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Effect of Recycled Concrete Aggregate on New Concrete

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Preface

This is the second report prepared during research into the use of crushed recycled concrete as virgin aggregate substitution in new concrete.

Acknowledgments

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Note

This report is intended for ready mixed concrete suppliers, aggregate suppliers, Local Authorities, waste handlers and recyclers.

EFFECT OF RECYCLED CONCRETE AGGREGATE ON NEW CONCRETE

BRANZ Study Report SR 101
S. G. Park

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ABSTRACT

This report summarises work carried out by BRANZ investigating the effect of including recycled concrete aggregate in new concrete. It also considers the findings of other testing carried out overseas. It concludes that concretes made with recycled concrete aggregates may have reduced compressive, tensile splitting and flexural tensile strengths, and increased drying shrinkage. It also concludes that such recycled aggregate concrete, made with good quality, clean recycled concrete aggregates, would be suitable for use in non-structural applications such as driveways and footpaths.

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1. INTRODUCTION

As with any new technology or development, the main reason that industry will voluntarily adopt it is if there is a demonstrable level of financial gain. Why therefore do we need to look at using recycled concrete as aggregate for new concrete? At the present time there is no desperate concrete aggregate shortage in New Zealand. It has been noted however that the demand for aggregates is on an increasing trend worldwide (Collins, 1998a). If New Zealand follows this course this may mean that in the near future there are areas where readily available aggregates, suitable for making concrete, may be in short supply.

In Auckland for example, urban development has overtaken many areas suitable for quarrying of concrete aggregates. Those areas that are not covered with development may be surrounded by it instead, to such an extent that there is a large amount of public opposition to noisy, dusty quarrying operations taking place "in their back yard".

The consequence of this is that aggregate for concrete must be brought in from further and further out of the centre of Auckland. This increased transportation distance can dramatically increase the cost of what is supposed to be a "cheap filler" in the concrete mix.

At the other end of the construction/demolition process, pressure on landfills in Auckland is also increasing due to urban development. Currently there are five landfills operating in Auckland. Of these, two are to close in 2003, and another is quite small, servicing only a small area of Auckland. The remaining two are reasonably large landfills with predicted lives of around 20 years each. They are, however, both situated 20 – 30 km from the centre of Auckland. Given these factors, the cost of dumping demolition rubble is also likely to rise in both actual dumping fees as well as in transportation costs.

These points mirror the reasons given by overseas researchers for carrying out work in this field (Buck, 1977; Frondistou-Yannas, 1977), these being:

- A shortage of readily available, high grade conventional aggregates.
- Environmental concerns, including lack of landfill sites for disposal of demolition rubble, and the environmental impact of transporting conventional aggregates greater distances.
- Economic concerns that parallel the environmental concerns. As aggregate supplies and rubble disposal sites become more scarce, the cost of these services increases, making recycling a cost-effective option.

A study carried out by Wilburn and Goonan (1998) states that, for the United States, "aggregate recycling rates are greatest in urban areas where replacement of infrastructure is occurring, natural aggregate resources are limited, disposal costs are high, or strict environmental regulations prevent disposal."

According to one author in the British Publication *Concrete* (Simpson, 1999), one of the main barriers to the increased use of recycled aggregates in concrete in the United Kingdom is that "designers and specifiers are unwilling to use them because of the lack of guidance documents". Simpson also lists recycled aggregate supply as a potential problem. If New Zealand ready mixed suppliers are to use recycled concrete as aggregate then they are going to need a large and, more importantly for their plant classification under NZS 3104 (Standards Association of New Zealand, 1991), consistent supply. These barriers to use are also mentioned by Lauritzen (1998) in his keynote paper to the international symposium Sustainable Construction: Use of Recycled Concrete Aggregate.

This report aims to supply the necessary information on recycled aggregate concrete to the construction industry to allow them to confidently use recycled concrete aggregates in concrete production, and to give local authorities the information necessary for deciding whether or not to accept their use.

Using recycled demolition rubble as aggregate for new concrete is a topic that has been investigated for about half a century. This can be evidenced by the publication in 1951 of a German standard, DIN 4163 *Concrete made with broken brick. Specification for production and use* (German Standard DIN 4163).

Rubble is generally crushed in one of two ways. Either a portable plant is taken to a demolition site and the rubble crushed there or the demolition rubble is taken to a central crushing site. A combination of these two options is sometimes used where a portable crusher is used at a central location but can from time to time move to a demolition site if the need arises.

Demolition rubble, like that seen in Figure 1, will generally come in quite large pieces, possibly with reinforcing steel still integral through it. This is then processed through a crusher to bring it down to the required maximum size. Figure 2 shows rubble that has been processed down to a maximum size of around 150 mm. This can be further crushed to reduce the maximum aggregate size to that required for making concrete. The steel is removed at the primary crushing stage and can be collected and stockpiled for recycling at a later date (see Figure 3).

There are however several contaminants that should be kept out of recycled aggregate as much as possible if it is to be used for making new concrete. The effect that different contaminants have on different properties, particularly the strength, of concrete made with recycled aggregate has been extensively investigated. RILEM Report 6 (RILEM, 1992) summarises this work and lists the following contaminants as being detrimental to the properties of concrete:

- lime plaster
- soil
- organic substances, e.g. wood
- hydrated gypsum
- asphalt/bitumen
- paint made with vinyl acetate

- chlorides
- glass
- fire-damaged concrete.

Of these perhaps chloride and asphalt/bitumen contamination are less of a concern in the New Zealand situation. The main sources of these contaminants in recycled aggregate overseas is when the source of the recycled aggregate is concrete roads. There are very few concrete roads in New Zealand, and de-icing salts, which contaminate concrete with chlorides, are not used. This is a common practice in many other overseas countries. Chlorides may be a problem if the source of the recycled aggregate was a structure situated near the sea. Chlorides in concrete can lead to the corrosion of reinforcing steel that may be present.

The other contaminants listed are more of a concern. Gypsum plaster could lead to expansions of the concrete through sulphate reactions (Gallias, 1998). Likewise, glass can cause problems through alkali-silica reaction. The other substances listed will generally cause a reduction in strength if present in great enough quantities.

RILEM has also released a Recommendation (RILEM, 1994) which gives a way of classifying the recycled aggregates into three different types, and states the maximum level of contaminants allowed. The three types of aggregate are defined as:

Type I: Aggregates which are implicitly understood to originate primarily from masonry rubble.

Type II: Aggregates which are implicitly understood to originate primarily from concrete rubble.

Type III: Aggregates which are implicitly understood to consist of a blend of recycled aggregates and natural aggregates.

The recycled aggregates tested during the project and reported herein would therefore be classed as Type II.

This report does not investigate the effects that contaminants have on recycled aggregate concrete, but attention is drawn to the detrimental effects that can occur by their inclusion in recycled aggregate concrete.

2. SCOPE

The scope of this research report is based on an extension to previous work carried out by Park (1999). This previous work investigated mixes that contained 100% recycled coarse aggregate as compared with corresponding virgin aggregate mixes. Three different cement contents were investigated. Concrete properties examined included compressive strength, flexural tensile strength, drying shrinkage, and modulus of elasticity. All of these mixes were made with two sources of recycled aggregate. One was the crushed concrete obtained by crushing up the samples from the virgin aggregate mixes after they had been tested. The second was obtained from a concrete recycler in Auckland.

The main points reported previously were as follows.

- The recycled aggregates tend to be lighter than the corresponding virgin aggregates. This means that concrete made with recycled aggregates have a lower density than the same concrete made with virgin aggregates.

- There is a reduction in strength in concrete made with recycled aggregate compared with the same concrete made with virgin aggregates. This strength drop is to be found in compressive, flexural tensile and indirect tensile strengths.

- There is an increase in the drying shrinkage of concrete made with recycled aggregates as compared with the same concrete made with virgin aggregates.

These effects on the properties of recycled aggregate concrete would be reduced if recycled coarse aggregate was used in combination with virgin aggregates.

Therefore, for this second stage, properties of concrete made with only partial substitution of virgin coarse aggregate with recycled coarse aggregate were investigated. This is a likely scenario in that a ready mixed concrete plant would use recycled aggregate at a fixed proportion of the total coarse aggregates rather than at a 100% replacement rate, and this would probably happen for some mixes only.

This second stage programme comprised two laboratory trials and three field trials using recycled concrete aggregate.

3. EXPERIMENTAL PROGRAMME

The experimental programme results are broken up into three sections.

The first section details the work done in the first laboratory trial. The second section describes the work carried out in the second laboratory trial, and the third covers the field trials.

For all trials reported in this report only coarse recycled aggregate was used. This is material passing a 19.0 mm sieve but retained on a 4.75 mm sieve. This is consistent with the earlier work carried out in this project (Park, 1999). The reason for only using the coarse aggregate fraction of the recycled aggregate is covered in Section 5.

3.1 First Laboratory Trial

The purpose of this phase of the testing was to determine if there was any discernable difference in the properties of mixes made with different sources of recycled coarse aggregate. The aggregates were sampled from a concrete recycler’s yard from three visually different recycled aggregates.

For this laboratory trial the nomenclature used for identifying the mixes is V1 for the control mix containing 100% virgin aggregate, and R1, R2, and R3 for the three mixes containing the recycled aggregate described below.

The aggregate described as R1 was crushed to a maximum aggregate size of approximately 20 mm. It was mainly crushed concrete with some pieces of clay brick and other similar construction debris visible as contaminants.

The R2 aggregate was crushed to a maximum aggregate size of 40 mm and was mainly crushed concrete with some virgin crushed basalt aggregate. It also contained some brick and other debris.

The R3 aggregate was similar to the R2 but was cleaner having virtually no contaminant material.

All of the recycled aggregates were sourced from Auckland. Here, the original concrete that was crushed to give the recycled aggregates was made using basalt aggregate. Basalt is a dense rock with densities as high as 3000 kg/m^3. This means that the recycled aggregate was also quite dense, around 2600 kg/m^3. The recycled concrete was crushed in a jaw crusher in the laboratory.

The virgin aggregates used in the laboratory trials, both coarse and fine, were commercially supplied, crushed greywacke from Wellington. Greywacke densities are generally around 2650 kg/m^3. This meant that the recycled and virgin aggregate densities were similar.

Four mixes were investigated, one made completely with virgin aggregate, and three with different recycled aggregates at 30% replacement of the coarse aggregate fraction. One cement content of 230 kg/m^3 was used in all the mixes corresponding to that used for a typical virgin aggregate, 20.0 MPa specified strength mix. In all mixes virgin sand was used. This mix was chosen as it is a typical residential concrete mix.

The aggregates saturated surface dry (SSD) densities were measured using the test method described in NZS 3111: 1986. The mixes were weigh-batched and mixed in an 80 litre pan mixer.

A common slump of 100 mm was targeted for all of these mixes. To achieve this superplasticisers were used if the target water content was not enough to bring the workability up to the required level. Superplasticisers are not normally used in residential type concrete. Instead the water content is increased to achieve the required slump. However, in this case, it was decided to keep the water-cement ratio constant, and so superplasticisers were used to obtain the required workability.

The slump, wet density, and air content of the mixes were determined according to the test methods described in NZS 3112: Part 1: 1986 (Standards Association of New Zealand, 1986). The yield and actual air content were also determined using the actual weights of the materials used in the mixes.

The hardened concrete properties measured included compressive strength at 7, 28 and 56 days, hardened density at each of these ages, 28-day tensile splitting strength, and 28-day flexural tensile strength, all to the methods described in NZS 3112: Part 2: 1986

(Standards Association of New Zealand, 1986). The specimens were also made and cured as specified by this Standard.

In addition, the drying shrinkage of the mixes was measured. The test method used to determine this was AS 1012.13 (Standards Australia, 1992).

3.2 Second Laboratory Trial

In the second laboratory trial one recycled aggregate was used at different levels of replacement. The levels were 30%, 50%, 70% and 100% replacement of the coarse aggregate fraction of the concrete mix.

The purpose of this phase of the investigation was to determine the effect of varying the level of recycled aggregate replacement at one cement content. The recycled aggregate used for this stage of the testing was made up by combining different recycled aggregates left over from previous stages of testing. This includes material used in the first laboratory trial reported above, the field trial reported below and some of the work reported in the previous study report on recycled aggregate (Park, 1999).

The cement content of these mixes was at a moderately high level of 285 kg/m^3 such that any variations in strength due to the variation in the aggregate would be more noticeable as a function of the concrete strength.

Aggregate properties were tested in accordance with the test methods described in NZS 3111: 1986 (Standards Association of New Zealand, 1986). The mixes were weigh-batched and mixed in the concrete laboratory's 80 litre pan mixer.

A common slump of 100 mm was targeted for all of these mixes. To achieve this superplasticisers were used if the target water content was not enough to bring the workability up to the required level. Fresh concrete tests for slump, wet density, yield and air content were carried out in accordance with the methods described in NZS 3112: Part 1: 1986 (Standards Association of New Zealand, 1986). Hardened concrete tests for compressive, flexural tensile and indirect tensile strengths, and hardened density were carried out to the methods described in NZS 3112: Part 2: 1986 (Standards Association of New Zealand, 1986). Drying shrinkage of the concrete was measured in accordance with AS 1012.13 (Standards Australia, 1992).

Crushing resistance testing was also considered as described in NZS 3111: 1986 (Standards Association of New Zealand, 1986). This test involves measuring the peak load achieved whilst crushing a sample of aggregate such that 10% of the material by mass passes through a 2.36 mm sieve after the crushing. However, previous work using this test showed that what happened was that small pieces of concrete still attached to aggregate particles were easily removed during this test, giving a large quantity of sub-2.36 mm material at relatively low loads. Visually inspecting the aggregate after the test showed that it had suffered very little distress at all, and hence the crushing resistance test appeared to give an artificially low result. Therefore, this test was not used for determining the properties of the aggregates.

3.3 Field Trials

There were several reasons for carrying out the field trials. These included the following:

- To check that the laboratory mix designs could be successfully used in the field.
- The need to demonstrate, especially to the concrete industry, the viability of recycled aggregate as a replacement for virgin aggregate in concrete.

Two field trials were carried out in Wellington and one in Auckland. The first Wellington field trial was a section of footpath at the BRANZ site, and the second was part of a residential driveway.

The Auckland field trial was a section of a footpath contract that a local Council, North Shore City, offered as a trial site.

4. RESULTS

The results are given here in three different sections. The first gives the results from the laboratory trials investigating the three different types of recycled aggregate used at the 30% replacement level. The second gives the results from the lab trials using one type of recycled aggregate at different levels of replacement. The third section gives the results from the field trials.

Unless otherwise specified, all aggregate weights given in the tables are saturated surface dry (SSD) weights.

4.1 First Laboratory Trials

4.1.1 Aggregate Properties

As described above, the three recycled aggregates were all slightly different. This is demonstrated in the saturated surface dry densities given in Table 1 below.

Table 1 Aggregate Saturated Surface Dry Densities

Aggregate	SSD Density (kg/m^3)
V1 (Control)	2660
R1	2370
R2	2510
R3	2550

4.1.2 Mix Designs

The mix designs for the trial mixes are given in Table 2 below. All of the values in the table are on a 'per cubic metre of concrete' basis. Although the densities of the recycled aggregates were slightly lower than the density of the virgin aggregate, the replacement was still made at a 1:1 ratio by weight. This only led to a slight increase in the yield of the mix.

Table 2 First Laboratory Trial Mix Designs (per cubic metre of concrete)

Materials	V1 (Control)	R1	R2	R3
19 mm Virgin Aggregate	545 kg	380 kg	380 kg	380 kg
19 mm Recycled Aggregate	0 kg	165 kg	165 kg	165 kg
13 mm Virgin Aggregate	545 kg	380 kg	380 kg	380 kg
13 mm Recycled Aggregate	0 kg	165 kg	165 kg	165 kg
Sand	818 kg	818 kg	818 kg	818 kg
Cement	230 kg	230 kg	230 kg	230 kg
Water Reducer	0.550 l	0.550 l	0.550 l	0.550 l
Air Entrainer	0.100 l	0.100 l	0.100 l	0.100 l
Target Total Water	170 l	170 l	170 l	170 l

4.1.3 Fresh Concrete Properties

Table 3 gives the fresh concrete properties of the mixes.

Table 3 Fresh Concrete Properties

Mix	Slump (mm)	Air Content (%)	Wet Density (kg/m^3)	Yield	Measured w/c*	Total Water (l/m^3)
V1	120	4.5	2340	0.98	0.68	160
R1	130	3.5	2350	0.98	0.74	173
R2	110	4.7	2310	1.00	0.72	166
R3	100	4.5	2310	1.00	0.72	165

* w/c: water to cement ratio

4.1.4 Hardened Concrete Properties

Table 4 gives strength and density results for the four mixes as tested. Table 5 gives the results for tensile splitting, flexural tensile strengths and drying shrinkage of concrete.

The compressive strength and drying shrinkage results are also shown graphically in Figure 4 and Figure 5 respectively.

Table 4 Mean Compressive Strength and Hardened Density Results

		Age at Test		
Mix	Property	7 Days	28 Days	56 Days
V1 (Control)	Compressive Strength (MPa)	17.0	27.0	31.0
	Hardened Density (kg/m^3)	2370	2380	2370
R1	Compressive Strength (MPa)	16.0	25.0	28.5
	Hardened Density (kg/m^3)	2330	2340	2340
R2	Compressive Strength (MPa)	16.0	26.5	28.5
	Hardened Density (kg/m^3)	2330	2340	2350
R3	Compressive Strength (MPa)	17.0	26.5	29.5
	Hardened Density (kg/m^3)	2350	2350	2360

Table 5 Other Hardened Concrete Properties

Mix	28 Day Tensile Splitting Strength (MPa)	28 Day Flexural Tensile Strength (MPa)	56 Day Drying Shrinkage (Microstrain)
V1 (Control)	3.4	4.2	620
R1	3.0	3.6	640
R2	3.0	3.4	590
R3	2.8	3.8	640

4.2 Second Laboratory Trials

4.2.1 Aggregate Properties

As noted in section 2.2, the recycled aggregate used for this laboratory was a mixture of many different recycled aggregates left over from previous work.

The saturated surface dry density of the combined recycled aggregate was 2660 kg/m^3. This was identical to the density of the virgin aggregate. The reason that the density was not lighter was that the recycled aggregate all came from Auckland. Here the virgin aggregates used to make concrete are basalt, which are significantly denser than Wellington's greywacke aggregates. This means that whilst the recycled aggregate is less dense than virgin Auckland aggregate, it is the same density as virgin Wellington aggregate.

4.2.2 Mix Designs

Table 6 gives the mix designs used for this laboratory trial on a 'per cubic metre of concrete' basis. The weights of the aggregates are the saturated surface dry (SSD) weights. The nomenclature used here is that the control mix had only virgin aggregate, R30 had 30% of the virgin coarse aggregate replaced with recycled aggregate, R50 had 50% of the virgin coarse aggregate replaced with recycled aggregate, etc.

Table 6 Second Laboratory Trial Mix Designs (per cubic metre of concrete)

Materials	Control	R30	R50	R70	R100
19 mm Virgin Aggregate	550 kg	390 kg	275 kg	165 kg	0 kg
19 mm Recycled Aggregate	0 kg	160 kg	275 kg	385 kg	550 kg
13 mm Virgin Aggregate	550 kg	390 kg	275 kg	165 kg	0 kg
13 mm Recycled Aggregate	0 kg	160 kg	275 kg	385 kg	550 kg
Sand	830 kg	830 kg	830 kg	830 kg	830 kg
Cement	285 kg	285 kg	285 kg	285 kg	285 kg
Water Reducer	0.550 l	0.550 l	0.550 l	0.550 l	0.550 l
Target Total Water	170 l	170 l	170 l	170 l	170 l

4.2.3 Fresh Concrete Properties

Table 7 gives the results of the fresh concrete tests.

Table 7 Fresh Concrete Properties

Mix	Slump (mm)	Air Content (%)	Wet Density (kg/m^3)	Yield	Measured w/c*	Total Water (l/m^3)	Super-plasticiser (l/m^3)
Control	130	3.0	2350	1.014	0.60	168	0
R30	60	3.2	2340	1.020	0.60	167	0
R50	70	3.5	2340	1.021	0.60	167	0.92
R70	80	3.6	2350	1.016	0.60	167	2.46
R100	70	2.8	2330	1.025	0.60	167	3.08

* w/c: water to cement ratio

4.2.4 Hardened Concrete Properties

Table 8 and Table 9 give the results of the hardened concrete tests.

Figure 6 and Figure 7 show the compressive strength and drying shrinkage graphically.

Table 8 Mean Compressive Strength and Hardened Density Results

		Age at Test		
Mix	Property	7 Days	28 Days	56 Days
Control	Compressive Strength (MPa)	30.5	41.5	45.0
	Hardened Density (kg/m^3)	2410	2420	2420
R30	Compressive Strength (MPa)	29.5	38.0	41.0
	Hardened Density (kg/m^3)	2380	2380	2390
R50	Compressive Strength (MPa)	29.0	38.0	40.5
	Hardened Density (kg/m^3)	2370	2380	2370
R70	Compressive Strength (MPa)	28.5	37.0	40.0
	Hardened Density (kg/m^3)	2390	2390	2390
R100	Compressive Strength (MPa)	31.5	40.0	42.0
	Hardened Density (kg/m^3)	2370	2370	2370

Table 9 Other Hardened Concrete Properties

Mix	28 Day Tensile Splitting Strength (MPa)	28 Day Flexural Tensile Strength (MPa)	56 Day Drying Shrinkage (Microstrain)
Control	4.2	5.0	680
R30	3.8	4.8	730
R50	3.8	4.8	730
R70	3.8	4.6	790
R100	3.8	4.4	850*

* This value is an estimate based on earlier and later readings, as the 56 day reading was not taken.

4.3 Field Trials

The field trials were conducted for several reasons. Firstly to check that the mixes used in the laboratory could also be used successfully in the field, and secondly to show industry that the use of recycled aggregate is a viable concept.

4.3.1 Footpath

A section of path 4.2 metres long by 1 metre wide had to be replaced at the BRANZ site at Judgeford near Wellington. Old pieces of concrete from around the concrete laboratory and left over recycled aggregate from earlier work was used to make the concrete for this trial. The replacement level was 100% of the coarse aggregate fraction. This mirrors what was done in the previous study (Park, 1999).

The mix design used for this job is given below in Table 10. Measures are given on a per cubic metre basis.

Table 10 Footpath Mix Design

Material	SSD Weight
19 mm recycled concrete aggregate	480 kg
13 mm recycled concrete aggregate	480 kg
River sand	820 kg
GP cement	230 kg
Water reducer	0.550 l
Air entrainer	0.100
Target air	5.5 %
Total target water	170 l

The results of the hardened concrete tests are given in Table 11 below.

Table 11 Footpath Hardened Concrete Results

Property	Result
7-Day Compressive Strength	13.5 MPa
7-Day Density	2180 kg/m^3
28-Day Compressive Strength	22.0 MPa
28-Day Density	2200 kg/m^3
28-Day Flexural Tensile Strength	3.4 MPa
56-Day Drying Shrinkage	870 microstrain

4.3.2 Residential Driveway

Here a sample of recycled aggregate was brought down from Auckland to Wellington for the purpose of the trial. The aggregate was washed and sieved in a commercial operation to obtain the necessary sample.

The concrete was mixed at a commercial ready-mixed concrete plant. Half of the driveway was made with concrete containing 30% recycled coarse aggregate and 70% virgin aggregate, the other half with 100% virgin aggregate concrete. The results of the tests carried out on the two different types of concrete are given in Table 12.

Table 12 Hardened Concrete Properties of Driveway Trial

Property	Recycled	Virgin
28-Day Compressive Strength	28.5 MPa	25.0 MPa
28-Day Density	2330 kg/m^3	2310 kg/m^3
28-Day Flexural Tensile Strength	3.6 MPa	3.6 MPa
56-Day Drying Shrinkage	880 Microstrain	820 Microstrain

4.3.3 Auckland Footpath

This project involved a relatively large volume of concrete placed in several sections as part of a footpath replacement programme. The volume of concrete involved was approximately 10 m^3. Pictures showing the site during placing and finishing are given as Figure 8 and Figure 9.

The mix design chosen for the job was to use the standard mix that would normally be used, except that one third of the coarse aggregate fraction was replaced with recycled aggregates sourced from a commercial recycler. The mix was a nominal 17.5 MPa mix, which means that the target strength was 22.0 MPa as defined by NZS 3104 (Standards Association of New Zealand, 1991) for a Special Grade plant. It was found that the concrete tended to need some water addition at site to increase the workability to the level where the contractors found it suitable for placing. This may have been needed if the recycled aggregate used for the testing was not at least saturated surface dry.

The concrete handled well and did not segregate either whilst being placing or under vibration. The finishing technique used on the concrete was a brush finish.

Samples were taken at the ready mixed concrete plant to determine the concrete's compressive strength, and the following results were obtained.

Table 13 Auckland Footpath Field Trial Strength Results

Age (days)	Strength (MPa)
7	16.5
28	20.0

The difference in strength between the 20.0 MPa achieved and the 22.0 MPa targeted may be due to simple variation in the concrete mix or, as is more likely, it may be due to inclusion of the recycled aggregate. The plant engineer for the ready mixed concrete plant that produced the concrete indicated that approximately 15 kg/m^3 of extra cement would be needed to bring the strength up to the required level. He also indicated that, at this time, the increased cost in providing this extra cement is not offset by the savings made by using recycled aggregate. To them, therefore, it is not economically viable to use recycled aggregate at this stage.

5. DISCUSSION

In this work only the coarse aggregate fraction of the mixes have been replaced with recycled aggregate. The reason for only using the coarse aggregate fraction of the recycled aggregate is that the fine portion can have a large and variable absorption and water demand. As pointed out by both Buck (1977) and Knights (1998) this high absorption and water demand can adversely affect the concrete performance. Large and variable absorption of fine aggregate makes it difficult to maintain good control over the concrete mix characteristics, especially strength. This was therefore the justification for not investigating fine recycled material. Other work carried out by Hansen and Narud (1983) and Montgomery (1998) also only investigated replacement of the coarse aggregate with recycled material. The reason for not looking at fine material is not given, but it is assumed to be for the same reasons.

In the past few years, however, some work has been carried out overseas by several different groups investigating the inclusion of the fine portion of recycled concrete aggregate in new concrete. Limbachiya, Leelawat and Dhir (1998) investigated mixes containing virgin coarse aggregate and 0, 20%, 30% and 50% recycled fine aggregate. They concluded that up to 20% of the fine aggregate could be replaced with recycled concrete with the strength performance staying similar to that of virgin aggregate concrete.

Dolara et al (1998) carried out work investigating the performance of recycled aggregate in large concrete beams. They had three different mix designs, one 100% virgin aggregates, one 100% recycled aggregates and one which was a 50:50 split between the two. They found that with 100% recycled aggregates there was a drop in 28-day compressive strength of about 23% and a decrease in the modulus of elasticity of about 31% when compared with the same mix design made with 100% virgin aggregates.

Work done by van Acker (1998) indicates that replacing 10% of the fines in concrete with recycled concrete aggregate does not appear to detrimentally affect the compressive or tensile strengths, the drying shrinkage or the modulus of elasticity. However, after 20 freeze-thaw cycles it was found that the tensile strength was reduced to a level which was deemed unacceptable. Tensile strength is one of the most important concrete characteristics for pavement construction.

Likewise, testing reported by Collins (1998b) that was carried out at four precast works "indicate that there is little if any effect from the replacement of 20% of the coarse aggregate and 10% of the fine aggregate by reclaimed product."

Van der Wegen and Haverkort (1998), who investigated both washed and unwashed fine recycled aggregate, found that the washed material displayed satisfactory performance in concretes whereas the unwashed gave a strength decrease of 25% at a 50% replacement level.

The previous work carried out by Park (1999) concluded the following main points:

- The recycled aggregates tend to be less dense than the corresponding virgin aggregates. This means that concretes made with recycled aggregates have a lower density than the same concrete made with virgin aggregates.

- There is a strength drop in concrete made with recycled aggregate compared with the same concrete made with virgin aggregates. This strength drop is to be found in compressive, flexural tensile and indirect tensile strengths.

- There is an increase in the drying shrinkage of concrete made with recycled aggregates as compared with the same concrete made with virgin aggregates.

These points are again borne out in this study. We can see from the results of both laboratory studies that recycled aggregates are less dense and make weaker concrete that have in general, higher drying shrinkages. It should be noted that the differences between virgin aggregate concrete and recycled aggregate concrete results are, in many cases, quite small.

In the first laboratory trial we see that the virgin aggregate concrete had a 28-day compressive strength of 27.0 MPa. The three recycled aggregate mixes had 28-day strengths of 25.0 MPa, 26.5 MPa and 26.5 MPa. The relative closeness of these results can probably be put down to the fact that there was only a 30 % replacement of the coarse aggregate fraction. Also the aggregate was of reasonably good quality in that it was both clean and contained mainly recycled concrete with very little other material such as brick, masonry, or wood.

Further, in the first trial we saw that the 56-day drying shrinkages for the recycled aggregate concretes were on a par with the virgin aggregate concrete. In fact, one of the mixes had a lower 56-day drying shrinkage value than the control mix.

However, the flexural tensile and indirect tensile strengths of the recycled aggregate concretes were lower when compared with the virgin aggregate concrete.

The second laboratory trial, which investigated the performance of concrete made with varying levels of recycled aggregate, showed greater difference between the virgin aggregate concrete and the recycled aggregate concretes.

The compressive, tensile splitting and flexural tensile strengths all showed a maximum loss of approximately 10% with the introduction of recycled aggregates, although the strength loss did not necessarily increase with an increasing level of virgin aggregate replacement.

Other researchers (Buck, 1977; Dessy et al, 1998; Sagoe-Crentsil et al, 1998) have also found drops in strength and density with the introduction of recycled concrete aggregates.

These tests, however, only investigate some of the physical aspects of concrete. If recycled aggregates are to be used in concrete for structural applications, then other testing related to durability issues, such as water permeability and chloride ion diffusion, should be undertaken.

The field trials demonstrated that whilst the production and utilisation of concrete containing recycled aggregates is physically viable, it may not be quite economically viable at this point in time. If it is not economically viable then the only way that recycled aggregates are likely to be used as aggregate for new concrete is if some form of legislation is introduced at a national or local level, which makes it compulsory to do so. This would not be the most desirable option as the business community is generally more accepting of technologies that they take on themselves as opposed to those which are forced upon them.

The concrete in all of the field trials performed well.

The residential driveway trial raised an interesting point. The recycled aggregate for this trial was sourced from a concrete recycler in Auckland. It was sourced in winter and there had been a lot of rain at the time the concrete was crushed into aggregate. A side effect of crushing concrete in wet conditions is that a large amount of the fine material that is a result of the crushing process remains attached to the coarser material. This meant that the recycled aggregate was very dirty, so dirty that it was not at all suitable for using in concrete. This meant that the aggregate had to be washed in order to make it suitable. This was done with an aggregate washer at a quarry. Consideration should therefore be given by aggregate recyclers to having some means of washing their aggregates to ensure a suitable supply for the production of concrete.

The Auckland field trial was successful not only in that the concrete was demonstrated to be suitable, but perhaps more importantly in that it brought many different groups together to see the project in action. These groups included the local regional council, the local city council, the contractor and the ready mixed concrete supplier. Good lines of communication between these parties have been opened as a result of this trial.

It has been suggested that there may be a need to rethink specifications for situations such as footpaths. Is it necessary for a footpath to be made from 20 MPa concrete in practice? Strength may not be a satisfactory measure of performance. Territorial Authorities could reconsider they way that they specify concrete for such jobs, for example by giving minimum cement or maximum water contents, or by accepting a lower strength when using recycled material.

6. CONCLUSIONS

- The density of recycled aggregates will generally be less than the density of virgin aggregates. This means that the density of concrete made with some fraction of recycled aggregates will generally be less than the density of the same concrete made with 100 % virgin aggregates.

- A drop in compressive strength was observed in all mixes made with recycled aggregates as compared to the corresponding virgin aggregate concrete, except for the residential driveway field trial. In the first laboratory trial the maximum drop was from 27.0 MPa to 25.0 MPa at 28 days. The second laboratory trial saw a maximum drop in strength of 4.5 MPa from 41.5 MPa to 37.0 MPa at 28 days.

- Likewise, a drop in both the tensile splitting strengths and flexural tensile strengths of all mixes made with recycled aggregates was observed when compared with the corresponding virgin aggregate concrete. In the first laboratory trial the tensile splitting and flexural tensile strengths were 3.4 MPa and 4.2 MPa, respectively, for the virgin aggregate concrete. the ranges for the same tests for the recycled aggregate concretes were 2.8 – 3.0 MPa and 3.4 – 3.8 MPa, respectively. In the second laboratory trial the control concrete (virgin aggregate) had a tensile splitting strength of 4.2 MPa and a flexural tensile strength of 5.0 MPa. The recycled aggregate mixes all had tensile splitting strengths of 3.8 MPa and a range of flexural tensile strengths of 4.4 MPa for the R100 mix to 4.8 MPa for the R30 mix.

- The 56-day drying shrinkages of the recycled aggregate mixes in the first laboratory trial were similar to that of the control mix, being around 620 microstrain. In the second laboratory trial, where the percentage of recycled aggregate in the mixes was varied, the drying shrinkage increased with an increasing percentage of recycled aggregate, going from 680 microstrain for the control mix up to approximately 850 microstrain for the R100 mix.

- All of the field trials involving recycled aggregates have demonstrated acceptable behaviour of the concretes involved.

- Given the results of the testing and field trials reported here, the use of good quality, clean recycled aggregates for non-structural concrete applications is viable in terms of the physical properties of the concrete.

7. FURTHER WORK

Areas where further work could be carried out under this research topic include:

- Cost/benefit analysis of using recycled aggregates in concrete, including looking at aspects such as reduced cartage, energy savings through reduced crushing or quarrying, and cheaper aggregates.

- Durability testing of concrete made with recycled aggregates, including permeability testing and chloride ion diffusion testing.

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9. FIGURES

Figure 1 Demolition Rubble Before Processing

Figure 2 Demolition Rubble After Processing

Figure 3 Reclaimed Reinforcing Steel

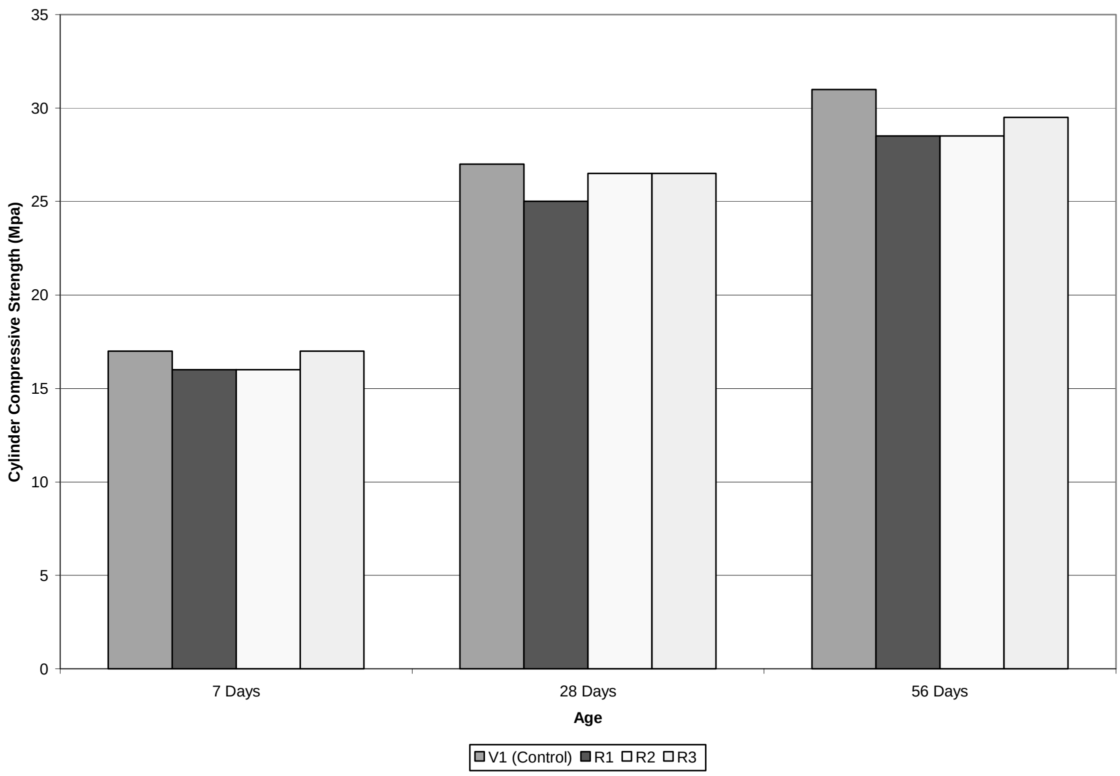

Figure 4 First Laboratory Trial Compressive Strengths

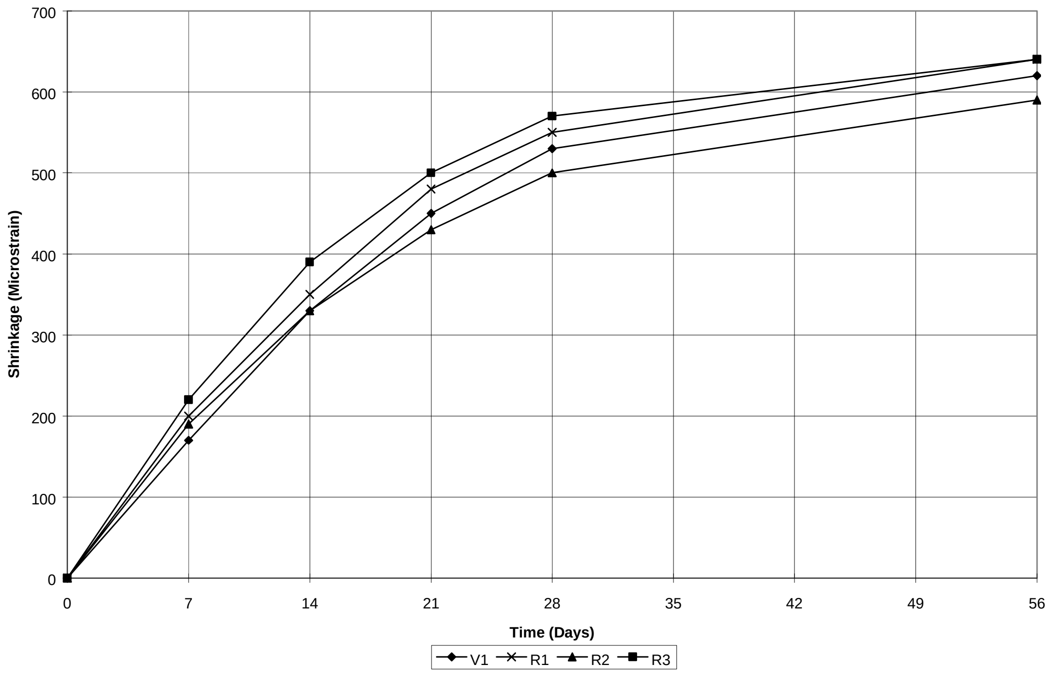

Figure 5 First Laboratory Trial Drying Shrinkages

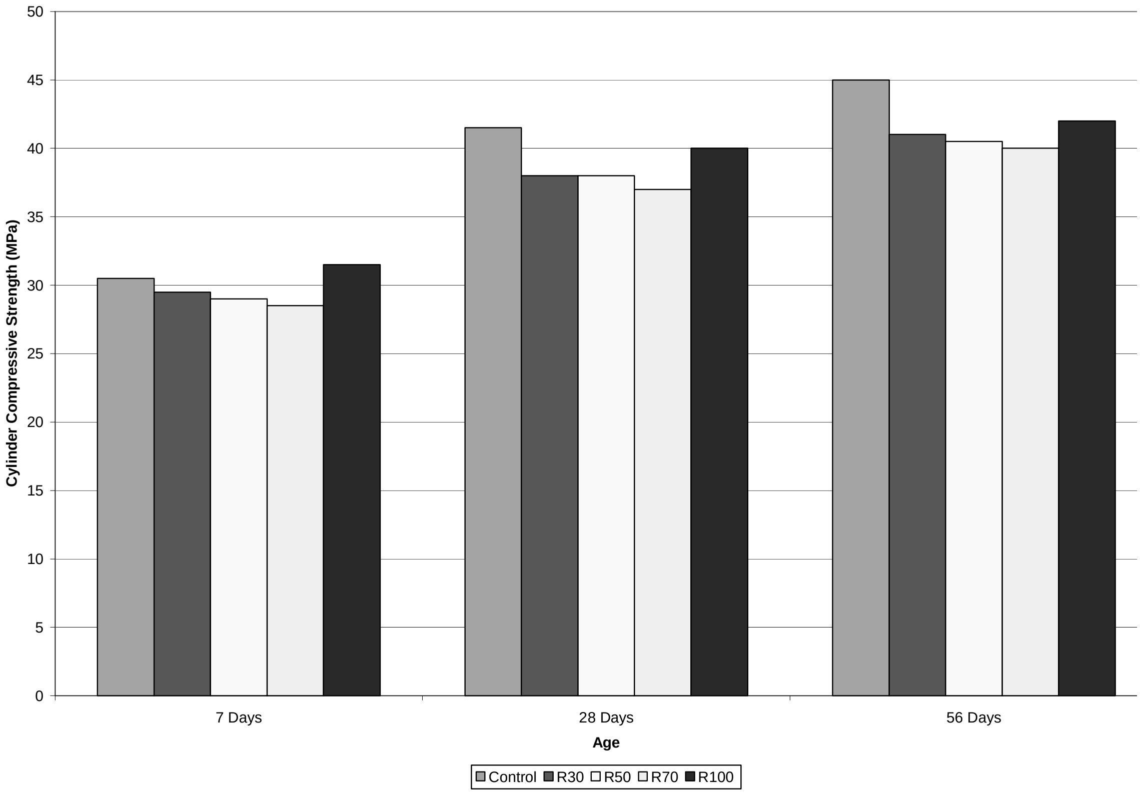

Figure 6 Second Laboratory Trial Compressive Strengths

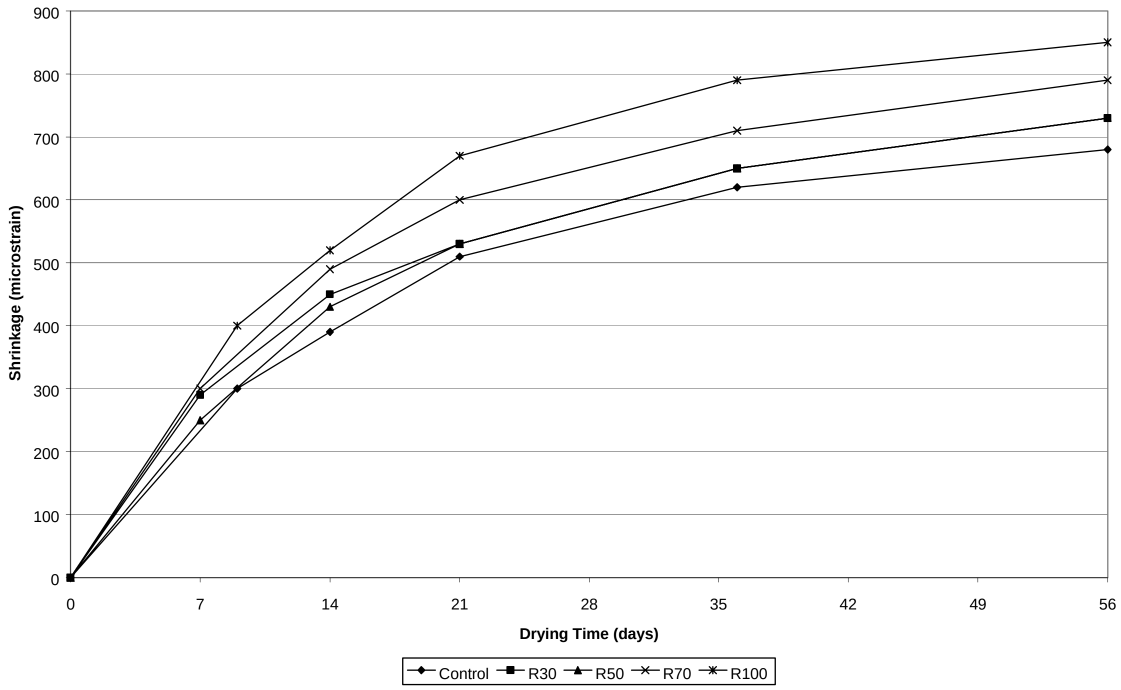

Figure 7 Second Laboratory Trial Drying Shrinkages

Figure 8 Placing Recycled Aggregate Concrete For Field Trial

Figure 9 Finishing Recycled Aggregate Concrete Field Trial