbed by concrete during its lifecycle. The amount of reabsorption depends on, amongst other things, the surface area of the concrete exposed to the atmosphere. By processing hardened concrete into aggregate-sized particles, its surface area is greatly increased, which increases its capacity to reabsorb CO_2. More recent research by Dayarem[11] using New Zealand cements indicated that the <10 mm fractions were almost completely recarbonated in the 21 day test duration[i]. The research found that recycled concrete aggregate with a water/cement of between 0.49 and 0.67 if allowed to recarbonate in a sufficient time frame, could reabsorb 70-83% of the original calcination CO_2 emissions. Higher strength concretes (and concrete containing SCM's) will take a longer time to carbonate.

The use of cement substitution and of recycled aggregate substitution is being acknowledged by the New Zealand Green Building Council with credit points (refer section 7.6). Currently (2011) this is a voluntary scheme, however the 'environmental lobby' is gaining in momentum and significant credibility is being placed on buildings with a 5 or 6 Star Rating. Government buildings are showing the way in that all new A-Grade office buildings being constructed to house Government staff in Central Business Districts must have a minimum 5 Star Rating, which represents New Zealand Excellence. A 4 Star Rating is required for B-Grade office buildings signifying New Zealand best practice standard. The Meridian building on the Wellington Waterfront was the first 5 star Green Star building in New Zealand and the use of concrete was instrumental in achieving that Rating[12]. To date, in New Zealand the use of recycled aggregate in concrete is usually driven by concrete building solutions for green credits through a stipulated level of recycled aggregate substitution and/or a level of cement reduction by using an SCM such as fly ash or blast furnace slag.

1.4 The Use of Recycled Aggregate in Concrete

The use of crushed aggregate from either demolition concrete or from hardened leftover concrete can be regarded as an alternative coarse aggregate, typically blended with natural coarse aggregate for use in new concrete. The use of 100% recycled coarse aggregate in concrete, unless carefully managed and controlled, is likely to have a negative influence on most concrete properties – compressive strength, modulus of elasticity, shrinkage and creep, particularly for higher strength concrete. Also the use of fine recycled aggregate below 2 mm is uncommon in recycled aggregate concrete because of the high water demand of the fine material smaller than 150 μm, which lowers the strength and increases the concrete shrinkage significantly.

Many overseas guidelines or specifications limit the percentage replacement of natural aggregate by recycled aggregate. In general leftover concrete aggregate can be used at higher replacement rates than demolition concrete aggregate. With leftover concrete aggregate, information will generally be known about the parent concrete – strength range and aggregate source etc., whereas

---

[i] The maximum CO_2 uptake was observed for the <10 mm fraction of the 20 MPa sample, which reabsorbed 420 kg CO_2/tonne cement. This equated to 83% of the calcination emissions originally released in cement production and reduces the net CO_2 released from 850 kg to 430 kg CO_2/tonne cement. Other recycled aggregate sizes showed some recarbonation but did not achieve the level of uptake of the 10 mm samples.

for demolition concrete very little information may be known about the parent concrete, and the resulting aggregate may be contaminated with chlorides or sulphates and contain small quantities of brick, masonry or timber which may adversely affect the recycled aggregate concrete. Often the sources of material from which a recycled aggregate came (and there could be more than one source), are unknown and the variability and strength of the recycled aggregate concrete could be adversely affected in comparison with a recycled aggregate concrete where the recycled aggregate came from one source with a known history of use and known strength. It is therefore necessary to distinguish between the properties of recycled aggregate concrete made using demolition concrete aggregate and that using leftover concrete aggregate.

Nevertheless, recycled aggregate concrete can be manufactured using recycled aggregate at 100% coarse aggregate replacement where the parent concrete, the processing of the recycled aggregate and the manufacture of the recycled aggregate concrete are all closely controlled. However as target strengths increase, the recycled aggregate can limit the strength, requiring a reduction in recycled aggregate replacement. Further details are given in section 6.2 and in the model specification in Section 8.0.

2.0 Processing Leftover Fresh Concrete

Typically between 2% and 5% of ready mixed concrete (termed leftover concrete) is surplus to requirements. It is estimated that around 30,000 m^3 of fresh concrete, mostly over-ordered surplus, requires disposal in Auckland alone per annum. Discharge on the construction site is no longer permitted and thus any leftover concrete is returned to the batch plant for disposal. It is estimated that washout volumes can be as high as 1,200 to 2,000 litres per truck per day[13].

Production of large amounts of waste wash water coming from ready mixed concrete plants has the potential to lead to problems of environmental impact. Local by-laws typically prohibit the discharge of such types of water, due to its extremely high pH value and suspended solids content, and require the water to be treated prior to discharge. Rainwater discharge from a ready mixed plant site also has to be contained and prevented from entering storm water systems or natural watercourses. All ready mixed plants have some type of wash water recycling system to minimise the need for resource consents to dispose of waste.

Renewal of long term resource consents often requires a complete replacement of the waste handling system to comply with higher environmental standards.

Recycling washout material reduces the amount of fresh water required for mix operations whilst minimising the amount of solid material which has to be disposed of.

2.1 Recycled Wash Water and Aggregate Recovery

Trucks returning from site to be washed out discharge into a 'concrete reclaimer' where the coarse aggregate and coarse sand are recovered from the 'liquid' fines for reuse.

Coarse aggregate recovered from fresh concrete can be recycled and considered as equivalent to virgin aggregate, provided the mortar is adequately washed out. Therefore, the use of recovered concrete aggregate is not specifically covered in this Guide.

The handling and disposal of the wash water, which contains cement and fine sand, presents a challenge to the concrete producer.

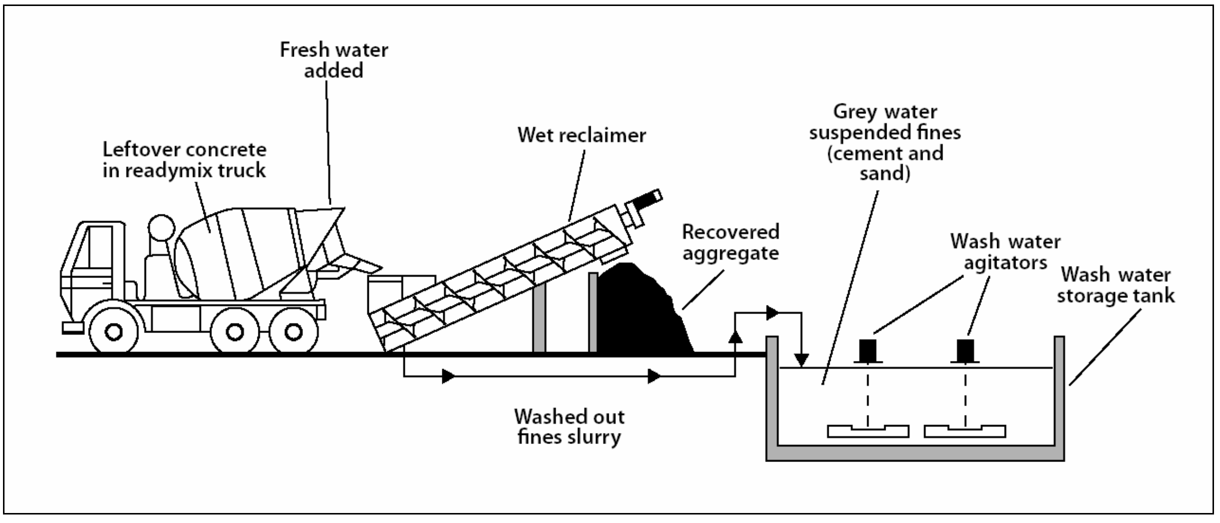


Figure 1: Typical system for recycling wash water/aggregate recovery

Typical rural low volume ready mixed plants operate a recycling system that settles the solids from the fines out of suspension and then allows reuse of the clear wash water. The solids that have settled are periodically removed and allowed to dry prior to disposal to landfill. For larger plants the amount of solid material to be disposed of is prohibitive, and a recycled wash water system (see Figure 1) is typically used.

Such systems agitate the wash water to maintain a suspension of cement and aggregate fines along with admixtures, pigments etc., termed 'grey water' or slurry. Its reuse in concrete manufacture, in comparison to using fresh water, is more technically demanding and requires additional control processes to ensure uniformity of the concrete. Agitation systems need to keep the solids material from settling out and forming a solid deposit at the bottom of the holding tank.

The consistency of recycled wash water is controlled by regular monitoring of its Specific Gravity (SG) and is adjusted by diluting the grey water with clear wash water or fresh water[13]. The SG typically can vary during the day or over a weekend from 1.07 to 1.20. The correct SG needs to be used in the mix design otherwise the added water and the yield of the concrete will be incorrect. Grey water from freshly recycled concrete will include cement particles that are still hydrating. This will then be mixed with partially hydrated or fully hydrated cements of varying ages, which can bring about unexpected setting properties of fresh concrete mixes. This is related to the chemistry of the grey water, and the fine particles acting as nucleation points for hydration. This effect on setting times, which also affects the finishing properties of concrete mix, is exacerbated in warmer weather. This can be overcome with the use of set-retarding admixtures. Also the use of hydration stabilising admixtures can be used to overcome the effect on setting times and even halt hydration completely for up to two or more days.

Mackechnie[14] examined the effect of the solids content of wash water on setting times. When slurry wash water was substituted for fresh water in the 17.5 MPa mixes, the initial set time, which was used as an indicator of the end of open time for finishing, was reduced by 2 hours in winter and 1½ hours in summer. The corresponding reduction in setting times for the 40 MPa mixes were 1½ hours in winter and one hour in summer. In contrast, the rate of slump loss was found to be similar for fresh water and wash water mixes. Comparison of final set times with respect to fresh water controls, shown in Figure 2, found that clear wash water reduces final set time by 5% on average.

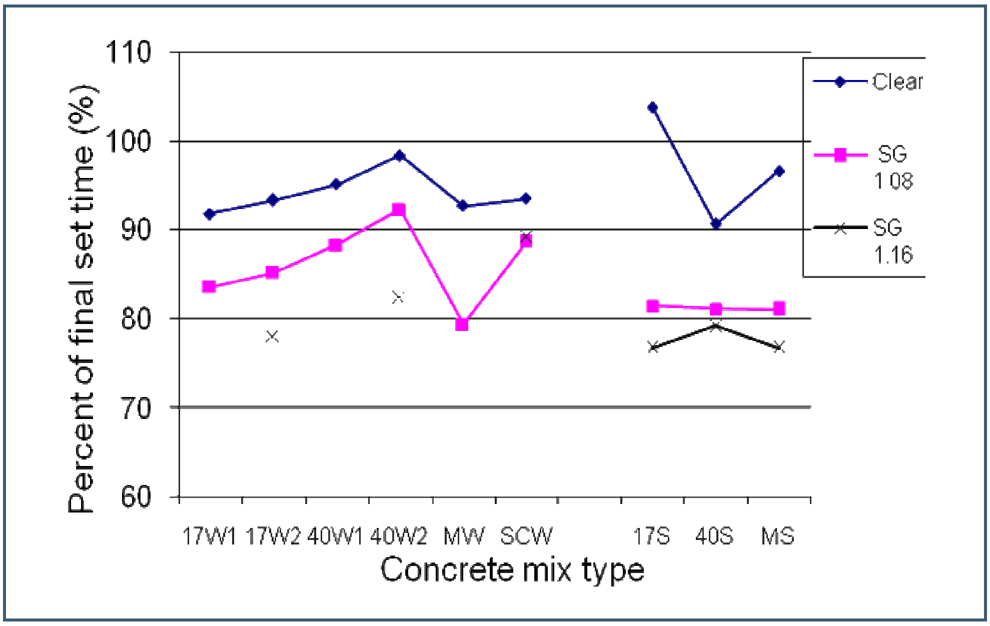


Figure 2: Comparison of final setting times with different wash water types

2.2 Requirements for Recycled Wash Water

New Zealand Standards do not specifically cover recycled wash water but such wash water would come under 'water from other sources' in NZS 3121:1986[15]. The compressive strength requirement of concrete using such water must be less than 90% of the compressive strength of concrete made with distilled water. At higher target strengths there is a significant loss of compressive strength with the use of grey water[16]. Recognising this, many ready mixed plants do not use grey water in concrete mixes for strengths greater than about 25 MPa.

NZS 3121:1986[15] limits sulphates as SO_3 to 1,000 ppm. The maximum limit for chlorides from all sources in concrete including wash water is specified in NZS 3101:2006[17] and NZS 3109:1997[18]. Also, the alkali in the wash water needs to be considered when assessing total alkalis for minimising the risk of ASR based on CCANZ's TR 3[19].

Overseas standards do have other controls on recycled water. For example, recommendations from BS EN 1008:2002[20] are shown in Table 2. In addition BS EN 1008:2002[20] requires that the total solids content of the wash water shall be less than 1% of the total mass of aggregates in the concrete.

Table 2: Controls on Wash Water (BS EN 1008:2002[20])

Substance	Maximum
Acids	PH > 4
Sugar	100 mg/l
Phosphates P_2O_5	100 mg/l
Nitrates NO_3^-	500 mg/l
Lead Pb^{2+}	100 mg/l
Zinc Zn^{2+}	100 mg/l

Hydrocarbon contaminants in grey water, arising from truck washing and mineral based formwork release agents, can be an issue[21].

The close control of grey water wash water systems is an important aspect in the quality control of a ready mixed concrete plant. Many plants limit the amount of grey water to about 30% of the wash water to limit the effects that the grey water has on setting times. The fresh concrete aspects of uniform setting time and finishing time in summer in particular are dependent on consistent SG's of the wash water. Overseas experience has found that no significant finishing issues arise provided that the SG is less than 1.07[22]. SG's can be maintained at or below this level by adjusting with fresh or clear water.

Generally, high volume city plants cannot rely on the recycled wash water system to recycle all their leftover concrete. The volume of slurry resulting is too high to utilise in the wash water with the '30% volume and below 25 MPa' restrictions quoted above. Therefore a proportion of the leftover concrete is allowed to harden and is crushed to make leftover concrete aggregate (see section 3.4), or is made into solid concrete blocks such as retaining wall blocks, which have commercial value.

3.0 Processing Hardened Concrete into Concrete Aggregate

New Zealand's production of natural aggregate per capita is relatively high at 11 tonnes per annum. In 2008 the UK and US the figures were approximately 5 tonnes and 8 tonnes[23] respectively. This is likely to reflect in the high New Zealand roading kilometres per capita. In Europe and North America, it is evident that where the demand for aggregates is high, and supplies of natural aggregates are scarce, the level of recycling activity is greatest. In New Zealand, this is becoming the case in Auckland where natural aggregate reserves are inaccessible because of land use constraint issues. In Auckland as the cost of quarrying and transporting aggregates (which are sourced some distance from urban areas) is high, the use of recycled aggregates can be economically viable. In other areas such as Christchurch, where river run gravel is sourced closer to the urban area, the cost of producing natural aggregates is low compared to the cost of recycled aggregate processing.

Worldwide there is a significant shortfall in the amount of demolition and waste concrete available, and the amount which could potentially be used as recycled aggregate in new concrete. In New Zealand it is estimated that there would only be enough to replace between 1% and 2% of natural aggregate[1]. In UK where there is a 10% levy on extraction of natural aggregate, the use of recycled aggregate and secondary aggregates is the highest in Europe. WRAP[4] reports that it is economic to use recycled aggregates along with natural aggregates, however this is currently limited to 25% replacement of coarse aggregate owing to the shortfall in recycled and secondary aggregate supply. There is scope for better utilisation of secondary aggregate sources in the future to increase this to 30%.

Processing of hardened concrete refers both to crushing demolition concrete and to crushing leftover concrete. However, recycled concrete aggregate is different from leftover concrete aggregate, as demolition concrete tends to have a higher level of contamination (chlorides, oils etc.). Moreover leftover concrete will generally be crushed at an earlier age so leftover concrete aggregate will have less adhered mortar than recycled concrete aggregate. The presence of adhered mortar on the surface of crushed concrete aggregate generally degrades the quality of the recycled aggregate and consequently the fresh and hardened properties of concrete made from it.

Recycled fine aggregate is rarely used in recycled aggregate concrete because of the increase in water demand and effect on compressive strength and shrinkage. Control of the amount of material passing the 150 µm sieve is an issue. Also it is difficult to accurately determine the absorption, saturated surface dry (SSD) condition and free water content of such fine material. Depending on the age of crushing, recycled fine aggregate retains some cementitious capacity, which can be desirable in low strength concrete applications such as trench fill.

3.1 Logistics of Recycled Aggregate Production

The location of recycled aggregate production will normally be dictated by the availability of a suitable aggregate crushing plant in the vicinity of the concrete plant making recycled aggregate. For use of leftover concrete aggregate, the ideal situation is where the concrete plant and aggregate plant are on the same site thus minimising the cartage of the leftover concrete to the crushing plant. It may be feasible to return leftover concrete from other plants nearby for processing; however the additional cartage distance of the returning trucks needs to be a consideration. The proximity of a source of demolition concrete to a crushing plant and onto the concrete plant is also a consideration.

Large cartage distances need to be weighed up against the cartage distances of natural aggregate. The use of mobile crushing plants strategically located can reduce the demolition concrete and recycled aggregate cartage distances and can be justified on larger projects.

Recycled aggregate requires additional space at the crushing plant and the concrete plant. The availability of space at each plant will dictate whether the recycled aggregate is stockpiled at the concrete plant in advance of production or if the aggregate is delivered on an 'as-required' basis. Urban crushing plants in particular may have limited storage space. Recycled aggregate bin storage and batch weighing at the concrete plant need to be accommodated.

Recycled aggregates in storage or stockpile will result in alkaline runoff which needs to be intercepted and directed to recycling ponds for treatment and safe disposal, thus preventing runoff from reaching storm-water systems discharging into natural watercourses.

3.2 Influence of Parent Concrete

Research on recycled aggregate concrete has clearly demonstrated that the processing level and the quality of the parent concrete has an influence on the quality and consistency of the recycled aggregate and the concrete made from it. Additional processing and a higher strength parent concrete results in an improvement to the strength of the recycled aggregate concrete. However the yield of coarse aggregate for each tonne of parent concrete reduces with prolonged processing, resulting in increased cost. If leftover concrete is crushed at an early age, there will be less adhered mortar because the cement aggregate bond in the parent concrete has not fully developed. This would be typical of aggregate recycled from returned concrete, most of which will be in the strength range 17.5 MPa to 25 MPa.

For natural aggregate concrete, it is generally recognised that that the controlling factor limiting the strength of the cement-aggregate matrix is a porous narrow band which forms at the cement paste/aggregate interface called the 'Interfacial Transition Zone'. For recycled aggregate concrete there are effectively two transition zones, between the old adhered mortar and parent aggregate, and between the old mortar and the new cement paste. Generally the recycled aggregate has more influence than natural aggregate on the properties of the recycled aggregate concrete. This is because the processing of the recycled aggregate can result in micro cracks at the parent aggregate/adhered mortar interface. The strength of the adhered mortar can also limit the strength of the recycled aggregate concrete particularly where the parent concrete strength is lower than the target compressive strength of the new recycled aggregate concrete.

3.3 Production of Concrete Aggregate from Demolition Material

Recycled aggregates to be produced from aged concrete that has been demolished and removed from foundations, pavements, bridges or buildings, is crushed and processed into various size fractions. Reinforcing steel and other embedded items, if any, must be removed and care must be taken to prevent contamination by dirt or other waste building materials such as plaster or gypsum. It is prudent to store old concrete separately to other demolition materials to help avoid contamination. Records of the history of the demolition concrete – strength, mix designs etc. – would seldom be available, but if available these will be useful in determining the potential of the recycled aggregate concrete.

3.3.1 Processing

There are few dedicated facilities for recycling infrastructure construction materials in New Zealand. However, recycled concrete aggregates can be produced in plants similar to those used to crush and screen conventional natural aggregates. Large protruding pieces of reinforcing steel are first removed using hydraulic shears and torches. Then most recyclers use a jaw crusher for primary crushing because it can handle large pieces of concrete and residual reinforcement. Jaw crushers also fracture a smaller proportion of the parent concrete aggregate. The residual reinforcement is removed by large electro-magnets. Impact crushers are preferred for secondary crushing as they produce a higher percentage of aggregate without adhered mortar. In general the shape of recycled aggregate is rounder and less flaky than natural aggregate.

Most recycling plants have both primary and secondary crushers. The primary crusher usually reduces material down to 60-80 mm which is fed into a secondary crusher. The material from the secondary crushing then passes through two screens that separate the aggregate into sizes greater than 19 mm, between 19 mm and 7 mm, with the material finer than 7 mm being removed (and used as road metal). The plus 19 mm material is fed back into the secondary crusher. The 7-19 mm fraction is screened to produce coarse aggregate complying with the grading requirements of NZS 3121:1986[15].

Aggregate reclaimed from demolition concrete with fully hydrated cement could contain a significant amount of adhered mortar. Prolonged processing will reduce the amount of adhered mortar. Moreover, there will be relatively more adhered mortar on the 13 mm aggregate than on the 19 mm aggregate.

Wet processing improves the quality of the aggregate, with less dust or organic matter and improved separation and classification; however such plants are more costly, have a significant water demand and therefore are few in number. However in the Netherlands the introduction of wet processing plants has played an integral part of the increase in use of recycled concrete aggregate[24].

3.3.2 Removing Contaminants

If contaminated recycled aggregate is delivered to the ready mixed concrete plant, resources for removing the contaminants are unlikely to be available and use of the material will be problematic. Contaminants requiring removal may include asphalt, cladding materials, soil and clay balls, wood, glass, gypsum, asbestos, reinforcement and metals, joint sealants, lightweight brick and concrete, plaster, plastics, rubber, tile, vinyl, paper and various roofing materials. If there is a significant amount of contamination, the cost of removal may prohibit use of the recycled aggregate as concrete aggregate, and instead its use as foundation material in civil works should be considered.

Significant contamination will largely be avoided if concrete is separated from other building materials early in the demolition process. Demolition companies typically are not set up to remove contaminants to the degree necessary for use as recycled concrete aggregate. Often bulk demolition concrete will be sold on to a concrete aggregate producer to process, crush and screen to the required standard.

3.3.3 Hazardous Demolition Materials

Materials from demolition sites may be contaminated with hazardous materials. Procedures on the demolition site to contain and treat hazardous materials to minimise this risk of contamination should be in place. However, there is still a risk that the material may become contaminated during subsequent handling, transportation and/or storage.

The demolition contractor should be able to provide documented evidence that recycled concrete from a known source is free of hazardous materials.

Demolition concrete from an unknown source, or multiple sources, is more difficult to assess for hazardous contamination.

As regards asbestos contamination, demolition concrete from an unknown source should be regarded as being contaminated, and the risks managed in accordance with a comprehensive guideline for the management and removal of asbestos, e.g. the *New Zealand Guidelines for the Management and Removal of Asbestos*[25].

3.4 Production of Leftover Concrete Aggregate

Leftover concrete that is to be left to harden and be crushed is usually discharged on return to the concrete plant in an area set aside for this purpose and convenient to the plant's operation. Where trucks are washed out, they should be discharged in a separate area for processing as outlined in Section 2.0.

At a typical plant, most of the leftover concrete would be in the strength range 17.5 MPa to 25 MPa. Normally no attempt is made to separate different grades of leftover concrete. However, this is feasible where leftover concrete of a higher strength from a particular project is discharged separately for later use as leftover concrete aggregate for a higher strength recycled aggregate concrete.

Production of crushed leftover concrete is based on the same crushing plant equipment and process as outlined in section 3.3.1. The source and compressive strength range of leftover concrete is generally known, and contamination is not the issue it is with recycled demolition concrete.

The age at which the parent concrete is crushed will influence the strength of the concrete made from the recycled material. Concrete made from leftover concrete aggregate that is processed at an early age, within a relatively short period, can benefit from cementitious action of any unhydrated or partly hydrated cement in the parent concrete. Canadian research[26] found that concrete made from leftover concrete crushed 24 hours after mixing achieved 25% higher strength than the control parent concrete. Concrete crushed seven days after casting only achieved 93% of the strength of the parent concrete. Thus there is potential to optimise the performance of leftover concrete aggregate by closely managing the crushing and management of stockpiles.

4.0 Characteristics of Recycled Aggregates

4.1 Physical Properties

A substantial UK based aggregate research programme was carried out for WRAP[4] by the Concrete Technology Unit, Dundee University, primarily to investigate a method for classifying recycled aggregates. 125 mixes were cast and tested using different types of aggregate, and results showed that the use of up to 20% recycled aggregate by mass of coarse aggregate had little effect on the performance of the concrete. Three classes of recycled aggregate were proposed, A, B & C as being suitable for mild, moderate and chemically aggressive/marine environments respectively. The results of the WRAP programme were considered when BS EN 12620[27] and BS 8500-26[28] were revised in 2008 and 2006 respectively, however the three recycled aggregate classes were not included in the standards.

The variability in the physical properties of recycled aggregate will depend on the variability of the parent concrete. Recycled concrete aggregate which has been sourced from a number of demolition concretes will have greater variability than recycled concrete aggregate from one demolition concrete source, and this is likely to have an effect on the uniformity of the recycled aggregate concrete.

The crushing resistance of recycled concrete aggregate, i.e. the *ten percent fines* value, when tested in accordance with NZS 3111:1986[29], will generally be lower than the value of the parent aggregate. The amount of adhered mortar present when dislodged under test load will influence the test result. However, recycled aggregate will still generally pass internationally industry accepted requirements.

Reasonably well graded coarse recycled aggregate can be produced with a jaw crusher. The gradation ranges of recycled aggregate need be no different to those for natural aggregates. Most New Zealand ready mixed plants use two coarse aggregate size ranges: 19 mm to 9.5 mm and 13.2 mm to 4.75 mm to NZS 3121:1986[15].

Use of fine recycled aggregate material (i.e. less than 4.75 mm) is not recommended in structural concrete because of the increased water demand, and related consequences.

Typically 30% to 60% by volume of old mortar will adhere to recycled concrete aggregate particles depending on the aggregate size and the nature of the parent aggregate, with the smaller size fractions, and rougher, more porous aggregate[30] having a higher volume. Because of the adhered mortar, the specific gravity of recycled aggregate will be somewhat less than natural aggregate. The recycled aggregate density will still exceed 2,000 kg/m^3 however, and is regarded as normal weight aggregate.

A classification system, *'Segregate',* was proposed by Tam & Tam[31] for assessing the quality of the adhered mortar. This has a close correlation with recycled concrete aggregate density and absorption. Derivation of the index is based on sieve analysis of the aggregate before and after a period of stirring and agitation which causes mortar samples to shear and rub off. The index can be used as a key factor in determining the behaviour of the recycled aggregate concrete.

The absorption values of recycled concrete aggregates at between 4% and 8% are significantly higher than the equivalent natural aggregate owing to the presence of adhered mortar. Therefore the aggregate bins need to be kept wet to ensure the moisture content is above saturated surface dry. Recycled aggregates may have more variable water absorption properties than natural aggregate, which demands closer attention to slump control.

Tests on drying shrinkage as part of the WRAP programme satisfied the BS 8500-2:2006[28] requirement of 0.075%.

Regarding abrasion resistance, research[5] in the US showed that all recycled aggregate, except that from the poorest concrete, met the minimum LA abrasion resistance requirements specified in ASTM C33/C33M-11a[32].
Weathering resistance of recycled aggregate can be considered satisfactory if the parent concrete was durable in its previous life. If the exposure environment of the new concrete is to be significantly more aggressive than the parent concrete, a weathering resistance test should be carried out such as that given in NZS 3111:1986[29]. Other ways in which recycled aggregate materials affect concrete durability are described in section 6.2.7.

Research on leftover concrete aggregate was carried out for the US National Ready Mixed Concrete Association (NRMCA)[5]. The findings of this research showed similar trends of higher absorption and lower density for recycled concrete aggregate, but the differences from natural aggregate were smaller owing to the fact that there is generally less adhered mortar on the leftover concrete aggregate.

4.2 Chemical Properties

Establishing chemical properties of recycled concrete aggregate is important because the history of the demolition concrete is unlikely to be known.

For leftover concrete, because the properties of the parent concrete correspond to the properties of natural aggregate processed by a particular ready mixed concrete plant, there is less uncertainty about the chlorides, sulphates and alkali present than for recycled aggregate concrete. Therefore contaminants are not the issue for leftover concrete aggregate that they are for recycled concrete aggregate.

4.2.1 Alkalis and Alkali Reactivity

When the use of recycled aggregate in concrete was first introduced, the potential for alkali leaching from recycled aggregate concrete was considered to be an issue. However comparative tests with standard concrete have shown that there is no additional leaching from recycled aggregate concrete when compared to concrete using natural aggregates[33].

Research by Shehata et al[34] on concrete made with recycled aggregate sourced from parent concrete that was exposed for 12 years and known to be undergoing active alkali silica reaction (ASR) expansion, found that the recycled aggregate was at least as reactive as the original siliceous limestone aggregate used for the parent concrete. This is thought to be due to:

(a) The alkali contributed from the adhered mortar.

(b) Expansion of the existing ASR gel in the recycled concrete aggregate when exposed to higher levels of moisture in the recycled aggregate concrete.

(c) Fresh exposed faces of the original aggregate broken during crushing of the parent concrete.

(d) Swelling of the adhered mortar on the recycled concrete aggregate is believed to compound the ASR expansion in the recycled aggregate concrete.

The fine recycled aggregate was found to be less reactive than the coarse aggregate as it contained less of the reactive aggregate component.

In other research by PCA[35], the ASR expansion in recycled aggregate concrete made from parent concrete undergoing active ASR was dependant on the alkali availability in the recycled aggregate concrete and not on the alkali present in the parent concrete. However the use of low alkali cement in the recycled aggregate concrete, as in concrete made from natural aggregate, did not always reduce expansions to safe levels. In some instances the use of supplementary cementitious materials (SCM's) will be necessary in recycled aggregate concrete to mitigate against ASR.

Thus provided measures are taken to minimise the risk of ASR in the new recycled aggregate concrete, it is possible to use concrete containing potentially reactive aggregates as recycled aggregate. However it is more straightforward to use concrete containing non-reactive recycled aggregate. In the case of leftover concrete aggregate, the source of the parent aggregate is generally known, however this is unlikely to be the case for recycled concrete aggregate processed from demolition concrete. Historic knowledge of concrete aggregate in the region where the demolition concrete was sourced may however indicate whether the aggregate is likely to be reactive. The replacement level of recycled aggregate is another factor to consider.

Recycled concrete aggregate has the potential to contribute alkali to new concrete from adhered mortar. The potential for ASR in recycled aggregate concrete, and criteria to avoid ASR, described in BRE Digest 330[36] and summarised in section 7.2.3.

4.2.2 Chlorides

The recycled concrete aggregate is a potential source of chloride which must be added to other chloride sources when checking for compliance with NZS 3109:1997[18] and NZS 3101:2006[17] requirements for the maximum allowable chloride levels in concrete.

4.2.3 Sulphates

NZS 3101:2006[17] specifies a maximum limit for acid soluble sulphate in concrete. It may be measured directly or calculated from the sulphate contents of the concrete constituents. The sulphate limit for recycled concrete aggregate in British Standard BS 8500-2:2006[28] is 1% by mass of aggregate.

4.2.4 Other Salts

NZS 3101:2006[17] stipulates that other salts shall not be added to concrete unless it can be shown that they do not adversely affect durability.

Gypsum contents less than 5% have been found to have no significant effect on recycled aggregate concrete strength[37].

5.0 Manufacture of Recycled Aggregate Concrete

5.1 Concrete Mix Proportions

Mix proportioning of recycled aggregate concrete will depend on the percentage replacement of coarse aggregate by recycled aggregate. Up to 20% replacement level, substitution of coarse aggregate with adjustment only for the specific gravity of the recycled aggregate may be all that is necessary. At higher aggregate replacement levels, adjustments may need to be made to the aggregate proportions to account for the grading, shape and texture of the recycled aggregate. Admixture quantities may also need adjustment.

At higher levels of coarse aggregate replacement, the water demand of the recycled aggregate concrete will increase for a given workability and either a small increase in cement content may be necessary, or alternatively the use of water reducing or superplasticising admixtures to maintain target strength requirements. The increase in water demand will be dependent on the recycled aggregate source and properties. The compressive strength of the parent concrete will also influence the strength potential of the recycled aggregate concrete, particularly at higher target strengths. (See sections 3.2 and 6.2).

The addition of a fly ash can be used to increase workability without increasing the mix-water and thus long term strength can be maintained. Because there is a significant strength gain beyond 28 days with some fly ashes, the age for acceptance of concrete could be increased from 28 to 56 days if fly ash is used. The use of fly ashes and other SCM's as a cement replacement in combination with recycled aggregate has the potential to gain maximum credit points under the current New Zealand Green Building Council[3] scheme.

Crushed recycled fines are not often used in recycled aggregate concrete. However one investigation into uses for recycled fines has found it viable to use 10% to 30% of recycled fines as a percentage of the total fine aggregate[38]. Use of fine recycled concrete aggregate generally results in comparatively higher strength gain beyond 28 days owing to ongoing cementing action of the fines.

5.2 Concrete Mixing Regime

Tam et al[39] proposed a two stage mixing approach (TSMA) for recycled aggregate concrete. This was advocated to improve the quality of recycled aggregate concrete. In the first stage, mixing takes place for 60 seconds but with only half the mix water added. A thick layer of cement slurry is created on the surface, which then permeates the porous adhered mortar, filling the cracks and voids. Microscopic analysis showed that a TSMA is thus instrumental in filling the unfilled cracks on the surface of the recycled concrete aggregate. The mixing process is completed in the (two minute) second mixing stage by adding the remaining water, creating a strengthened interfacial zone (ITZ), which leads to improved performance in the recycled aggregate concrete.

In another study it was reported[40] that dry mixing of the recycled concrete aggregate before adding the other ingredients resulted in higher compressive and tensile strength and modulus of elasticity. It was theorised that the dry mixing improved the shape of the recycled concrete aggregate, and adhered mortar is removed from the recycled concrete aggregate during this premixing. Also fine particles of unhydrated cement are released in the breaking up of the adhered mortar, and contribute to overall cement hydration.

Nevertheless, the two studies showed that the mixing procedure can influence concrete properties. Modification of the standard mixing process may in some cases help to improve the properties of recycled aggregate concrete without significantly altering the mix proportions.

Special mixing procedures such as those outlined above may not be very practical in a conventional ready mixed concrete plant. In practice most recycled aggregate concrete can be produced in conventional ready mixed concrete plants without modification to the standard mixing cycle.

6.0 Recycled Aggregate Concrete Properties

6.1 Fresh Concrete Properties

6.1.1 Concrete Density and Air Content

The fresh density of recycled aggregate concrete at 100% replacement of coarse aggregate will generally be 5% to 10% lower than the corresponding natural aggregate concrete owing to the adhered mortar on the recycled coarse aggregate[4].

The entrapped air content of the recycled aggregate concrete is generally higher than corresponding natural aggregate concrete and thus the air entraining admixture dosage may need to be reduced to maintain the target air content. However the use of fine recycled aggregate will require an increase in air entraining agent.

6.1.2 Workability

Recycled aggregate concrete made from crushed leftover concrete may in general require a small cement adjustment to compensate for increase in water demand. Concrete made from demolition concrete, which generally has a harsher texture from the increased adhered mortar will have an even higher water demand.

Increased cement contents are more likely to be necessary for higher percentages of recycled aggregate replacement and for higher specified strengths of the recycled aggregate concrete. Adjustment to air entraining and plasticising admixtures will assist in minimising any increase in cement content.

Mixes which have high contents of recycled concrete aggregate can become harsh, less cohesive and exhibit increased bleeding. These problems can be reduced by using a suitable SCM[24].

In New Zealand research by Zhang et al[41], three grades of recycled concrete aggregate were made by crushing 20 MPa, 40 MPa and 60 MPa purpose-made natural aggregate concrete slabs. The concrete slabs were approximately one month old when crushed. Three grades of recycled aggregate concretes – 20 MPa, 40 MPa and 60 MPa – were made from each of these recycled concrete aggregates, making nine mixes in total. The recycled concrete aggregates were used at a 100% replacement level, along with natural fine aggregate. The cement contents of the recycled aggregate concrete mixes were increased approximately 5% from the equivalent natural aggregate mixes to maintain target water/cement ratios. The initial slumps were between 100 mm and 120 mm.

On average the recycled aggregate concrete mixes tested by Zhang et al[41] showed a greater rate of slump loss than the natural aggregate equivalents. The 40 and 60 MPa recycled aggregate concretes showed significantly greater slump loss than their natural aggregate counterparts; thus as the recycled aggregate concrete strength increases, there is a greater rate of slump loss.

It is important that recycled concrete aggregates are stored for at least 24 hours at or above SSD moisture state, otherwise there will be a rapid slump loss as water is drawn into the recycled aggregates on mixing.

6.2 Hardened Concrete Properties

6.2.1 Compressive Strength

Figure 3 shows the compressive strength development to 56 days of the 100% recycled aggregate concretes made from the three parent concretes and the corresponding natural aggregate concrete from the Zhang et al[41] research described in section 6.1.2.

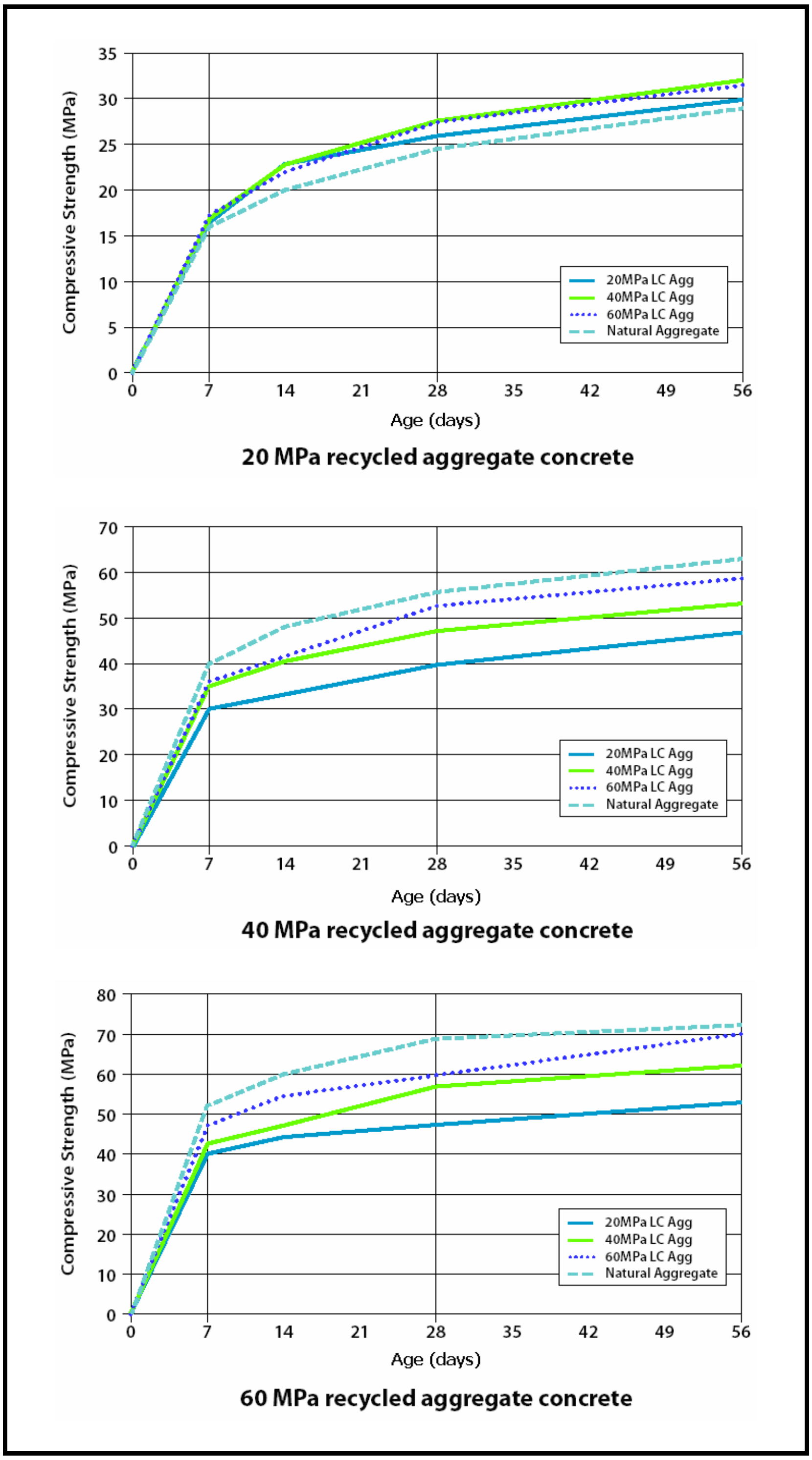


Figure 3: Compressive strength development of recycled aggregate concrete by Zhang et al[41]

The graphs in Figure 3 show:

- All three 20 MPa recycled aggregate concretes were stronger at 28 and 56 days than their natural aggregate concrete counterparts, and their 28 day strengths exceeded the target 28 day strength of 24.5 MPa

- All three 40 MPa recycled aggregate concretes were weaker at all ages than their natural aggregate concrete counterparts. The concretes made with 40 and 60 MPa recycled concrete aggregate reached the 28 day target strength of 47.5 MPa, but the recycled aggregate concrete made with 20 MPa recycled concrete aggregate had not reached this target even at 56 days

- All three 60 MPa recycled aggregate concretes were weaker at all ages than their natural aggregate concrete counterparts. They did not reach the target 28 day strength of 69 MPa at 28 days, but the 60 MPa recycled aggregate concrete made with the 60 MPa recycled concrete aggregate reached this strength at 56 days.

- The 60 MPa recycled aggregate concrete made with 60 MPa recycled concrete aggregate was 10 MPa weaker than its natural aggregate counterpart at 28 days.

- Specifying 56 day compressive strengths instead of 28 day compressive strength may help to achieve the desired concrete performance, but this needs to be determined on a case by case basis by trial mixing and testing.

It should be noted that Zhang et al[41] used 100% recycled aggregate in their mixes. Lower replacement levels of recycled aggregate would have less effect on the concrete strengths. However, the strength of the parent concrete has the effect of providing a ceiling strength for a recycled aggregate concrete derived from that parent concrete, as explained in section 3.2.

Research at Kingston University in the UK[42] compared natural gravel aggregate concrete with concretes made from up to 100% recycled concrete aggregate, which contained 1.7% masonry and 4.1% asphalt. The cement and water contents were kept the same for natural aggregate and recycled aggregate mixes. Replacement rates of up to 30% coarse aggregate did not affect compressive strength. This suggests that maintaining the water/cement ratio is more important.

Recycled aggregate concrete is generally reported to be between 15% and 40% weaker than natural aggregate concrete. Many factors influence this strength reduction, including:

1. The strength of parent concrete.
2. Multiple sources of parent concrete verses one source.
3. The source of the recycled aggregate (demolition waste vs. leftover concrete).
4. The specified strength of recycled aggregate concrete.
5. Amount of adhered mortar on recycled aggregate.
6. Percentage replacement of recycled coarse aggregate.
7. Use of fine recycled aggregate.
8. Adjustments to entrained air and water content to maintain workability.

The Kingston University research[42] concluded that the use of recycled concrete aggregate as partial replacement for natural aggregate has potential. However, there may be areas where the use of recycled aggregate concrete should be viewed with caution. Special design considerations may be required for higher compressive strengths, members sensitive to creep and shrinkage, and where precautions against ASR or chloride attack need to be taken.

6.2.2 Tensile Strengths

Tensile and flexural strengths of recycled aggregate concrete at 100% replacement level have been found to have the same or at most 10% lower strength than the natural aggregate concrete counterpart[4]. Using recycled fine aggregate could reduce this by a further 20%.

6.2.3 Modulus of Elasticity

Various researchers have shown that there is a reduction in the modulus of elasticity (MOE) of recycled aggregate concrete at 100% replacement level compared to its natural aggregate equivalent by between 6% and 33%. Generally, recycled aggregate concrete with lower proportions of recycled concrete aggregate has a smaller reduction in MOE.

6.2.4 Drying Shrinkage

Twenty to 50% higher shrinkage levels are reported in recycled concrete aggregate mixes at 100% replacement level when compared to their natural aggregate counterpart. This increases to 70% to 100% when fine recycled concrete aggregate is used[43]. The higher shrinkage compared to natural aggregate concrete is thought to result from the adhered mortar on the coarse aggregate, which does not provide the degree of restraint to shrinkage that a natural aggregate does.

Any increase in water demand stemming from the use of recycled aggregate will increase concrete drying shrinkage relative to natural concrete aggregate[4]. The judicious use of water reducing admixtures could alleviate this.

6.2.5 Creep

Researchers have found recycled aggregate concrete to have 30% to 60% greater creep compared with natural aggregate concrete depending on the replacement level. Theoretically the combined effects of creep and shrinkage would moderate any increased risk of shrinkage cracking in flatwork using recycled aggregate concrete.

6.2.6 Abrasion Resistance

The abrasion resistance of concrete is largely influenced by compressive strength, mix proportions, finishing and curing. WRAP[4] research showed only small differences in the abrasion resistance of concrete for up to 30% replacement level of recycled coarse aggregate.

Abrasion resistance is a consideration for heavy duty floors and pavements, and the use of recycled aggregate concrete for these applications is not generally recommended. However, it may be suitable if the recycled aggregate meets or exceeds ASTM C33/C33M-11a[32] requirements, and accelerated abrasion tests show that a suitable abrasion resistance can be achieved.

6.2.7 Durability

In the Kingston University research[42] referred to in section 6.2.1, there was no reduction in freeze thaw resistance or increase in permeability or penetrability in the concrete for recycled aggregate replacement levels of up to 30%.

The WRAP[4] research reported that the carbonation depth actually decreased as the recycled aggregate content increased. This was thought to be due to the increased alkalinity from the increased cement content used and the adhered mortar on the aggregate. There is likely to be an optimum level at which the increased porosity from recycled aggregate replacement overrides the increased alkaline reserve.

Further research from Dundee[44] on high strength recycled aggregate concrete showed that water absorption and air permeability increased significantly when the recycled coarse aggregate replacement level is above 30%. This research also showed that chloride diffusion rates were not affected even at 100% replacement, but chloride induced corrosion rates increased slightly.

It has been shown, generally, that chloride ion penetrability increases with increasing replacement percentage of recycled concrete aggregate. The porous surface of the recycled aggregate due to the adhered mortar may provide a less tortuous route for chloride ion ingress. Research in Argentina[45] looked at the effect of recycled aggregate on chloride penetration and binding capacity under marine exposure. Whilst there was an increase in chloride ingress, this was compensated for by an increase in chloride binding capacity. Thus the water soluble chloride contents in natural aggregate concrete and recycled aggregate concrete were similar for up to 18 months exposure. The influence of water/cement ratio on the recycled aggregate concrete was found to be more important than the recycled aggregate porosity.

Other researchers[46,47] who have looked at chloride ingress only, have found that the addition of SCM's has given recycled aggregate concrete a similar performance in marine environments to natural aggregate concrete, i.e. the effect of the recycled aggregate is less than the effect of cover depth and binder composition. Consequently, the durability design principles of NZS 3101:2006[17] for natural aggregate concrete should also apply to recycled aggregate concrete.

6.3 Recycled Aggregate Concrete Production Variability

In general, coefficients of variation for recycled aggregate concrete compressive strength up to 100% replacement level can be similar to those for natural aggregate concrete. If demolition aggregates are drawn from a variety of sources, however, then the coefficient of variation will increase.

ACI 555R-01[48] gives the variation in compressive strength of 12 recycled aggregate concretes with 100% coarse aggregate replacement based on a single mix design but using recycled aggregate crushed from various 15 year old demolition concrete sources with strengths ranging from 39 to 85 MPa. The target water/cement ratio of the recycled aggregate concrete was 0.57 and the resulting compressive strength ranged from 30 to 49 MPa (mean 39.7 MPa).

The coefficient of variation (COV) was 12%, which is greater than the maximum value given in NZS 3104:2003[8] for all but grade 17.5 MPa concrete. The standard deviation (S_d) was 5, which is classified as a 'Fair' standard of control for concretes with a strength up to 35 MPa in ACI 214R-11[49].

The variation in recycled aggregate concrete strength is strongly influenced by the recycled aggregate variability, whereas in natural aggregate concrete the variability of aggregate quality is not generally a primary controlling factor on strength. Leftover concrete aggregate from a single source will generally have less variability than demolition concrete.

7.0 Regulatory Environment for the use of Recycled Aggregate Concrete

The following section outlines existing standards, regulations and guidelines related to the use of recycled aggregate in concrete overseas[50]. The British and USA regulations are the only ones of those described herein to distinguish between recycled concrete aggregate and leftover concrete aggregate. It can be assumed that the regulations for all other countries listed refer to recycled concrete aggregate in particular, but should also cover leftover concrete aggregate.

7.1 New Zealand Standards

The current New Zealand Standard NZS 3121:1986[15] does not specifically mention recycled aggregate. However, the deleterious material requirements and performance criteria generally applying to coarse aggregate can be used to apply to natural aggregate blends with recycled aggregate.

7.2 United Kingdom

7.2.1 Limits on Aggregate Quality

BS EN 12620:2002 + A1:2008[27] specifies requirements for testing recycled aggregates. These requirements include chloride content, influence on initial setting time of cement, constituents of coarse recycled aggregates, particle density and water absorption, water soluble sulphate and alkali content. BS 8500-2:2006[28] sets out recycled aggregate material composition restrictions and production control procedures based on composition and loose bulk density.

BS 8500-2:2006[28], which is the complementary British Standard to BS EN 206-1:2000[51], refers to two types of recycled aggregate: recycled concrete aggregate (RCA) and recycled aggregate (RA). Table 3 gives the allowable limits for contaminants in both recycled concrete aggregate (RCA) and recycled aggregate (RA).

Table 3: BS 8500-2:2006[28] Requirements for coarse recycled concrete aggregate (RCA) and coarse recycled aggregate (RA) (% by weight)

Type of Aggregate	Maximum masonry content	Maximum fines	Maximum lightweight material < 1,000 kg/m³	Maximum asphalt	Maximum glass, plastic, wood.	Maximum acid-soluble sulphate
RCA[(a)]	5	5	0.5	5.0	1.0	1.0
RA[(b)]	100	3	1.0	10.0	1.0	[(c)]

(a) Where the material is to be obtained by crushing hard concrete of known composition that has not been in use and has not been contaminated during storage, as for leftover concrete aggregate, the only requirements shall be for grading and maximum fines.

(b) RA may only be used for non-structural, unreinforced concrete 16 MPa or below. See Table 6.

(c) Limits and test methods for sulphate to be determined on a case by case basis.

BS 8500-2:2006[28] specifies some general requirements for coarse recycled aggregate. Because the potential composition of recycled aggregate (RA) is so wide, additional specification clauses may be required on a case by case basis. In particular, a project specification should include maximum acid soluble sulphate, method for determining the alkali content, ASR reactivity and any limitations on use in concrete. Recycled aggregate (RA) is limited to concrete cylinder strength of 16 MPa.

Provisions for the use of fine recycled concrete aggregate and fine recycled aggregate are not given in BS 8500-2:2006[28], but it does not preclude their use where it can be demonstrated, due to the source of material, that significant quantities of deleterious materials are not present. Fine recycled concrete aggregate should be assessed on a project specific basis. For instance, crushed gypsum plaster from building demolition waste can end up in fine recycled concrete aggregate, and excess gypsum can lead to cement setting problems, and the formation of ettringite in the concrete after it has hardened (which can crack the concrete).

Amendment A1 to BS 8500-2:2006[28] requires the proportions of constituent materials in coarse recycled aggregate to be determined in accordance with a visual sorting test - BS EN 933-11:2009[52]. This allows the producer to declare conformity with the requirements of BS EN 12620:2002[27].

7.2.2 Limit on Recycled Aggregate Concrete (RAC)

Table 3 of BS 8500-2:2006[28] limits the cylinder strength of concrete using coarse recycled concrete aggregate to 40 MPa. Recycled aggregate concrete containing crushed leftover concrete has no strength limitation provided the aggregate is not contaminated. For concrete cylinder strengths of 20 to 40 MPa, a maximum of 20% replacement of coarse aggregate applies, for designated concrete.

BS 8500-2:2006[28] also places a restriction on the exposure classes in which recycled aggregate concrete can be located. Recycled aggregate concrete can be used for unreinforced concrete, internal concrete, and external concrete not exposed to chlorides or subject to de-icing salts, but is effectively excluded from sites with marine and other chloride exposure, from all but 'moderate' freeze thaw environments, and in aggressive soils. It also cannot be used in designated concrete for foundations or paving. However the recycled aggregate concrete can be used in such excluded zones if durability tests can demonstrate its suitability for the intended environment.

In determining whether the maximum chloride content of the concrete specified meets the requirements of BS EN 206-1:2000[51], the variability of the chloride contents of the recycled aggregates shall be taken into account.

7.2.3 Alkali Silica Reaction

The following details are taken from BRE Digest 330 Part 2 2004[36], which is referenced in BS 8500-2:2006[28].

Recycled aggregate (RA), for which the composition has a wide range, is by default classified as being highly reactive.

Recycled concrete aggregate (RCA) can be classified as being of normal reactivity (non-reactive in New Zealand) provided:

1. The alkali contribution from recycled concrete aggregate (RCA) is assumed to be:
   - 0.2 kg Na_2O eq. per 100kg of recycled concrete aggregate (RCA), or
   - Where the composition of the recycled concrete aggregate (RCA) is known, the alkali content can be calculated from the parent concrete.
2. The 0.6 kg Na_2O eq./m^3 limit on alkalis contributed to the fresh concrete from sources other than the cement combination need not include the alkali contributed by the recycled concrete aggregate (RCA).
3. The recycled concrete aggregate (RCA) does not contain potentially reactive mineral components, or the natural aggregate used in combination with the recycled concrete aggregate (RCA) is not highly reactive (potentially reactive in New Zealand).

Recovered aggregates have no special ASR provisions and should be classified based on the parent concrete aggregate.

7.3 Australia

Standards Australia's 'Guide to the use of recycled concrete and masonry materials' (HB 155:2002)[7] defines two classes of recycled aggregate for use as aggregate for new concrete:

- *Class 1A* recycled concrete aggregate is predominantly recycled concrete.
- *Class 1B* recycled concrete aggregate can contain up to 30% brick content.

Specification details are given in Table 4 and the allowable contaminant levels in Table 5.

HB 155:2002[7] also defines two classes of recycled aggregate concretes (RAC's):

- *Grade 1* recycled aggregate concrete is defined as concrete with up to 30% substitution level of Class 1A recycled concrete coarse aggregate. Grade 1 recycled aggregate concrete has a maximum specified strength limit of 40 MPa.
- *Grade 2* recycled aggregate concrete is allowed up to 100% substitution level of Class 1A or Class 1B recycled concrete coarse aggregate. Grade 2 recycled aggregate concrete has a maximum specified strength limit of 25 MPa.

Neither grade is permitted to contain recycled fine aggregate.

Table 4: (HB 155:2002[7]) Physical Requirements for Recycled Concrete Aggregate

RCA Property	Class 1A RCA	Class 1B RCA	Test Method
Brick content (max.)	0.5%	30%	-
Stony material < 1,950 kg/m^3	1%	5%	-
Friable material (max.)	0.1%	0.1%	-
Particle shape, 2:1 ratio	35%	35%	AS 1141.14[53]
Particle density SSD (min.)	2,100 kg/m^3	1,800 kg/m^3	AS 1141.6[53]
Bulk density (min.)	1,200 kg/m^3	1,000 kg/m^3	AS 1141.4[53]
Water absorption (max.)	6%	8%	AS 1141.6[53]
Aggregate crushing value (max.)	30%	30%	AS 1141.21[53]
Total impurity level (max.)	1%	2%	-
LOI (max.)	5%	5%	-
Lost substances in washing (max.)	1%	1%	-
Soundness loss (max.)	9%	-	AS 1141.24[53]
Particle size distribution by dry sieving	-	-	AS 1141.11[53]

Table 5: (HB 155:2002[7]) Composite Requirements for Recycled Aggregate Concrete

Contaminant Limit	Class 1A RCA	Class 1B RCA	Test Method
Total contaminant (max.)	1%	2%	-
Sulphate content SO_3 (max.)	0.5%	0.5%	-
Contaminants < 1,950 kg/m^3	10 kg/m^3	10 kg/m^3	-
Contaminants < 1,950 kg/m^3	2 kg/m^3	2 kg/m^3	-
Chloride content, Cl^-	0.05%	-	AS 2758.1[54]
Periclase (MgO)	0.01 (max.)	0.01 (max.)	-
Alkali-silica Reactivity	-	-	AS 1141.38[53]

7.4 United States

The NRMCA report[5] on Crushed Returned Concrete specifically deals with returned leftover concrete. Its recommendations include the use of leftover concrete aggregate 'as received all-in' (coarse + fine) in non-structural applications up to 30% by total weight of aggregate. This recommendation presumes that there is some sorting of the leftover concrete to use only leftover concrete 20 MPa and above. Up to 100% replacement of coarse aggregate only is allowed for all non-structural applications.

For structural applications it recommends that ASTM C94/C94M-11b[55]' allows up to 10% by total weight of aggregate (equivalent to 20 to 25% by weight of coarse aggregate) generally; and 100% coarse aggregate replacement by recycled coarse aggregate should be allowed for concrete strengths up to 20 MPa.

7.5 Other Countries

Table 6 summarises overseas criteria[50] applied to the use of recycled aggregate concrete, including the UK, Australia and US limits described above.

7.6 Green Star New Zealand Building Credits Scheme

As at July 2011, the New Zealand Green Building Scheme awards up to three points to encourage and recognise the reduction of embodied energy and resource depletion associated with the use of concrete. Two options are available for gaining maximum points. Either:

1. The concrete used in the building construction is independently certified as having lower environmental impact than standard concrete.

   OR

2. One point is awarded if 10% of all aggregate is recycled

   Two points are awarded if 20% of all aggregate is recycled

   One additional point is awarded if 20% of cement used in in-situ construction and 15% in precast construction is replaced with inert filler and/or industrial waste by-product and/or pozzolanic material which is sourced locally to the cement manufacturing plant. Type GP (General Purpose) cement manufactured in New Zealand contains up to 10% inert filler at source.

Concrete aggregate crushed either from demolition concrete or hardened leftover concrete can be regarded as recycled aggregate. However, recovered coarse aggregate is not eligible for points under the current scheme. The points awarded for a project are based on the average of all concrete mixes used in construction.

Green Star New Zealand[3] has a close association with its Australian counterpart Green Star Australia. Green Star Australia has recently (2011) completed a review of its concrete credits scheme. Green Star New Zealand also proposes a review of its concrete credit scheme in 2011-2012, and the revised Australian concrete credits scheme will form part of that review. A summary of credits available in the draft Australian scheme is as follows:

- One point where Portland cement is replaced by up to 30% supplementary cementitious material.
- Two points where Portland cement is replaced by up to 40% supplementary cementitious material.

- One additional point where all cement is sourced from manufacturers with an alternative fuels programme in place.

PROVIDED The mix water contains at least 50% non-potable water, and

EITHER 40% of the coarse aggregate in the concrete is recycled aggregate and the Portland cement content does not increase by more than 5 kg/m^3 from the control concrete.

OR 25% of the fine aggregate is from a manufactured source and the Portland cement content does not increase by more than 5 kg/m^3 from the control concrete.

Table 6: Summary of requirements for recycled aggregate concrete in different countries[50]

Country/ Organisation	Recycled Aggregate (Type/Name/ Classification)	Aggregate Genre	Maximum RCA Substitution[a]	Maximum Recycled Aggregate Concrete 28 Day Cylinder Strength	Other Restrictions
United Kingdom	RCA	RCA	NR	40 MPa	RCA and LCAgg. No chloride exposure. No freeze thaw
			20%	Designated concrete 20 to 40 MPa	
	LCAgg	LCAgg	NR	NR	-
	RA	RA		16 MPa	Only mild exposure.
Australia	Class 1A	RCA	30%	40 MPa	-
	Class 1B	RCA	100%	25 MPa	
USA	LCA	LCAgg	100%[b]	20 MPa	-
			25%	50 MPa	
			60%[c]	NS Concrete	
RILEM	RCAC Type I	RA	100%	16 MPa	Masonry Aggregate. Exposure restrictions.
	RCAC Type II	RCA	100%	50 MPa	
	RCAC Type III	RCA	20%	NR	
Korea	-	RCA	30%	27 MPa	-
			30%[c]	21 MPa	
Germany	Type 1	RCA	35%	25 MPa	In dry or low humidity environments.
	Type 2		25%	30 MPa	
Portugal	ARB1	RCA	25%	35 MPa	-
	ARB2		20%	40 MPa	
Hong Kong	-	RCA	20%	≤35 MPa	-
			100%	20 MPa NS Concrete	

Notes:

(a) Percentages are of coarse aggregate fraction unless otherwise stated
(b) Assumes leftover concrete aggregate separated by strength class
(c) Coarse and fine fraction

NS = Non structural concrete
RCA = Recycled concrete aggregate
LCAgg = Leftover concrete aggregate
RA = Recycled aggregate
NR = No restriction

8.0 Model Specification for Recycled Aggregate and Recycled Aggregate Concrete

This section provides suggested model specification clauses for the supply and use of recycled aggregates and recycled aggregate concrete in New Zealand. It is designed to be used in combination with NZS 3121:1986[15], NZS 3104:2003[8] and NZS 3109:1997[18] in the absence of appropriate clauses in these standards to accommodate recycled materials. However the specification does not carry any regulatory status. Feedback from users of the specification will enable it to be refined and eventually developed into revisions of or amendments to the relevant New Zealand standards.

The model specification aims to maintain the quality of concrete currently provided by the industry. The combination of the incentives provided by Green Star and the low risk approach of the model specification should encourage the uptake of the technology.

8.1 Supply of Recycled Aggregates

8.1.1 Composition

Recycled coarse aggregates suitable for use in new recycled aggregate concrete are types recycled concrete aggregate (RCA), recycled aggregate (RA) and leftover concrete aggregate (LCAgg) complying with Table 7.

Commentary: *Uncontaminated coarse aggregate that has been recovered from fresh concrete shall be considered as natural aggregate, which has been adequately washed (to satisfy the cleanliness value stipulated in NZS 3121:1986[15]), and is not included in these specification clauses.*

This model specification does not cover secondary aggregates from other industries.

Table 7: Composition of coarse recycled aggregates acceptable for use in recycled aggregate concrete (% by mass)

Type of Recycled Aggregate	Maximum masonry content	Maximum fines	Maximum lightweight material < 1,000 kg/m³	Maximum asphalt	Maximum glass, plastic, wood.
RCA[(a)]	5	5	0.5	5.0	1.0
RA[(b)]	100	3	1.0	10.0	1.0
LCAgg[(c)]	-	5	-	-	-

(a) RCA: Recycled concrete aggregate. (Predominantly from demolition waste concrete).

(b) RA: Recycled aggregate. (Predominantly demolition waste including concrete, masonry and asphalt).

(c) LCAgg: Leftover concrete aggregate. (Aggregate processed from hardened leftover concrete of known composition that has not been in use and has not been contaminated in storage).

Commentary 1: *Fine recycled aggregate is not generally used in concrete because of increase in water demand and the effect on compressive strength and shrinkage. However, recycled aggregates (RCA, RA and LCAgg) may be suitable for use in special applications in concrete. Because of their wide range of composition, their use should be specified on a case by case basis, taking into account the particular source of fine recycled aggregate, and the application of the concrete. Fine recycled aggregate is not generally used in concrete because of increase in water demand and the effect on compressive strength and shrinkage.*

***Commentary 2:** BS EN 933-11:2009[52] gives a classification test for determining the constituents of coarse aggregate. This visual sorting test allows the proportions of the constituent materials in coarse recycled aggregate to be determined, in order that the producer can declare conformity with the requirements in Table 7.*

8.1.2 Grading

Each recycled coarse aggregate size shall meet the grading requirements of NZS 3121:1986[15], clause 5.1. The natural and recycled components of the coarse aggregate shall be stored separately and batched in accordance with clause 2.4.3 of NZS 3104:2003[8].

The overall grading of the coarse aggregate, comprising a combination of natural and recycled material, shall be based on the recommendations of Table 2.1 of NZS 3104:2003[8].

8.1.3 Contaminants

All aggregates shall comply with the cleanness and deleterious materials requirements of NZS 3121:1986[15]. Specific testing requirements for deleterious contaminants shall be determined by the Plant Engineer (as defined in NZS 3104:2003[8]) on the basis of the origin of the recycled aggregate and its exposure to deleterious materials.

***Commentary**: In addition to the deleterious materials requirements of NZS 3121:1986[15], recycled aggregates from demolition waste (RCA and RA) may be contaminated with gypsum, asbestos, and other waste material:*

- *RCA and RA manufactured from demolition waste may contain asbestos. Appropriate safety precautions should be taken unless either test results from an IANZ accredited laboratory show that aggregate sampled from the stockpile does not contain asbestos, or the structure being demolished does not contain asbestos or asbestos product.*
- *LCAgg does not normally require testing for deleterious materials.*
- *Gypsum contents of less than 5% have been found to have no significant effect on recycled aggregate concrete strength[62].*

8.1.4 Reportable Properties

In addition to the cleanness and deleterious materials requirements of NZS 3121:1986[15], clauses 4 and 5, the properties given in Table 8 shall be measured and the results reported if requested by the specifier or the purchaser.

Table 8: Reportable Properties of recycled material used as coarse aggregate

Aggregate Property	Test Method
Water Absorption/Bulk Density	NZS 3111:1986 Section 12[29]
Aggregate Crushing (10% fines)	NZS 3111:1986 Section 14[29]
Unit Mass and Voids Content of Aggregate	NZS 3111:1986 Section 1[29]
Loss on Ignition	NZS 4402:1986 Section 3.1.2[56]
Friable Material – Weak Particles[(a)]	AS 1141.32:1995[53]
Particle Shape – Flakiness Index[(a)]	AS 1141.15:1995[53]
Elongation Index[(a)]	BS 812.105.2:1989[57]
Soundness[(b)]	ASTM C88-05[58]
Weathering Resistance	NZS 3111:1986 Section 15[29]

(a) Tests based on particle shape or friability may be replaced by visual assessment if there is a history of satisfactory use of the recycled aggregate in recycled aggregate concrete.

(b) Sodium sulphate soundness testing should only be necessary if the exposure environment of the new concrete is significantly more demanding than that of the parent concrete.

8.1.5 Sampling and Testing Frequency

The composition of recycled aggregates (RA, RCA and LCAgg) as described in Table 7 shall be determined by the aggregate supplier, in agreement with the Plant Engineer, at the rate of one test per 1,000 m^3 of aggregate delivered/produced from a single source, but not less than once per fortnight.

Composition testing shall also take place at every significant change of source material.

Testing for individual aggregate grading and combined aggregate grading shall meet the frequency requirements of NZS 3104:2003[8].

8.2 Supply of Recycled Aggregate Concrete

Recycled aggregate concrete shall be produced in accordance with NZS 3104:2003[8] and supplied in accordance with NZS 3109:1997[18], with the addition of the following provisions:

8.2.1 Normal Concrete and Special Concrete

Recycled aggregate concrete specified by 28 day strength not exceeding 30 MPa, shall be classified as Normal Concrete in accordance with clause 2.10.1 of NZS 3104:2003[8].

Recycled aggregate concrete specified by 28 day strength greater than 30 MPa or with any of the following characteristics shall be classified as Special Concrete in accordance with clause 2.10.2 of NZS 3104:2003[8]:

- The fine aggregate includes recycled aggregate.
- Properties other than slump and 28 day compressive strength are specified.
- Compressive strength at any age other than 28 days is specified.

Commentary: *The Specifier needs to specify acceptance criteria for Special Concrete.*

Compressive strengths greater than 30 MPa require a negotiated supply contract between the Purchaser and the Supplier (as defined in NZS 3104:2003[8]). This is necessary because for higher strength recycled aggregate concrete, the quality of the parent concrete may have a significant influence on the properties of the new concrete, which is not usually the case for natural aggregate concrete.

The specified 28 day compressive strength of recycled aggregate concrete containing recycled fine aggregate shall not exceed 17.5 MPa.

Other specified properties for a Special Concrete may include shrinkage, creep, abrasion resistance, etc.

Recycled aggregate concrete with high replacement rates of recycled concrete aggregate may exhibit high creep and shrinkage characteristics.

Supplementary Cementitious Materials (SCMs) may be used to offset higher water demand of recycled aggregate concrete. If the SCM delays strength development, then strength may be evaluated at a later age of 56 or 90 days.

The adhered mortar found on recycled aggregate can contribute to late strength gain beyond 28 days. Also fine recycled concrete aggregate and leftover concrete aggregate can produce concrete with additional strength gain beyond 28 days.

8.2.2 Recycled Coarse Aggregate Addition Rates

(a) Normal Concrete

(i) Except as provided in (ii) below, recycled coarse aggregate addition rates for recycled aggregate concrete classified as Normal Concrete shall be in accordance with Table 9.

(ii) The maximum recycled coarse aggregate content specified in Table 9 may be exceeded for Normal Concrete if the supply for the preceding six months or more meets the requirements of NZS 3104:2003[8].

Table 9: Maximum recycled coarse aggregate replacement rates

Specified Compressive Strength (Cylinders)	Recycled Aggregate Type	Percentage on Coarse Aggregate Fraction
Up to and including 17.5 MPa non-structural concrete	RA, LCAgg or RCA	100%
17.5 MPa structural concrete	LCAgg or RCA	100%
20 MPa structural concrete	LCAgg	100%
	RCA	50%
25 and 30 MPa structural concrete	LCAgg	40%
	RCA	30%

Key: LCAgg = Leftover concrete aggregate
RCA = Recycled concrete aggregate
RA = Recycled aggregate

(b) Special Concrete

Recycled aggregate concrete classified as Special Concrete may contain fine recycled aggregate in combination with recycled or natural coarse aggregate.

8.2.3 Restrictions on the Exposure Class of Recycled Aggregate Concrete

Recycled aggregate concrete shall not be used in exposure classifications C, XA 1, XA 2, XA 3, U as defined by Section 3 of NZS 3101:2006[17] unless durability test results show it will provide adequate durability in the intended environment.

Commentary: *The replacement level of recycled aggregate may affect the durability performance of the concrete. The use of SCM's will generally improve durability performance.*

Recycled concrete to be located in the B2 zone shall have a maximum of 20% recycled coarse aggregate replacement unless test results based on Section C3 of NZS 3104:2003[8] show a higher recycled aggregate content provides adequate durability.

Commentary: *The limitation placed on the maximum replacement rate in the B2 zone is based on current uncertainty of the influence of recycled aggregate on chloride diffusion and corrosion initiation of reinforcement.*

8.2.4 Industrial Floor Applications

For industrial floor applications AR 2 and above as defined by NZS 3101:2006[17] Table 3.8, the recycled aggregate content shall not exceed 30% of the coarse aggregate unless accelerated abrasion testing show that satisfactory abrasion resistance for the intended environment can be achieved with a higher recycled aggregate content.

Commentary: *The abrasion resistance of concrete is largely determined by surface finish and curing, in addition to strength. Adhered mortar on recycled aggregate could potentially compromise abrasion resistance of heavy duty industrial floors.*

8.2.5 Alkali Silica Reaction

The risk of alkali silica reaction (ASR) in recycled aggregate concrete shall be minimised in accordance with the provisions of CCANZ TR3[19], with the addition of the following clauses.

(a) Potential Reactivity of Recycled Aggregate

The potential alkali reactivity of recycled concrete aggregate (RCA) and leftover concrete aggregate (LCAgg) shall be determined in accordance with CCANZ TR3[19], on the basis of the potential reactivity of the parent aggregate. If the source of the parent aggregate is unknown, the recycled concrete aggregate should be classified as potentially reactive.

Recycled aggregate (RA) shall be classified as potentially reactive in all situations.

Commentary: *Recycled aggregate (RA) contains a wide range of constituents so its reactivity is difficult to determine.*

(b) Alkali Content of Recycled Aggregate

The alkali contribution from recycled aggregate shall be assumed to be:

- 0.2 kg Na_2O eq. per 100 kg of recycled aggregate, or
- Where the adhered mortar content and alkali content of the parent concrete is known, the alkali content can be calculated from the alkali content of the parent concrete.

Recycled aggregate concrete may contain potentially reactive aggregate (either natural or recycled) provided precautions are taken to minimise the risk of ASR.

Commentary: *The amount of releasable alkali from natural aggregate cannot be calculated or measured, therefore CCANZ TR3[19] cautions against using potentially reactive aggregate and alkali-releasing aggregate together in the same concrete. In contrast, the alkali contributed by recycled concrete aggregate can be measured or calculated. Therefore potentially reactive aggregate may be used in conjunction with recycled concrete aggregate provided that the precautions specified in CCANZ TR3[19] for normal or special concrete, as appropriate, are taken.*

8.2.6 Target Mean Strengths and Variability Control

(a) Normal Concrete

The provisions of clause 2.13.1 of NZS 3104:2003[8] shall apply for specified 28 day compressive strengths up to and including 30 MPa.

(b) *Special Concrete*

For recycled aggregate concrete classified as Special Concrete (refer clause 8.2.1 above), the provisions of clause 2.13.2 of NZS 3104:2003[8] shall apply.

9.0 Secondary Recycled Materials Used as Aggregate in Concrete

Research into new and innovative uses of waste materials is continually advancing. Several types of wastes and by-products can be substituted for aggregates in construction[59]. It is, however, the suitability and secondary processing requirements of waste materials that dictate their application and market uptake. Other factors that restrict widespread use of many types of secondary resources include material variability and cartage costs to construction sites or concrete plant sites. Increased use of secondary materials will largely depend on the development of suitable technical guidelines and standards, as well as demonstrated cost competitiveness.

This section outlines the use of waste materials from other industries as recycled aggregate in concrete. In such applications the burden of waste from other industries is being relieved by the concrete industry. Some of the waste materials listed may not be available in sufficient quality or quantity to be used as concrete aggregate in New Zealand. The challenge for the concrete industry is to ensure that concrete made from such aggregate is of the same quality as concrete made from natural aggregate.

More information on the use of secondary recycled materials is given in a publication by Cement, Concrete and Aggregate Australia[59].

9.1 Glass

Research on the use of crushed bottle glass as replacement coarse aggregate in concrete have found the shape of the glass is a major drawback. The flat smooth and elongated particle shape of coarse aggregate glass and the chemical and physical nature of the surface do not normally make its use viable in concrete. However the use of fine glass to replace the sand fraction has proved viable providing the risk of ASR can be controlled by limiting the percentage replacement by glass fines and suppressing the ASR by use of an SCM. The smoother surface texture of the glass aggregate and non-absorption characteristics improves the rheology of the fresh concrete. In fact research[60] found that the mechanical properties (compressive strength, flexural and splitting strength) of concrete incorporating up to 20% replacement of fine aggregate with glass actually increased and the workability was not affected. This increase of the strength is due to the surface texture and strength of the glass particles compared to that of sand.

A substantial research programme[37,61,62] was carried out in the UK under the WRAP programme. The programme evaluated the performance of crushed and ground glass in concrete as a replacement for cement and/or aggregates. The study found that the reactivity of glass with concrete increases with cement alkali and presence of particle sizes above 1 mm. The effects of glass colour were unclear and it was felt that differences in reactivity for different colours was more related to crushing technique than glass chemistry. All four colours of glass aggregates assessed in research[63] evaluating different ASR test methods and were found to be very alkali-silica reactive when tested using ASTM C1260-07[64] (with extended test duration) and ASTM C227-10[65] (within normal test duration).

A WRAP research programme at the University of Dundee[66] entitled *'Realising a High-Value Sustainable Recycling Solution to the Glass Cullet Surplus'* produced guidelines and model specifications for the use of crushed glass as a fine aggregate or filler aggregate for use in concrete.

Naik and Wu[67] studied the feasibility of using crushed, post-consumer glass as a partial replacement of sand in concrete. To minimize ASR, they replaced cement with Class F fly ash at 15, 30, and 45% by weight. For each combination of cement and fly ash, 15, 30, and 45% of the concrete sand was replaced with crushed glass. The crushed glass alone did not fall within the ASTM C33/C33M-11a[32] envelope but the combination sands did come within the ASTM C33/C33M-11a[32] fine sand grading limits. The compressive strength and splitting tensile strength were determined for each mixture. The occurrence of ASR was also evaluated.

Based on the test results, Naik and Wu[67] concluded that:

- The compressive strength of concrete is slightly reduced when sand is partially replaced by crushed glass.
- Crushed glass is highly reactive with alkalis in the cement. Expansion of mortar bars without fly ash increased almost linearly with increase in the amount of crushed glass.
- At cement replacement levels up to 30%, fly ash only delays the onset of expansion; long-term expansion is still high.
- Deleterious expansion can be successfully suppressed by replacing 45% or more of the cement with Class F fly ash, regardless of the amount of crushed glass in the concrete.

Tests specific to an application need to be carried out to establish ASR suppression using Class C flyash and other SCM's.

A New Zealand construction project[68] using crushed glass as fine concrete aggregate was the Lion Brewery and warehousing facility in South Auckland. This project examined the processing of the glass and its application in concrete in some detail and found the cleaning, crushing and screening of glass a significant challenge. Salient points were:

- Rotating trammel type brushed screens were superior to flat vibrating screen which tend to clog from contamination in the glass stockpile, particularly paper labels. Glass is abrasive and causes accelerated wear on the crushing equipment.
- The upper size of the glass aggregate was 4.75 mm which is larger than CSIRO[69] or WRAP[61] recommend.
- An alkali limit of 1.8 kg/m^3 was adopted which is less than the 'normal' value of 2.5 in TR3[19].
- Glass aggregate gives exposed concrete surfaces architectural appeal.
- Glass aggregate concrete can be competitive with normal concrete.
- The level of glass replacement was between 5 and 10%.

Trials by Mackechnie and Munn[30] found that waste glass could replace up to 10% sand with minimal detrimental effect if ASR risks are effectively managed.

Another New Zealand venture called Glasscrete™ contained waste glass aggregate and waste paint to replace chemical admixtures and provide fluidity to the mix [70]. This concrete was trialled for use in the Ribraft™ waffle slab type floor. Alkali silica reaction was suppressed using fly-ash in the mix.

Note: Powdered glass has pozzolanic properties and has been considered for use as a filler or a supplementary cementitious material.

Associated with the development of Glasscrete™ in New Zealand was the development of Paintcrete[ii].

9.1.1 Model Specification Clauses (from WRAP Research[61])

The grading of crushed glass fine aggregate shall have a maximum size of 4 mm.

Commentary: *Crushed glass fine aggregate may be used to replace part of the natural fine aggregate fraction. The limiting fraction is controlled by minimising the risk of ASR. Typically this is done by limiting the alkali content and the percentage of glass, and using SCM's to suppress the alkali reactivity. Typical replacement rates of crushed glass as a proportion of fine aggregate are between 5% and 20%*

The crushed glass aggregate shall be assessed for the effect on stiffening time and compressive strength in accordance with BS EN 1744-1:1998, 15.3[71].

The proportions of organic material shall be such that they do not:

(a) Increase the mortar stiffening time by more than 120 minutes.

(b) Decrease the 28 day compressive strength of mortar test specimens by more than 20%.

(c) Deleteriously affect air content.

Crushed glass fine aggregate shall be classed as Potentially Reactive in accordance with TR3[19]. The alkali contribution of the crushed glass shall be determined in accordance with BS 1881-124:1998[72]. Refer 8.2.5 of this Guide (TR 14).

9.1.2 Typical Contaminants in Recycled Glass

Sugar: When mixed in concrete, sugar can cause an unpredictable increase in setting time and a decrease in the ultimate strength. Visual inspection of otherwise clean glass cullet may not reveal the presence of sugar residue from previous food contents. AS 1141.35:2002[53] gives a method to measure sugar content of aggregate. Therefore, all cullet should be washed prior to its use as aggregate in concrete; if possible, a high temperature wash should be used to expedite the removal of sugar from the cullet. The glass can then be air-dried to minimise the addition of any uncalculated moisture to the concrete mix.

Ceramics: Ceramic contamination is a broad category including dishware, porcelain caps, pottery, heat-resistant cookware (e.g. Pyrex), mirror glass, laboratory glass, light bulbs, and crystal and window glass. Ceramics can be removed manually or with automated systems.

Metal: Metal contaminants are generally in the form of container lids or seals. Typical ferrous metals include iron and steel, which are magnetic, and can be removed through magnetic separation techniques. Non-ferrous metal contamination includes brass, aluminium, lead and stainless steel.

Organics: Organic contamination includes paper and plastic labels and their adhesives, plastic caps, cork, paper bags, wood debris, plants, food residue (e.g. sugar), and any other combustible or

---

[ii] Paintcrete™ is a masonry blockfill concrete which utilises waste and leftover waterborne acrylic and latex paint to replace conventional chemical admixtures and impart fluidity to the concrete without any associated concrete compressive strength reduction. In fact the paint addition allows an 8-12% replacement of water by paint and hence the cement content can be reduced from that of a standard blockfill mix. The development of Paintcrete™ was based on work by Haigh & Ingham. (Haigh and Ingham. (2008, October). *Waste Paint as Admixture in Concrete Masonry Blockfill.* New Zealand Concrete Industries Conference Technical Papers TR 40). Paintcrete™ has the potential to recycle all the waste paint in New Zealand. Other uses for Paintcrete™ are also being explored.

degradable material. Washing or passing the cullet through a screening device can remove organic material. Both metal and organic contaminants can be removed with a properly sized screen, as these are less friable than glass and do not fracture as easily in glass crushers.

9.1.3 Safety

While glass is produced with silica sand, the manufacturing process converts the crystalline structure to an amorphous state. Container glass is made from over 70% silica. Crystalline forms of silica, also known as 'free' silica, can contribute to certain lung diseases. An understanding of the difference between glass dusts and silica dusts in the crystalline form, and what the permissible exposure limits are, is necessary to ensure worker safety.

The production of glass aggregate requires crushing, which inevitably creates fine particles of glass.

When the aggregate is handled and transported, these particles can become airborne as dust. Therefore, general procedures for worker protection and dust control should be implemented. Cullet users should carefully evaluate the potential effects of each type of contaminant on the intended application, and develop specifications for contaminant tolerance and removal.

9.2 Slags

9.2.1 Blast Furnace Slag

Blast furnace slag is produced when iron ore is converted to iron, also known as pig iron. The resulting material is either rapidly discharged and treated with high-pressure water jets to produce a lightweight material known as 'foamed slag' or slowly cooled in the air to produce a crystalline, dense material commonly referred to as 'air-cooled slag'. The wet and sandy foamed slag is subsequently dried and milled to produce ground granulated blast furnace slag, a cementitious product widely used as a supplementary cementitious material to enhance concrete properties.

Though not widely used, air-cooled slag is generally considered suitable as an aggregate in concrete.

The compressive strengths of concrete made with blast furnace slag aggregate are typically comparable to equivalent conventional concretes.

9.2.2 Steel Slag

Research has also been conducted on the use of steel slags. Steel slag essentially contains fused mixtures of oxides and silicates, primarily calcium, iron, unslaked lime and magnesium. Results indicate that although steel slag has a mineral composition similar to that of Type GP cement clinker, steel slag aggregates generally exhibit a propensity to expand and become unstable because of their free calcium oxide. The free lime and magnesium oxides that have not reacted with silicate structures can hydrate and expand in humid environments. To control this reaction, adequate ageing is required to allow the potentially destructive hydration to offset this expansion, by causing such expansion to take place prior to the use of the material in aggregate applications.

Before its use as a construction aggregate material, steel slag is crushed and screened to meet the specified grading requirements for the particular application. Processed steel slag has favourable mechanical properties for aggregate use, including good abrasion resistance and high bearing strength.

9.3 Mining and Quarrying Wastes

Large amounts of wastes are produced in mining and quarrying operations. Mineral mining wastes are termed 'waste rock' or 'mill tailings'. Processing of crushed stone for use as construction aggregate consists of crushing, washing, screening and stockpiling operations. Such quarry by-products produced during crushing and washing operations can have widely varying physical and chemical characteristics. The cost of storage and non-value-added disposal of this material warrants investigation into its beneficiation and potential use as a blend or raw manufactured sand substitute product. Generally, these wastes have not as yet found any significant application partly because they are produced at locations far removed from populated areas. Some possible uses of these wastes include the manufacture of bricks, lightweight aggregates and autoclaved concrete blocks.

9.4 By-products from Power Plants

Modern coal combustion plants for electric power generation produce a wide range of by-products. The combustion gases carry residual particles upwards, which are then electrostatically precipitated or collected by other means to produce fly ash (pulverised fuel ash) used as a supplementary cementitious material to enhance concrete properties. The solid ash particles that fall to the bottom of the furnace to produce furnace bottom ash are much less used as a construction material. Bottom ash has a similar chemical make-up to fly ash but has a much coarser grading. Some studies on its use as a sub-base material suggest it has sufficient engineering properties to perform adequately. Bottom ash has also been marketed as an aggregate for lightweight concrete.

9.5 Incinerator Bottom Ash Aggregate (IBAA)

Incinerator ash is a by-product of incineration of municipal solid waste during energy-from-waste recovery. It comprises non-combustible solid waste constituents, and following grading and processing it can be used as a natural coarse aggregate replacement. It is recommended that fine IBBA (< 5 mm) is not used in concrete. IBBA should not be used in concrete with reinforcing or embedded fixings and concretes which are exposed to sulphates or freeze thaw.

IBBA comprises non-combustible clinker, stone, masonry and glass; metals and unburned lightweight material are removed in processing. IBBA aggregate is lighter than natural aggregate but the dry density is still over 2,000 kg/m^3.

Controls on the properties of bottom ash for use in concrete include LOI, Loss Angeles abrasion, sulphate content and chloride content[73]. BS 8500-2:2006[28] limits the proportion of IBBA to 25% mass fraction of the total coarse aggregate.

9.6 Rubber

The disposal of used tyres has become a global problem and most countries do not allow the disposal of whole tyres or shredded tyres to landfill. Granulated rubber (GR) concrete[74,75, 76] has the potential to provide specialist properties as freeze-thaw resisting concrete, impact resistant concrete and thermal insulating concrete. GR concrete can attain similar levels of freeze thaw resistance to air entrained concrete and there is potential for its use in areas where the use of air entraining admixtures is unsuitable – for instance low workability mixes and concrete in locations with long haulage from the plant. Different gradings can be used from fine to coarse sand to fine aggregate.

The use of 25% replacement of sand with GR in foamed concrete has been found to reduce the thermal conductivity by up to 30% (typically to 0.4 W/m^2 K). This can be used to effect in ground floor slabs. The ability of GR to modify concrete from a brittle material to a tough resilient material has potential in specialist applications.

Research by Pierce & Blackwell[77] on the use of crumbed rubber in flowable fill produced a lightweight (1,200 to 1,600 kg/m^3) flowable fill with an excavatable 28 day compressive strength from 0.2 to 0.9 MPa. This has potential over plain flowable fill in bridge abutment backfills, trench backfills and foundation backfills.

9.7 Polystyrene Concrete

Expanded polystyrene (EPS) concrete is a lightweight, low strength material with good energy-absorbing characteristics. However, due to the light weight of EPS beads and their hydrophobic surface, EPS concrete is prone to segregation during placing, which results in poor workability and lower strength.

Research by Chen & Liu[78] showed that EPS concrete with a density of 800 to 1,800 kg/m^3 and a compressive strength of 10-25 MPa can be made by partially replacing coarse and fine aggregate by EPS beads. A premix method similar to the 'sand-wrapping' technique was utilized to make the EPS concrete. Fine silica fume greatly improved the bond between the EPS beads and cement paste and increased the compressive strength of EPS concrete. In addition, adding steel fibre significantly improved the drying shrinkage.

9.8 Wood Chip Concrete

Wood-chip concrete is a non-structural open texture concrete comprising between 50% and 90% wood chips as aggregate by volume. Examples for the use of wood-chip concrete are hollow blocks for flooring systems, shuttering blocks, slabs, facing elements, acoustic or thermal facing elements, partitioning elements and motorway noise barriers.

Thus wood-chip concrete is a specialist concrete with a density range of between 920 to 1,250 kg/m^3. The concrete is manufactured by pre-packing the mould with wood-chips to the desired packing ratio and then injecting the mould with grout.

10.0 Standards and References

1 Cement and Concrete Association of New Zealand (2008, July). *Recycled Crushed Concrete in New Zealand* (Project 8-H14 Final Report). Wellington, New Zealand.

2 New Zealand Aggregate and Quarry Association. *Best practice New Zealand guideline for the supply of recycled concrete material for use in pavements and other civil works.* Wellington, New Zealand.

3 New Zealand Green Building Council. *Green Star New Zealand.* Accessed from www.nzgbc.org.nz.

4 WRAP. *Performance Related Approach and Engineering Properties of Concrete containing Recycled Aggregates: WRAP Aggregate Research Programme.* Accessed from www.wrap.org.uk.

5 National Ready Mixed Concrete Association. *Crushed Returned Concrete as Aggregates for New Concrete.* Silver Springs, MD, USA.

6 *Recycling of Demolished Concrete and Masonry.* (RILEM Report 6). (1992). RILEM Publications, Bagneaux, France.

7 Standards Australia. *Guide to the use of recycled concrete and masonry materials* (HB 155:2002). Sydney, Australia.

8 Standards New Zealand. *NZS 3104:2003 Specification for concrete production.* Wellington, New Zealand.

9 World Business Council for Sustainable Development. *The Cement Sustainability Initiative – Recycling Concrete.* Geneva, Switzerland.

10 Englesen, J et al. (2005) *Carbon dioxide uptake in demolished and crushed concrete.* Nordic Innovation Centre, Oslo: Norwegian Building Research Institute (Byggforsk).

11 Dayaram, Karan. (2010, February) *The Recarbonation of Crushed Concrete from a New Zealand Perspective.* New Zealand: University of Canterbury.

12 Cattanach, A. (2008) *ESD is a structural issue too: Meridian Building – The first 5 star green building in New Zealand.* New Zealand Concrete Industries Conference.

13 Cement and Concrete Association of New Zealand. (2004, January) *The Use of Recycled Wash Water in Ready Mix Concrete Production.* Wellington, New Zealand.

14 Mackechnie, JR. (2004, September). *Influence of Recycled Water on Fresh Properties of Concrete.* University of Canterbury, Christchurch, New Zealand.

15 Standards New Zealand. *NZS 3121:1986 Specification for Water and Aggregate for Concrete.* Wellington, New Zealand.

16 BRANZ. (1996) *An Evaluation of Concrete made using Recycled Slurry from Concrete Plant Operations as Mix Water* (BRANZ Study Report 74). Judgeford, Wellington, New Zealand.

17 Standards New Zealand. *NZS 3101:2006 Parts 1 and 2. Concrete Structures Standard – The Design of Concrete Structures.* Wellington, New Zealand.

18 Standards New Zealand. *NZS 3109:1997. Concrete Construction.* Wellington, New Zealand.

19 Cement and Concrete Association of New Zealand. (2003). *TR 3 Alkali Silica Reaction* (Technical Report). Wellington, New Zealand.

20 British Standards Institution. (2002). *BS EN 1008:2002. Concrete – Mixing water for concrete – Specification for assessing the suitability of water recovered from processes in the concrete industry.* London, UK.

21 Nielsen and Glavind. (2007, February). *Danish Experiences with a Decade of Green Concrete.* Journal of Advanced Concrete Technology 5(1): 3-12. Japan Concrete Industry, Tokyo, Japan.

22 New Zealand Ready Mixed Concrete Association. *Reuse of Wash Water.* (NZRMCA Technical Note 2). Wellington, New Zealand.

23 Gaimster, R and Kirby, A. (2008). *Recycled Waste Concrete - European and North American Practice and its Applicability to New Zealand* (Technical Papers TR 40). New Zealand Concrete Industries Conference.

24 Desai, SB and Limbachiya, MC. (Kingston University, 2006, July). *Coarse recycled aggregate – a sustainable concrete solution.* The Indian Concrete Journal: 17–23. ACC Limited, Maharashtra, India.

25 New Zealand Demolition and Asbestos Association. (2011 March). *The New Zealand Guidelines for the Management and Removal of Asbestos.* New Zealand Demolition and Asbestos Association, Auckland, New Zealand.

26 Rashwan, MS and Abourizh, S. (1997, July). *The Properties of Recycled Concrete.* Concrete International: 56–60. ACI, Farmington Hills, MI, USA.

27 British Standards Institution. (2008). *BS EN 12620:2002 + A1:2008. Aggregates for Concrete.* London, UK.

28 British Standards Institution. (2006). *BS 8500-2:2006. Concrete – Complementary British Standards to BS EN 206-1 – Part 2: Specification for constituent materials and concrete.* London, UK.

29 Standards New Zealand. *NZS 3111:1986 Methods of Test for Water and Aggregate for Concrete.* Wellington, New Zealand.

30 Mackechnie, J and Munn, C. (2011). *Characterising recycled aggregates for use in New Zealand ready-mix concrete production.* Concrete Institute of Australia Conference, Perth, 2011, Australia.

31 Tam and Tam. (2007). *A new approach in assessing cement mortar remains on recycled aggregate.* Magazine of Concrete Research August 59(6):413-422. ICE Publishing, London, UK.

32 ASTM International. ASTM C33. *Standard Specification for Concrete Aggregates (*ASTM C33/C33M–11a). West Conshohocken, PA, USA.

33 Sani D, Moricon G, Fava G, Corinaldesi V. *Leaching and Mechanical Behaviour of Concrete Manufactured with Recycled Aggregates.* Waste Management Issue 25(2):177–182. Elsevier, Amsterdam, Netherlands.

[34] Shehata et al. (2010). *Reactivity of reclaimed concrete aggregate produced from concrete affected by alkali–silica reaction.* Cement and Concrete Research (40):575-582. Elsevier, Amsterdam, Netherlands.

[35] Portland Cement Association. *The Use of Recycled Concrete Aggregate from Concrete Exhibiting Alkali-Silica Reactivity* (R Start – Research and Development Bulletin RD 114). Stokie, Ill., USA.

[36] Building Research Establishment (2004). *Alkali-silica reaction – Detailed guidance for new construction* (BRE Digest 330). Watford, Hartfordshire, UK.

[37] Dhir RK, Paine KA, Caliskan S. *Use of Recycled Glass in Concrete* (Technology Application Document 2). University of Dundee, Scotland, UK.

[38] Evangelista and Brito. (2007, May). *Mechanical Behaviour of concrete made with recycled fine aggregates.* Cement and Concrete Composites 29(5):397-401. Elsevier, Amsterdam, Netherlands.

[39] Tam, Gao and Tam. (2006, September). *Comparing performance of modified two-stage mixing approach for producing recycled aggregate concrete.* Magazine of Concrete Research, 58(7):477–484. ICE Publishing, London, UK.

[40] *Mechanical Properties of Recycled Aggregate Concrete - Recycling of Demolished Concrete and Masonry.* (RILEM Report 6), (1992) Part 1.8. RILEM Publications, Bagneaux, France.

[41] Zhang, Munn, Ingham. (2009). *Recycled Concrete Aggregate and its Application in New Zealand Ready mixed Production* (Technical Papers TR 42). New Zealand Concrete Industries Conference.

[42] Limbachiya et al. (Kingston University, 2000, November). *Use of recycled aggregate in high-strength concrete.* Materials and Structures 3(3): 574–580. RILEM Publications, Bagneaux, France.

[43] Chakradhara, Roa, et al. (2011). I*nfluence of field recycled coarse aggregate on properties of concrete.* Material and Structures 44:205-220. RILEM Publications, Bagneaux, France.

[44] Dhir RK, Paine KA, Caliskan S. *Use of Recycled Concrete Aggregate in Concrete - Technology Application Document 1.* University of Dundee, Scotland, UK.

[45] Zalcardi et al. (2008, June). *Chloride Penetration and Binding in Recycled Concrete.* Journal of Materials and Civil Engineering: 449-455. ASCE, Reston, VA, USA.

[46] KY Ann et al. (2007). *Durability of recycled aggregate concrete using pozzolanic materials.* School of Civil and Environmental Engineering, Seoul, Republic of Korea.

[47] Berndt, ML. (2007). *Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate.* Construction and Building Materials, Elseivier, Amsterdam, Netherlands.

[48] American Concrete Institute. (2001). *ACI 555R-01 Removal and Reuse of Hardened Concrete.* ACI, Farmington Hills, MI, USA.

[49] American Concrete Institute. (2011). *ACI 214R-11 Guide to Evaluation of Strength Test Results of Concrete.* ACI, Farmington Hills, MI, USA.

[50] Goncalves and Brito. (2010, May). *Recycled Aggregate Concrete (RAC) – comparative analysis of existing specifications.* Magazine of Concrete Research 62(5):339–346. ICE Publishing, London, UK.

[51] British Standards Institution. (2000). *BS EN 206-1:2000. Concrete – Part 1 Specification, performance, production and conformity.* London, UK.

[52] British Standards Institution. (2009). *BS EN 933-11:2009. Tests for Geometric Properties of Aggregate, Part II Compaction Test for the Constituents of Coarse Recycled Aggregate.* London, UK.

[53] Standards Australia. (2007). *AS 1141. Method for Sampling and Testing Aggregates.* (Various parts and dates). Sydney, Australia.

[54] Standards Australia. *AS 2758.1-1988 Aggregates for Rock and Engineering Purposes: Part 1 Coarse Aggregate.* Sydney, Australia.

[55] ASTM International. *ASTM C94/C94M–11b. Standard Specification for Ready mixed Concrete.* West Conshohocken, PA, USA.

[56] Standards New Zealand. *NZS 4402:1986. Methods of testing soils for civil engineering purposes.* Wellington, New Zealand.

[57] British Standards Institution. *BS 812.105.2:1989. Testing Aggregates. Methods for determining elongation index.* London, UK.

[58] ASTM International. *ASTM C88-05. Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfate.* West Conshohocken, PA, USA.

[59] Cement Concrete and Aggregates Australia. (2008, May). *Use of Recycled Aggregates in Construction.* Sydney, Australia.

[60] Bateyneh, Marie, Asi. (2007). *Use of selected waste materials in concrete mixes.* Waste Management 27:1870-1876. The Hasemite University. Elseivier, Amsterdam, Netherlands.

[61] Concrete Technology Unit. *Glass Aggregate – using recycled aggregate in construction from WRAP. Guidance to the use of Crushed or Powdered Glass in Concrete. Specification Clauses for the Use of Crushed Glass Fine Aggregate and Crushed Glass Filler Aggregate. Specification for Crushed Glass as a fine aggregate or Filler aggregate for use in concrete* (CD). University of Dundee, (2003), Scotland, UK.

[62] *Conglasscrete 1 Final Report.* University of Sheffield. (2004, March). *Conglasscrete 2 Final Report.* University of Sheffield, (2004), UK.

[63] Huiying Zhu, Wen Chen, Wei Zhou and Ewan Byars. (2009). *Expansion behaviour of glass aggregates in different testing for alkali-silica reactivity.* Materials and Structures 42:485–494. RILEM Publications, Bagneaux, France.

[64] ASTM International. *ASTM C1260-07. Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar Bar Method).* West Conshohocken, PA, USA.

[65] ASTM International. *ASTM C227-10 Standard Test Method for Potential Alkali Reactivity of Aggregate Combinations (Mortar Bar Method).* West Conshohocken, PA, USA.

[66] Dhir RK, Paine KA, Caliskan S. *Realising a High-Value Sustainable Recycling Solution to the Glass Gullet Surplus.* University of Dundee, Scotland, UK.

[67] Naik, T R and Wu, Z. (2001). *Crushed Post-Consumer Glass as a Partial Replacement of Sand in Concrete.* Fifth CANMET/ACI International Conference on Recent Advances of Concrete Technology, SP-200:553-568.

[68] Copland, Robertson, Slaughter. (2009, October). *A brewery built from millions of beer bottles: Use of glass aggregate concrete.* New Zealand Concrete Industries Conference Technical Papers TR 42.

[69] Sageo-Crentsil K, Brown T and Taylor A. (2001). *Building construction and engineering: Recycled glass as a sand replacement in premix concrete.* CSIRO, Victoria, Australia.

[70] Almesfer, Norton and Ingham. (2009, December). *Implementation of Waste Materials in Concrete.* Symposium on Sustainable Cement Technologies. Auckland, New Zealand.

[71] British Standards Institution. (1998). *BS EN 1744-1:1998. Tests for Chemical Properties of Aggregates. Chemical Analysis.* London, UK.

[72] British Standards Institution. (1998). *BS 1881-124:1998. Testing concrete. Methods for Analysis of Hardened Concrete.* London, UK.

[73] Dhir RK, Paine KA, Caliskan S. *Use of Incinerator Ashes in Concrete.* Technology Application Document 5. University of Dundee, Scotland, UK.

[74] Dhir RK, Paine KA, Caliskan S. *Use of Granulated Rubber in Concrete.* Technology Application Document 6. University of Dundee, Scotland, UK.

[75] Dhir, Paine, Moroney. (2003, October). *Recycling of used tyres in concrete.* Concrete: 47–48. Concrete Society, Camberley, Surrey, UK.

[76] Siddique and Naik. (2004). *Properties of concrete containing scrap tyre rubber – an overview.* Waste Management 24: 563–569. Elseivier, Amsterdam, Netherlands.

[77] Pierce, CE, Blackwell, MC. (2003). *Potential of scrap tire rubber as lightweight aggregate in flowable fill.* Waste Management 23:197-208. Elseivier, Amsterdam, Netherlands.

[78] Chen and Liu. (2004, July). *Properties of lightweight expanded polystyrene concrete reinforced with steel fibre.* Cement and Concrete Research 34(7):1259–1263. Elseivier, Amsterdam, Netherlands.