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RECYCLING WASTE CONCRETE INTO ROAD PAVEMENT AGGREGATE

by

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A thesis submitted in fulfillment of the requirements for the degree of Master of Engineering at the Victoria University of Technology.

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May, 1995.

DECLARATION

This thesis contains no material which has previously been submitted for an award or degree at any University. To my knowledge the work reported in this thesis is original and contains no material published by other investigations, except where appropriate reference has been given to the source of the material.

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B.J.E. Richardson

SYNOPSIS

The use of recycled concrete aggregate (RCA) as a road pavement material in Australia is relatively recent and confined mainly to Victoria and New South Wales.

Samples of RCA were taken at six, monthly intervals from a local producer of RCA. A range of tests was carried out to provide initial information as to the suitability of RCA as a road pavement material. The results were then compared to a newly written specification for the material. Comparisons were also made with local natural aggregates. In addition, laboratory samples of RCA were produced from concrete with strengths of 32MPa and 80MPa.

The commercial RCA was found to have a grading suitable for use as a road pavement material and was non-plastic. The softer, lower density, attached cement paste caused increases in Los Angeles abrasion loss, and particle breakdown under compaction. It also lowered the specific gravity and increased moisture absorption. This caused a lower maximum dry density and higher optimum moisture content when compared to natural aggregates. The results obtained using the laboratory produced RCA samples were similar to the commercial RCA, indicating that variations in source concrete have only limited influence.

Repeated triaxial load testing showed that the resilient modulus of RCA is reduced by the addition of brick, but does not vary significantly with source concrete strength. When cured over a 28 day period a significant increase in modulus was observed. Reduction in the compactive moisture content also increased the modulus. A 120,000 pulse RTL test showed that RCA had a considerably lower permanent strain than two basalt aggregates tested under the same conditions.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the following people and organizations for their assistance throughout this research:

- Mr D.O. Jordan, Senior Lecturer, Department of Civil and Building Engineering, for his support, patience, advice, assistance and friendship in his role as my principal supervisor.

- Mr D. Bell, General Manager, Alex Fraser Pty. Ltd., for his helpful advice, particularly during the initial stages of the project, and ensuring that the research would be relevant to the concrete recycling industry.

- The Victorian Education Foundation for financial support in the form of a Research Fellowship.

- The Department of Civil and Building Engineering (VUT) for providing resources and equipment for parts of the experimental program.

- Mr. Rod Flentje, Concrete Laboratory Technician (VUT) for his tireless assistance in the collection and preparation of samples.

- Mr. Jamie McKellar and Alex Fraser Pty Ltd for the supply of as much recycled concrete aggregate as was needed and the use of all testing equipment at their disposal, and to all staff at Alex Fraser Pty who provided a great deal of advice and assistance, in particular, Messrs Andrew and Mark Chandler and Mr Peter Dobell.

- Dr. Ahmed Shayan and Mr Peter Westgate of CSIRO Division of Building, Construction and Engineering for their invaluable assistance with the repeated triaxial loading tests and subsequent interpretation of the results.

- Mr Paul Low, Mr Matt Walsh, Mr Barry Fielding and Mr Roy Gilmour of VicRoads for their assistance in the initial development of the testing program and use of equipment.

- Mr W. Payne of QuarryCrete for his advice and assistance on testing procedures, particularly specific gravity and moisture absorption tests.

- All of the boys from Room D432, Anthony, Paul, Simon, Soheil and Stuart for providing friendship and a positive working environment.

Finally, I would like to thank all of my family for their encouragement and support during the course of my studies.

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LIST OF ABBREVIATIONS

AASHTO	American Association for State Highways and Transportation Officials
APRG	AUSTROADS Pavement Research Group
AAR	Alkali Aggregate Reaction
ACP	Attached Cement Paste
AS	Australian Standard
ASTM	American Society for Testing and Materials
BCSJ	Building Contractors Society of Japan
BS	British Standard
CBR	California bearing ratio
CSIRO	Commonwealth Scientific and Industrial Research Organization
DRTSA	Department of Road Transport South Australia
ISO	International Standard Organization
LA	Los Angeles
LL	Liquid Limit
LVDT	Linear Voltage Displacement Transducer
MDD	Maximum Dry Density
NA	Natural Aggregate
NAASRA	National Association of Australian State Road Authorities
OMC	Optimum Moisture Content
PI	Plasticity Index
PL	Plasticity Limit
PSD	Particle Size Distribution
RCA	Recycled Concrete Aggregate
RTL	Repeated Triaxial Loading
RILEM	International Union of Testing and Research Laboratories for Materials and Structures

SAA	Standards Association of Australia
SG	Specific gravity
SSD	Saturated surface dry
ZAV	Zero air void

TERMINOLOGY

The following terms are used throughout the text. For the purpose of clarity the following definitions are based upon those contained within RILEM Report 6: Recycling of Demolished Concrete and Masonry (Hansen, 1992):

Demolition or waste concrete

Concrete debris from demolished structures, as well as fresh and hardened concrete rejected by ready-mixed concrete producers.

Original source concrete

Concrete produced with natural sand as the fine aggregate and natural rock as the coarse aggregate.

Cement paste or old mortar or attached cement paste

Hardened mixture of cement, sand and water. Some cement paste is always attached to the original aggregate.

Original aggregate

The natural aggregate used to produce the original source concrete.

Recycled concrete aggregate

Aggregate produced from the crushing of demolition or waste concrete. Fine recycled concrete aggregate is any material passing a 4.75mm sieve - any other material is defined as coarse.

NOTATION

a = Cross sectional area of the loading ram (m^2)

A = Cross sectional area of specimen (m^2)

d = Sieve aperture (mm)

D = Maximum particle diameter (mm)

F_v = Vertical force applied to the loading ram

G_s = Specific gravity

$I_{g(n)}$ = Gauge length over which the deformation is measured for that cycle (mm)

I_i = Initial gauge length, the height of the specimen, for external displacement measurement (mm)

K^1 K^2 = Experimental test constants

$M_{r(n)}$ = Resilient modulus at that cycle (MPa)

n = Cycle number

V_a = Air voids (%)

w = Water content (%)

x = Grading exponent

δ_1 = Vertical displacement at the commencement of the test with no confining stress(σ_3) and no deviator stress (σ_d) applied (mm)

δ_2 = Vertical displacement when the confining stress (σ_3) is first applied (mm)

$\delta_{3(n)}$ = Vertical displacement with the confining stress (σ_3) and the deviator stress (σ_d) applied (mm)

$\delta_{4(n)}$ = Vertical displacement with the confining stress (σ_3) applied and the deviator stress (σ_d) released (mm)

$\varepsilon_{p(n)}$ = Permanent strain (%)

$\varepsilon_{r(n)}$ = Resilient vertical strain at that cycle (%)

$\sigma_{d(n)}$ = Deviator stress at that cycle (kPa)

$\sigma_{m(n)}$ = Mean normal stress (kPa)

$\sigma_{l(n)}$ = Maximum vertical stress applied to the specimen for that cycle (kPa)

$\sigma_{3(n)}$ = Static confining stress applied to the specimen for that cycle (kPa)

$\theta_{(n)}$ = Bulk stress (kPa)

ρ_d = Dry density (t/m^3)

ρ_w = Density of water (t/m^3)

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND TO THE PROBLEM

In Australia, well-located, high quality, natural aggregates are in reasonably plentiful supply, particularly when compared to Europe and Japan. However, suitable landfill sites close to major cities, particularly Melbourne and Sydney, are becoming scarce. In 1991 it was estimated that Melbourne had a landfill capacity of approximately 9Mt, which will service current demands for only the following 5 years (McHaffie, 1992).

It is estimated that between 1.5 and 3 million tonnes of demolition rubble is produced each year in Australia, most of which is concrete. In 1991, building rubble contributed 11% of all waste to landfill sites in Melbourne (Industry Commission, 1991a). Tip fees range from \$20 to \$50 per tonne (Robertson, 1991) and, when the transportation costs to the tips are added, an unproductive cost of at least \$50,000,000 per year to the Australian community is estimated. Compounding the problem, a European study done in 1980 indicated that, at that time, it was expected the amount of demolition rubble world-wide could double by the year 2000 and triple by 2020 (Environmental Resources Limited, 1980).

Cost of Disposal.

While vast amounts of potentially valuable building rubble is disposed of into landfill sites, the search for new quarry locations to produce crushed rock continues. As with landfill sites, quarries are being located further away from the point of demand as existing resources diminish. Stringent environmental laws now make it increasingly difficult to find viable locations for new quarries. Recycling of building rubble would allow existing quarries to remain in operation for longer periods.

It is obvious that, even though rock is a relatively abundant resource within Australia, a limit on its availability, imposed by economic and environmental costs, will eventually be reached. To keep removing it from the ground and throwing it away is ultimately unsustainable. Removal of demolition concrete from the waste stream via recycling will increase the lifespan of existing landfill sites.

In Europe and Japan a major push towards concrete recycling has occurred over the last twenty years. These regions have considerably higher population densities than Australia, which has placed a greater strain on the availability of natural aggregates and suitable landfill sites. The recycling of waste concrete has now become standard practice as it enables high cost of disposal into landfill sites to be avoided. This is also becoming the case in Melbourne and Sydney due to the escalation of waste disposal charges.

The high demand for landfill sites, particularly in Melbourne and Sydney, will ensure an increase in the production of recycled concrete in the foreseeable future. Until 1992, concrete recycling in Australia has been limited to a few private companies and local councils, mostly operating in Sydney and Melbourne during the previous four to five years. The recycled material has primarily been used for fill and road subbases, which are both relatively low level applications requiring only limited information on material properties. The research done for this project has provided some initial information on the engineering properties of recycled concrete aggregate (RCA), to enable wider use of the material in road construction applications.

1.2 OPTIONS FOR THE USE OF RCA IN AUSTRALIA

RCA is widely used in other countries for concrete production, as well as for fill and road pavements. In Australia its use as a concrete aggregate has been very limited because current production of RCA in Australia is targeted towards use as either fill or road pavement material, which is discussed in greater detail in Chapter 3: The current state of concrete recycling in Australia. It is therefore important that any initial research carried out is relevant to the industry, especially when so little local information is available.

RCA is only used as a concrete aggregate by necessity in regions or countries that have a shortage of natural aggregates. It is a second choice material because concrete made with it has properties that are generally inferior to concrete made with virgin aggregate. A brief examination of some of these properties is made in section 2.3. A shortage of aggregate is unlikely to arise in Australia within the foreseeable future. Melbourne, for example, has current estimates of secured aggregate reserves well in excess of the needs that have been forecast for the next 25 years (McHaffie, 1992).

Taking these two points into consideration it is doubtful that RCA will be used as a concrete aggregate whilst adequate quantities of virgin material are currently available at an economic price.

1.3 AIMS OF THE RESEARCH

Although RCA is used in Victoria and New South Wales, one aim of the research was to overcome a major obstacle blocking wider acceptance of its use as a road pavement material, namely the lack of technical information on basic engineering properties and the perceived variability of the finished product. The aim of this research was to assess the suitability of recycled concrete for use in road pavements within Australia. This assessment was made by determining the engineering properties of the material by means of a detailed testing program. Factors thought likely to cause variation in those properties, such as differences in source concrete strength, were also examined. The recently developed VicRoads specification 820 'Crushed Concrete for Subbase Pavement' (VicRoads, 1992) was examined and commented upon. Guidelines for quality control and the production of RCA have also been developed. It was envisaged that this research would enable an increase in the use of RCA as a road construction material within Australia.

1.4 THESIS LAYOUT

Chapter One of the thesis gives the reader an appreciation of the need to recycle concrete, primarily due to benefits of waste minimisation and the preservation of existing rock resources. Having established environmental positives, the need to provide appropriate technical information which will stimulate the use of RCA is discussed.

Chapter Two is a review of literature related to the research and Chapter Three includes the results of an Australia-wide survey of Metropolitan Municipal Councils on the use of RCA. These two chapters provide a framework for the research which was carried out.

Chapter Four discusses the various materials used for testing and the methods of obtaining them. Detailed descriptions of the tests, and the reasons for performing them are also outlined. Sufficient information is provided to enable the reader to carry out any comparative testing.

Chapter Five contains the results and discussion of all tests. Statistical analysis and modeling of some results has also been carried out. Comparisons with virgin aggregates are made and explanations for differences between the materials are offered.

Chapter Six examines the VicRoads specification for RCA produced in 1992 and provides quality control guidelines and recommends areas for future research.

The final chapter states the conclusions of the investigation.

CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION

This literature review summarises research carried out relating to the use of RCA as a road pavement material. References were obtained from two RILEM-sponsored symposia -one on the Reuse of Demolition Waste, held in Tokyo, Japan in 1988, and the other on Demolition and Reuse of Concrete and Masonry, held in Odense, Denmark in 1993. A large amount of information was also obtained from RILEM Report 6: Recycling of Demolished Concrete and Masonry (Hansen, 1992). Other sources were European, Japanese and American research papers, most of which discussed the use of RCA in concrete. Information on the use of RCA as an unbound granular pavement material was found in the American Transportation Research Record. Other articles in general concrete journals, such as Concrete International, briefly discussed the economic and environmental benefits of recycling concrete, without providing any substantial technical data.

Computer searches using Compendex and the Australian Road Research Board database failed to produce any published Australian research on RCA. It is believed that this work is the first independent research carried out on RCA in Australia.

2.2 CURRENT EXTENT OF CONCRETE RECYCLING AROUND THE WORLD

Recycling of concrete on a large scale began within Europe after World War II. In Germany, recycling became an important way of using debris created during the war.

Prior to 1955, about 11.5 million cubic metres of brick and concrete were used as concrete aggregate, and a standard for use of the material was produced in 1951. Most building rubble is now used for road bases and fill for excavated areas. Currently, there are around 100 recycling plants operating in Germany, mainly on a small scale (Schulz, 1988).

Within the United Kingdom approximately 20 million tonnes of demolition rubble is produced each year, of which 50-55% is estimated to be concrete (Mulheron, 1988). Collins (1993) later reported that 11 million tonnes of waste concrete is re-used, primarily as fill or hard-core. In 1986, requirements for the use of recycled concrete were set out in the 'Specification for Highway Works', Department of Transport (1986), which has subsequently been revised and is now in its seventh edition. The specification allows the material to be used in applications such as permeable layers, earthworks and as granular subbase layers.

In France approximately 25 million tonnes of demolition rubble is produced per annum. Of this, 10-15 million tonnes is believed to be recyclable, although it is estimated that only 20-30% of this amount is being recycled. Approximately 60% of the demolition rubble is clean concrete. Recycled aggregates represent only 1% of the national aggregate output. The material is being used primarily in road construction and as landfill (Morel et al, 1993).

In Spain the development of concrete recycling was accelerated by the holding of the Olympic Games in Barcelona. Over 1.5 million tonnes of recycled material was used in the construction of roads and highways prior to the 1992 Olympic Games (Morel et al, 1993).

The use of RCA in the Netherlands has been encouraged because of a predicted future shortfall in the production of natural sand and gravel. These materials are mainly obtained from river dredging, which is having an adverse effect on the landscape. In addition to this, the cost of dumping demolition rubble has escalated to $100 per tonne. Currently, around 14 million tonnes of demolition rubble is produced per annum and it is estimated that this will increase in the future. Government policy states that, by the year 2000, 90% of demolition waste must be re-used. Holland currently has the capacity to produce 9.3 million tonnes per annum from 55 permanent, and over 100 mobile, crushing plants, The majority of this material is being used on civil engineering projects (De Vries, 1993).

Recycling concrete on a large scale did not commence in America until the 1970s when work was being carried out by the Army with significant benefits in the area of runway construction (Buck, 1973). Some states, concerned about the conservation of natural resources, the environment, and the increasing costs of road construction materials, began to investigate the use of recycled aggregates. The Texas State Department of Highways has used RCA for Portland Cement concrete pavements, lean concrete bases, shoulder concrete, porous granular fill, unstabilised base courses, asphalt pavements, porous concrete shoulders, cement-treated base courses and open-graded drainage layers. Other states to use RCA as a flexible pavement on major highway projects are Louisiana, Florida and Illinois, all on interstate routes (Transport Research Board, 1989).

Japan has a very high population density and a limited amount of land available for landfill sites. In 1975 the first plant for recycling concrete was constructed, and produced road base material. Demand steadily increased and, in 1984, the 'Technical Guideline for Recycling and Utilising Waste Pavement Materials (Draft)' was produced by the Japan Road Association. This document led to further increases in the use of the material. In 1990 the amount of demolition rubble produced per annum was estimated to be 25.4 million tonnes and, of this, approximately 48% was recycled, mostly as a road pavement material (Kasai, 1993).

In Denmark, 5 million tonnes of building waste is produced per annum, 40% of which is estimated to be concrete. In 1986 12% of building waste was re-used and by 1993 the figure had risen to 25%. The target for the year 2000 is 60% (Lauritzen, 1993).

2.3 PROPERTIES OF CONCRETE MADE USING RCA

Information previously presented in section 1.2 suggests that the best use of RCA in Australia is as a road pavement material, as its use in concrete has disadvantages. Research into the use of RCA as an aggregate for new concrete is relatively extensive. This section gives a very brief overview of the findings made in the major areas of research.

The compressive strength of concrete made from RCA is generally lower than that made using natural aggregate (NA). The difference in strength has been reported as being from 4% to 14% (Froundistou-Yannas, 1977), up to a maximum of 40% reported by Ikeda et al (1988). The lower strength is mainly caused by the recycled concrete fines less than, and it is found that increasing the amount of recycled fines decreases the strength of the concrete. To achieve strengths comparable with concrete made using NA, the RCA fines must be replaced with natural sands (Ravindrarajah and Tam, 1988).

Reduction in the strength of concrete made using RCA is probably due to weaker bonds between the aggregate and the cement matrix, which is discussed in Froundistou-Yannas (1977).

De Pauw (1981) showed that the strength of concrete made using RCA was influenced by the strength of the original source concrete, this is shown in Figure 2.1. All concrete was approximately 15 years old, and had been originally mixed at water/cement ratios ranging from 0.5 to 0.81, was crushed and used to make fresh concrete at a water/cement ratio of 0.57. There was a correlation between the compressive strength of the original concrete and the strength of the new concrete produced with RCA. As the strength of the original concrete increased, so too did the strength of the fresh concrete.

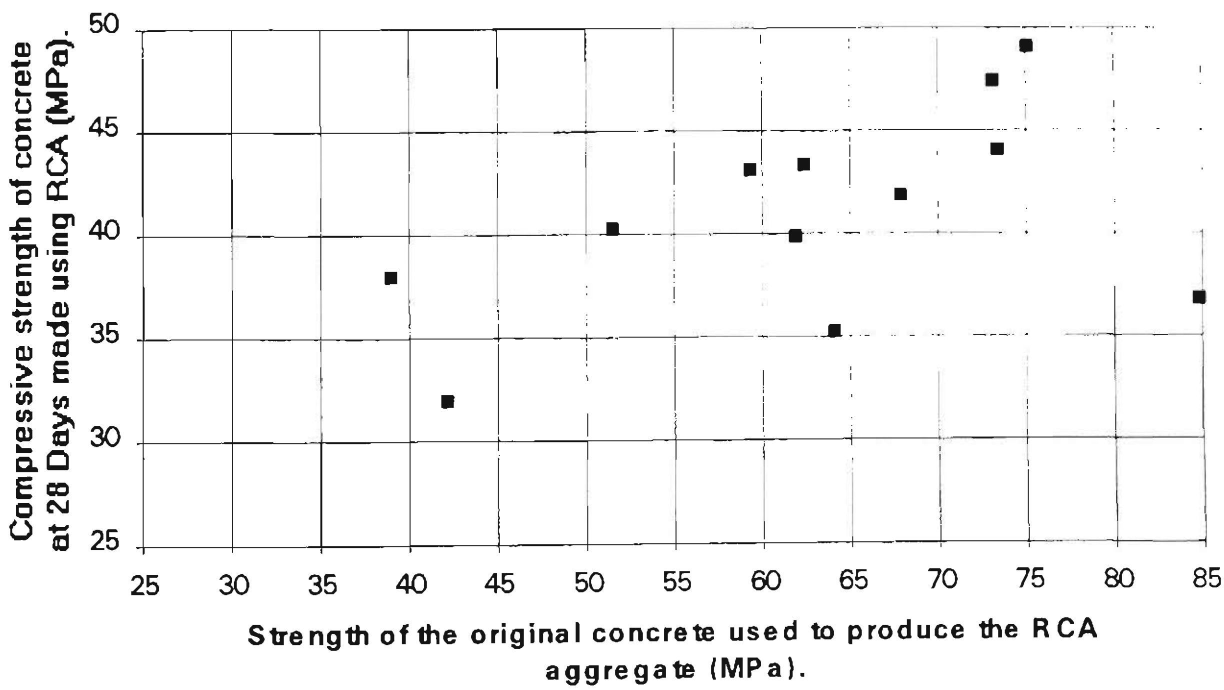


Figure 2.1: Relationship between original strength of RCA and compressive strength of concrete made with it. (Based on De Pauw, 1981)

Ravindrarajah et al (1985) used ASTM C 403-77 to determine the strength development of concrete made using RCA. A representative mortar sample was obtained by sieving fresh concrete and at regular time intervals, the resistance of the mortar to penetration by standard needles was measured. A plot of the penetration resistance versus elapsed time was used to determine initial set (resistance to 3.5MPa) and final set (resistance to 27.6MPa) times. The authors found that concrete made using RCA had a slightly faster initial setting time (240 minutes) compared with the NA (270 minutes). The final setting times also showed a similar pattern- 340 minutes for RCA compared to 375 minutes for concrete made with NA. The authors concluded that the variation in setting times was probably due to the increased water absorption of the RCA and presence of a higher proportion of alkalis.

Frondistou-Yannas (1977) reported that RCA-produced concrete had modulus of elasticity values which were between 60% and 100% of the control concrete mixes. The control mixes were made using granite coarse aggregate and a combination of Ottawa and granite sand. When the RCA fines were replaced with natural sands the reduction in modulus was less pronounced - from no reduction for concrete made with a water/cement ratio of 0.55, up to 25% reduction when a water/cement ratio of 0.75 was used. When both the RCA fine and coarse aggregate was used the modulus was reduced by 40% at a water/cement ratio of 0.55 and 20% for a water/cement ratio of 0.75. Ravindrarajah and Tam (1988) also reported similar results. Frondistou-Yannas (1977) further reported that the modulus of concrete is influenced by the modulus of the aggregate used to produce it. The assumption is made that RCA has a lower modulus than natural aggregate because of the weak cement paste attached to the original stone. This in turn reduces the modulus of concrete made with RCA.

Ravindrarajah and Tam (1988) found that, under uni-axial loading, the creep of concrete made using coarse RCA and natural sand was 30%-60% greater than the control concrete made with NA. Hansen (1992) reported that this is to be expected as creep is proportional to the content of cement paste or mortar, and concrete made using RCA contained approximately 50% more mortar.

Hansen and Boegh (1985) and Ravindrarajah and Tam (1988) reported that the drying shrinkage of concrete made using coarse RCA with natural fines was 40% to 60% higher than control mixes. The use of RCA fines resulted in even higher shrinkage values. The reason for the increase in drying shrinkage is the same as that outlined for creep ie. an increase in cement paste or mortar results in an increase in the drying shrinkage. Because RCA fines contain the largest percentage of attached cement paste (section 2.5.2) they are often replaced with natural sand to reduce the problem of shrinkage.

Buck (1973) found that freeze-thaw resistance of concrete made with RCA was better than concrete produced using NA, but the concrete is not totally frost resistant. It should be noted that freeze-thaw resistance is not a major consideration in Australia.

The BCSJ (1978) found that the permeability and water absorption of concrete made from RCA is 2-5 times higher than concrete using NA. The BSCJ believed that corrosion of the reinforcement was more likely to occur in concrete made with RCA.

Nishibayashi and Yamura (1988) tested the sulphate resistance of RCA concrete. Samples were subjected to cycles of immersion in a sulphate solution followed by oven drying. The specimens were then assessed for changes in length, weight and dynamic modulus. The results showed that the concrete was equal to or slightly inferior to the control concrete.

A detailed examination of the alkali-aggregate reaction (AAR) of RCA was carried out by Gottfredsen and Thogersen (1993), who performed mortar bar expansion tests on concrete made using a control RCA, old concrete from a demolition site, old concrete cores taken out of a pavement severely damaged by AAR, and new concrete made with a highly reactive sand and a non-reactive coarse aggregate. The investigation showed that expansion and cracking of RCA concrete can occur, but the addition of fly-ash would reduce this. No assessment was made as to whether RCA concrete was more susceptible to AAR reaction than virgin aggregate concrete.

2.4 PRODUCTION OF RCA

2.4.1 Types of RCA production plants

RCA is produced carried in the same manner as virgin aggregate, with some relatively minor alterations. The raw material must be reduced in size to the appropriate grading and any contaminants removed. The contaminants in RCA can be steel, which is generally removed by a self-cleaning electro-magnet, or low density material, such as wood, paper, plastic or plaster, which is generally removed manually either before or after the crushing process.

The RCA production plants can be broadly divided into two categories - mobile and fixed. Mobile plants are those which process the rubble on-site. Schultz (1988) defined a typical mobile plant as one which processes pre-selected rubble through an impact crusher and then screens it. The material does not receive secondary crushing and, generally, the only contaminant removed is steel, using the self-cleaning electro-magnet. The fixed plants are generally more sophisticated and will usually incorporate additional crushing and contaminant removal features (Hansen, 1992). Figure 2.2 shows a typical production plant flow-chart.

2.4.2 Crushers, screens and sorting devices

The crushers used in the production of RCA are the same as those used for virgin aggregate. They can be divided into two groups - pressure (jaw and cone crushers) and impact (impactors and hammer mills). Jaw and cone crushers use pressure or a squeezing motion and tend to separate old mortar from the original aggregate. Because the mortar is considerably weaker than the original stone, it will generally break away without damaging the source aggregate during the process. The impactors and hammer mills, on the other hand, treat source aggregate and mortar alike, smashing the waste concrete down in size using blow bars revolving at high velocity. This process generally causes more damage to the original stone when compared with the pressure crushers (Hansen, 1992).

The BCSJ (1978) reported that the only real difference in the physical properties of RCA crushed by impact and pressure crushers was the particle size distribution and aggregate shape. Impact crushers produce more fines and more angular particles than the pressure crushers, which produce a coarser grading and a more cubical product. Other properties, such as Los Angeles (LA) abrasion loss, water absorption and specific gravity, were not significantly affected by the crusher type.

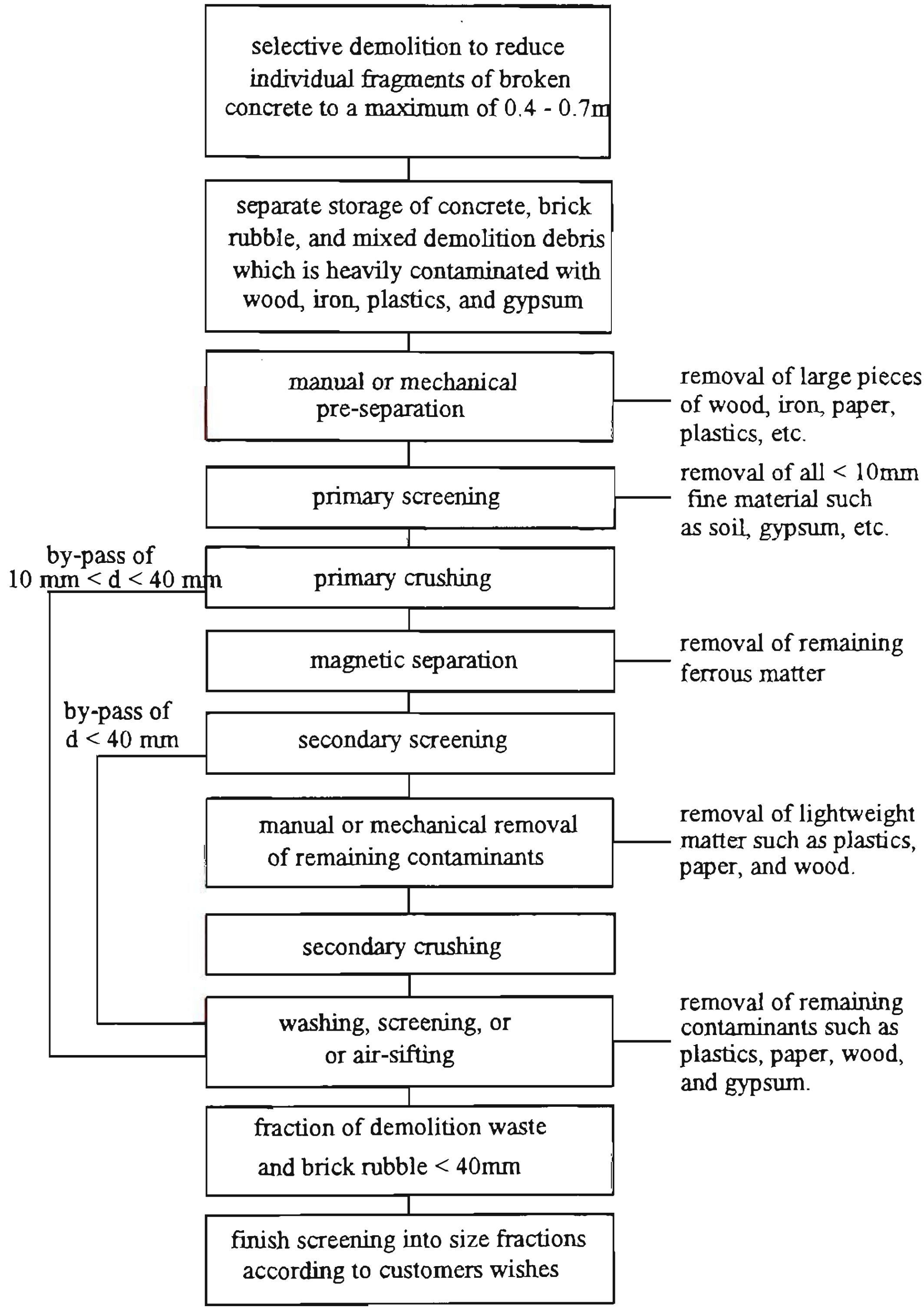


Figure 2.2 Processing procedure for building and demolition waste

(Based on Hansen, 1992).

Kaga et al (1988) reported on the use of secondary processing with an ordinary concrete drum mixer. The RCA was placed in the mixer for approximately 5 minutes. It was observed at the end of this period that the coarse RCA particles had become rounder, as some of the soft cement paste had been removed from the edges of more angular particles. The mixed material also had improved engineering properties, such as an increase in specific gravity, reduced moisture absorption (by 10% to 20%), and slightly improved BS aggregate crushing value and LA abrasion loss. Kakizaki et al (1988) reported similar improvements using hammer and roll crushers for secondary crushing.

Hansen (1992) concluded that impact crushers are more likely to produce material with more fines, which is more suitable for road construction. Material crushed by jaw crushers generally has a coarser grading, which is more suitable when the material is re-used as concrete aggregate. However the amount of cement paste attached to the stone is quite high. A better product for re-use as a concrete aggregate is obtained when impact crushing follows jaw crushing, as a finer grading is produced. When the fines (<4.75mm) are removed, the remaining coarse aggregate has less cement paste attached and is, therefore, a better material for concrete production because of lower moisture absorption, increased specific gravity, and lower LA abrasion loss, for example (Kaga et al, 1988 and Kakizaki et al, 1988).

2.5 PHYSICAL AND ENGINEERING PROPERTIES OF RCA

2.5.1 Particle size distribution, aggregate shape and texture

The crushing characteristics of RCA are similar to those of conventional crushed rock, and are not significantly affected by the strength of the source concrete

(Yoshikane, 1988), although stronger concrete tends to produce less fine material below 5mm (Ravindrarajah and Tam, 1988). Gorle and Saeys (1988) reported that gradings from ten different crushing plants in Belgium were suitable for roadbase or subbase under Belgian specifications although, in some instances, the gradings were coarser than required. The type of crushers used, and the layout of the various plants in the investigation, was not discussed. Yoshikane (1988) reported that RCA could be produced to conform with the Japanese specification by using a fixed plant with primary and secondary crushing. Busch (1988) reported on the construction of a runway at Copenhagen Airport, in which the RCA had a grading that closely approximated the Fuller idealised grading curve. After compaction, some degradation of the material occurred.

It should be noted that, as with crushed rock, any desired grading may be achieved with appropriate choice of crusher settings and sorting of materials through screens, etc.

Kawamura and Torii (1988) described RCA particles as angular, with the surface being porous because of the attachment of the original cement paste. Morloin et al (1988) carried out particle shape index analysis and found that the RCA had virtually the same shape as the original aggregate. Kaga et al (1988) believed that the shape of RCA depended on the type of crusher used, although no reason was given.

2.5.2 Attachment of cement paste to the original stone

The fundamental difference between RCA and conventional aggregate is the attachment of cement paste to the original stone. Figure 2.3 shows the results of a Japanese investigation (BCSJ, 1978) which established that the percentage by weight of attached cement paste decreases as the particle size increases. The amount of cement paste was determined by immersing the RCA particles in hydrochloric acid at 20°C, and dissolving the cement paste.

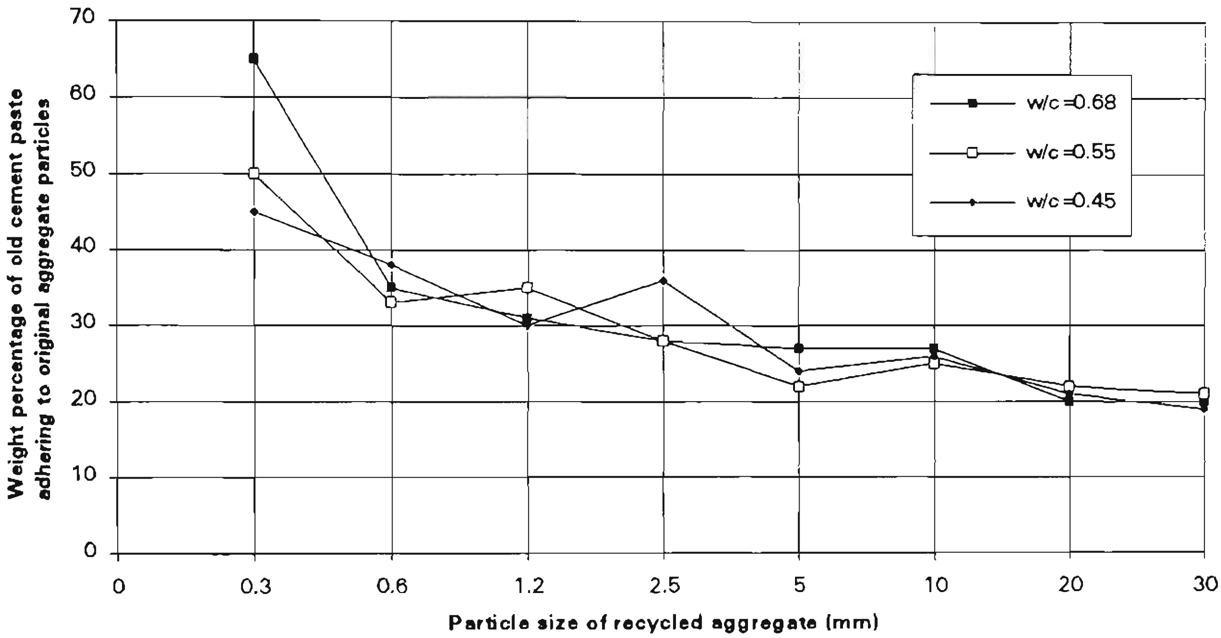


Figure 2.3: Relationship between nominal size of RCA and cement paste adhering to original stone (Based on BSCJ, 1977)

Hansen and Narud (1983) adopted a different approach to determining the amount of cement paste attached to the original aggregate. They cast cubes of concrete made using RCA as the aggregate and mixed it with red cement. Each cube contained different aggregate sizes and had different water/cement ratios. Slices of the cubes were made and examined under a microscope using a linear traverse method, similar to that described in ASTM C 457-71 (1987). The use of the red mortar enabled a clear distinction to be made between it and the original mortar attached to the source stone. Examination of the sliced sections of the cubes showed that variation in the water/cement ratio does not significantly influence the amount of attached cement paste, which was 25% to 35% for 16mm to 32mm, approximately 40% for 8mm to 16mm and 60% for 4mm to 8mm. These values are significantly higher than the BCSJ (1978) findings, shown in Figure 2.3.

2.5.3 Specific gravity and water absorption

The common method of determining the specific gravity and water absorption is in the saturated and surface dry condition (SSD). This condition is achieved by immersing the sample in water for a period of 24 hours, after which all free water is removed from the surface and the sample is weighed. The sample is then weighed whilst submerged in water. The two values are then used to calculate the specific gravity. Hansen and Marga (1988) expressed concerns over the accuracy of this method when used on RCA. The high porosity of the material and rough surface texture make it difficult to establish when surface dryness has occurred. This conclusion was also reached by Puckman and Henrichsen (1988), who developed a graphical approach to determination of water absorption.

Using the graphical method a sample, after saturation, is constantly weighed whilst being dried under an infra-red lamp. A drying curve is plotted and used to determine an approximate SSD condition. Using this method water absorption's of 3.6% for 0-4mm particles, 1.8% for 4-8mm, and 1% for 8-25mm particles were obtained. Values obtained using a standard SSD procedures (ISO 6783) on the same size particles were approximately double, being 7.4%, 4.2% and 3.2% respectively. Additional comparisons were made by storing the samples in a controlled environment until equilibrium was achieved at a relative humidity of 100%. The results obtained using this method compared favorably with the graphical approach, giving 2.7% water absorption for particles between 0-4mm, 1.9% for 4-8mm and 1.6% for 8-25mm.

The BCSJ (1978) found that the specific gravity in the SSD condition was 2.10 for fine material and 2.43 for coarse RCA. The specific gravity of the natural aggregates used to produce the RCA were 2.34 for the fine and 2.7 for the coarse aggregate. In general the RCA had a specific gravity up to 15% lower than the natural aggregate. They also found that variations in the water/cement ratio did not alter the specific gravity, which was confirmed by Hansen and Narud (1983). RCA will always have a lower specific gravity than the NA used to produce it because of the low density cement paste attached to the original stone (Hansen, 1992).

RCA absorbs significantly more water than natural aggregates. The BCSJ (1978) found that RCA less than 5mm absorbed up to 9 times as much water as NA and the coarse RCA (greater than 5mm) absorbed 7 to 8 times that of NA. Typical values of 11% water absorption for fine RCA and between 6.8% and 7.2% for coarse RCA were obtained. Numerous other researchers have found that RCA has significantly higher water absorption than natural rock because of the cement paste attached to the source stone. Ravindrarajah and Tam (1988) found that the rate of water absorption is very rapid, with 80% of water being absorbed within the first five minutes of a 24 hour test. Morloin et al (1988) obtained similar results.

The relationship between specific gravity and water absorption was examined by Schulz (1988), Ravindrarajah and Tam (1988) and Mulheron and O'Mahony (1991). They all concluded that a decrease in the specific gravity of RCA resulted in an increase in the water absorption. This is to be expected given that a lower specific gravity generally corresponds to a greater amount of attached cement paste, which absorbs greater quantities of water than a NA.

Difficulty in achieving a SSD condition with RCA samples has been expressed by some researchers and results obtained using this approach should be viewed with some caution. At present the SSD procedure remains the primary method of determining specific gravity and moisture absorption, until other methods such as the graphical procedure is further developed. The latest RILEM Technical Committee TC121 draft specification for 'Concrete with Recycled Aggregates' (1993) adopts a SSD procedure (ASTM C123) for the determination of water absorption and specific gravity.

2.5.4 Hardness of RCA

The hardness of RCA has primarily been examined using the LA abrasion loss test. This is the hardness test most commonly used in Australian specifications for aggregates and road pavement materials.

Petrarca and Galdiero (1983) carried out 112 LA abrasion tests on RCA produced from a commercial plant in Hicksville, New York, between 1977 and 1982. Over this period the material had a mean LA abrasion loss of 36.5% with a standard deviation of 3.6%. This was well below the local requirements for a dense-graded aggregate base or subbase. They also observed that changes and adjustments to the crushing plant over time did not significantly alter the LA abrasion loss.

Hansen and Narud (1983) found that laboratory-produced concrete with a water/cement ratio of 0.4 had a LA abrasion loss of 30.1% for 4-8mm aggregate and up to 22.4% for 16-32mm material. When the water/cement ratio was increased to 1.2, the corresponding values were 41.4% and 31.5%, indicating that the water/cement ratio influences the LA abrasion loss. In all instances the LA abrasion loss values were higher than for the original aggregate used to produce the RCA. Similar results were observed by Ravindrarajah and Tam (1985).

2.5.5 Plasticity

Petrarca and Galdiero (1983) carried out 106 plasticity index tests on the fine fraction of recycled concrete aggregates between 1977 and 1982, and found every sample to be non-plastic. The same outcome was reported by Yoshikane (1988), who carried out 24 such tests between January and December 1986.

Hansen and Narud (1983a) found that recycled concrete fines contain approximately 4% calcium hydroxide $Ca(OH)_2$ i.e. hydrated lime. The exact percentage depends on the amount of cement used to produce the original concrete. Hydrated lime has long been used to improve the workability and strength of clayey soils (Lay, 1990). The presence of $Ca(OH)_2$ within the crusher fines would reduce the influence of any clayey material on the plasticity of recycled concrete aggregate.

2.5.6 Compaction

Petrarca and Galdiero (1983) performed 143 compaction tests on material produced from a fixed site crusher between 1977 and 1982. Over this period the maximum dry density averaged 1.66t/m^3 with a standard deviation of approximately 0.03t/m^3. The maximum dry density values were also analyzed during two periods, from 1977 to 1981 and for 1982. The plant was altered in 1982 with the addition of a fine cone crusher and triple-deck vibrating screen. The mean maximum dry density before 1982 based on 119 tests was 1.65t/m^3 with a standard deviation of 0.03t/m^3, compared to a mean maximum dry density of 1.67t/m^3 with a standard deviation of 0.02t/m^3 for the 24 tests in 1982. This indicates that the additional crushing slightly increased the mean maximum dry density and decreased the variability of the test results. The optimum moisture content was not discussed.

Yoshikane (1988) performed 24 compaction tests on RCA between January and December 1986, and over this period a mean maximum dry density of 1.97t/m^3 was obtained with a standard deviation of 0.02t/m^3. The mean optimum moisture content of the samples was 9.8% with a standard deviation of 0.42%.

O'Mahony and Milligan (1991) performed compaction tests on demolition rubble according to BS5835 (1980). For this test a vibrating hammer is hung from a frame under a standard surcharge and layers of material are compacted for periods of 3 minutes. The material gave a maximum dry density of approximately 1.90t/m^3 at an optimum moisture content of 13%. For some tests the densities were to the right of the zero air voids line which in theory and if calculations were carried out correctly, is impossible. The authors believed this was caused by difficulties in obtaining an accurate figure for the specific gravity of the material. The specific gravity tests were repeated but a wide range of results was obtained, and did not help to clarify the original values.

2.5.7 CBR testing

Petrarca and Galdiero (1983) performed 157 laboratory CBR tests on RCA from a fixed crusher site in New York State between 1977 and 1982, obtaining an average

CBR of 148% over that period. During the six years the CBR value steadily increased from an average of 113% in 1977 to 169% by 1982. This increase was attributed to improvements in the crushing plant, which have previously been discussed within section 2.5.6. Throughout the testing period the CBR was always well above the specified limit for dense-graded aggregate bases and subbases.

O'Mahony and Milligan (1991) compared the performance of RCA to crushed limestone, which is commonly used as a road subbase material in England. Results from the investigation showed that the RCA tested has CBR values comparable with limestone, which is over 30% higher than the minimum requirement of the British 'Specification of Highway Works' (Department of Transport, 1986). The authors did however question the relevance of the laboratory CBR test as, in their opinion, it does not simulate conditions in the field.

2.5.8 Repeated triaxial load testing of RCA

Barksdale et al (1991) carried out repeated triaxial load (RTL) tests on RCA and compared the results to those from tests on a dense graded dolomite and coarse RCA with dolomite fines (material passing 8mm was defined as fine). The tests were carried out at between 95% and 100% of modified maximum dry density using AASHTO T-180, which is comparable to AS1289.E2.2(1977). The specimens were tested at both optimum moisture content (OMC) and saturation.

Resilient modulus (M_r) values were determined at bulk stresses of 345kPa and 145kPa, these values representing typical pavement stresses at the base level under a moderately thick and a thin asphalt layer, respectively. Testing was carried out using

1200 and 8600 load pulses, in order to examine the effect of an increased number of load cycles.

M_r values for RCA recorded were up to 30% lower than those for the crushed dolomite, as shown in Table 2.1. For the materials tested it was found that the degree of compaction, level of saturation and the number of load repetitions all influenced the final M_r value. An increase in moisture content from optimum to saturation decreases M_r.

Table 2.1: Resilient modulus values (MPa) at bulk stress of 345kPa

(From Barksdale et al, 1991)

	Resilient Modulus Values (MPa)					
Material	**100% MDD at OMC**		**95% MDD at OMC**		**100% MDD Saturated**	
Load pulses	**1200**	**8600**	**1200**	**8600**	**1200**	**8600**
Dolomite-open graded	159	179	145	166	124	124
RCA	132	155	107	116	92	99
RCA with dolomite fines	145	166	132	131	119	138

The second phase of their test program was to determine permanent deformation characteristics, which were then related to a rutting index defined as permanent strain at 70,000 load cycles, multiplied by 10,000 (Barksdale, 1972). The index is used to compare the potential relative performance of different aggregate bases. Increases in moisture content, reduced compactive energy, and the addition of dolomite fines, all increased the permanent strain of the RCA sample, as shown by the rut index values in Table 2.2.

Table 2.2: Rutting index values (From Barksdale et al, 1991).

Material	**100% MDD at OMC**	**95% MDD at OMC**	**100% MDD Saturated**
Dolomite-dense grading	55	92	76
RCA	51	86	81
RCA with dolomite fines	58.6	100	82

Barksdale believed that the values recorded for recycled concrete were likely to less than will occur in practice. He referred to work carried out by Sweere (1990) on the stiffness of full-scale pavements constructed using RCA. It was found that the stiffness of pavements constructed using RCA did increase over time. Barksdale et al (1991) postulated that this was due to either rehydration, or to the increase in fines which occurs as the aggregate degrades under wheel loading.

Gorle and Saeys (1988) also examined RCA under RTL. In their investigation RCA was compared to limestone and to a limestone and sand mixture. The materials were tested at a bulk stress of approximately 160kPa over 50 load cycles. The results of the investigation were similar to Barksdale et al (1991) in that the RCA had a lower M_r than the two natural materials, but had a greater resistance to permanent deformation.

2.5.9 Residual setting of RCA

Residual setting of unhydrated cement particles in the crusher fines has been suggested by researchers (Busch (1988), Barksdale et al (1991), Petrarca and Galdiero (1983), Gorle and Saeys (1988)) as the likely reason for high resilient modulus and low permanent strain for pavements constructed using RCA. No specific test data on actual hydration occurring within the pavement is given to support this theory.

One example of residual setting was discussed by Yoshikane (1988), who extracted cores from an unbound pavement constructed using RCA after it had been subjected to three years of traffic. The cores had an unconfined compression strength of approximately 4MPa, indicating an increase in strength over time, similar to that which occurs with cement stabilisation.

Hansen and Narud (1983a) reported investigations into the cause and magnitude of residual setting in RCA fines. They concluded that any unhydrated cement within the crusher fines below 2mm is so diluted that the fines have insufficient hydraulic binding capacity to harden a soil or granular mass. Hansen (1992) made a mortar mix from 0-4mm RCA fines. The original concrete used to produce the mortar had a water/cement ratio of 0.40 and a cement content of 410 kg/m^3. No increase in strength of the RCA mortar over the 28 day period was observed. It was observed that the mortar did not set but developed a hard brittle crust, and only after 180 days had the entire specimen hardened. As 410 kg/m^3. is a high cement content, and no residual setting occurred in the RCA mortar, it seems unlikely that residual setting will occur in commercial RCA which is made from concretes with generally lower cement content.

Hansen and Narud (1983b) using thermo-gravimetric analysis found that RCA fines contained between 2% and 4% of calcium hydroxide, and that this value was related to the original cement content. It was concluded that the setting of the RCA fines was due to carbonation of the calcium hydroxide. This form of setting is similar to that of lime stabilisation, in which a slow and relatively small increase in compressive strength occurs. Cement-stabilised material tends to set more rapidly and has a higher compressive strength.

2.5.10 Comparisons between RCA and natural aggregates

It is recognized that the composition of RCA may be different from time to time and place to place. It seems likely that, in a given area, the aggregate in the original concrete will be similar to that which is currently being quarried, and used for comparison with the RCA pavements. Because of the cement paste coverage it may be that RCA more similar from place to place than natural aggregate.

2.6 RCA IN ROAD PAVEMENTS

2.6.1 Insitu testing

Petrarca and Galdiero (1983) reported on Benkelman beam testing carried out in the New York area on three pavements of different construction (natural stone base, full depth asphalt pavement, and RCA base), all designed for the same wheel and traffic loading A Benkelman beam was used to measure pavement deflection under a standard truck axle of 8150kg. Experience has shown that maximum serviceability (i.e. minimum maintenance of the pavement is required over its design lifetime) is obtained if the deflection is equal to, or less than, 1.27mm.

Deflection tests were first carried out on the original pavement before re-construction. The second phase of testing commenced after the three new pavements were constructed. The first was a 150mm thick dense graded, natural crushed stone base; the second was a full depth 75mm asphalt base; and the third was a 150mm dense graded RCA base. All pavements were topped with a 40mm binder course and a 25mm wearing course. Table 2.3 summarises the deflection testing carried out between 1974 and 1983.

Table 2.3: Summary of pavement deflections

(Based on Petrarca and Galdiero, 1983)

Description	**Stone Base**	**Asphalt Base**	**RCA Base**
Weighted average, final characteristic deflection (mm)	1.27	0.864	0.584
Weighted reduction in deflection (%)	33.13	44.90	60.88
Number of projects	3	12	5
Total square metres of pavement tested	32,500	283,900	259,000

The conclusion reached in this investigation was that pavements constructed using RCA were stiffer and stronger than the equivalent crushed stone and full depth pavements. It should be noted that the deflection testing carried out in the investigation was at a number of different locations. Further to this it, is not clear whether each of the three test pavements, or only one pavement, was constructed at each site. Given this, any variations in subgrade strength at the different sites and the likely effect it has had on the deflection results has not been addressed. The results contained in Table 2.3 should therefore be viewed with some caution.

Busch (1988) carried out quasi-static plate loading tests on a test pavement constructed using RCA as a basecourse material. The project was part of the re-construction of a runway at Copenhagen Airport in 1982. The most important finding was that the modulus of the crushed concrete basecourse was 33% higher than for normal gravel basecourse material. This allowed the asphalt layers to be 10% to 12% thinner than would than with NA.

Busch put forward two possible explanations for this increase in modulus. The first is that RCA develops greater inter-particle contact between the large aggregate particles because it consists of a soft outer crust with a hard inner core. He further suggested that the number of contact points was one of the factors governing stiffness of an unbound pavement. The second explanation was that some of the original cement within the concrete may be unhydrated and, once re-mixed with water, may re-set. Nothing has been found during the literature search regarding investigations of the first explanation. The second phenomenon is examined in greater detail in section 2.5.9.

Gorle and Saeys (1988) from the Belgian Road Research Centre carried out repeated plate bearing tests immediately, and at intervals, after the completion of construction of pavements. On average it was found that pavements constructed using RCA had a modulus of 410MPa compared with 680MPa for virgin aggregates. However, they noted a significant increase in the modulus of compressibility (between 20% and 100%) in the RCA pavement several weeks after construction and attributed this to unhydrated cement present in the crusher fines. Information was presented which showed that the pavement water contents decreased with time, from 6% to 4.5%, but no mention was made of this in relation to the change in modulus. The drying out of any material, RCA included, will tend to result in an increase in modulus (Barksdale, 1991). Therefore, there is more than one possible cause for the increase, and it is not necessarily correct to attribute it only to residual setting.

2.6.2 Road pavement specifications for RCA

Specifications for the use of RCA as a concrete aggregate have been specifically developed, such as the RILEM Technical Committee TC121 draft specification for 'Concrete with Recycled Aggregates' (1993). However, for use as a road pavement material, RCA generally must comply with the same standards as NA., such as the 'Specification for highway works' in Britain (Department of Transport, 1986). This can cause problems in meeting some specification requirements, particularly hardness tests, as RCA is a softer material than NA.

In Australia, a draft specification, 820 'Crushed Concrete for Subbase Pavement' (1992) has been developed by VicRoads, for the use of RCA as a road subbase material. The specification is essentially the same as 818 'Crushed scoria for base and subbase pavement material' (1984), in that similar grading, plasticity and hardness values are specified. The major variation is an additional section that outlines the maximum amounts of low density (plastic, plaster, timber etc.) and high density contaminating material (asphalt, slag, brick etc.) allowable.

2.7 CONCLUSIONS

From the literature reviewed it is evident that no work on the use of RCA has been published in Australia and that majority of work carried out internationally appears to concentrate on the use of RCA as a concrete aggregate. It is therefore appropriate that the research carried out in this investigation provides information on the basic engineering properties appropriate to the local conditions and requirements.

CHAPTER THREE: CURRENT STATE OF CONCRETE RECYCLING IN AUSTRALIA

3.1 INTRODUCTION

Information regarding the use of recycled concrete in Australia was sought in the report 'Recycling' (Industry Commission, 1991a), which is based on the information paper 'Waste Management and Recycling: Survey of Local Government Practices', also by the Industry Commission (1991b). The report identifies concrete recycling as a source of material recovery, but contains limited information about its usage. A survey was therefore devised to determine current recycling practices and uses of the recycled concrete. The survey was distributed to 156 metropolitan councils in Melbourne (54), Sydney (39), Brisbane (8), Adelaide (29) and Perth (26) and a response rate of 68% was achieved, as shown in Table 3.1. The survey was not sent to country municipalities as it was felt that concrete recycling was less likely to occur due to increased availability of landfill sites.

A copy of the survey and a full list of the municipalities surveyed is contained within Appendix A.

In addition to the survey, discussions were held with Australia's two largest producers of RCA, Alex Fraser Pty. Ltd. in Melbourne and Concrete Recyclers in Sydney. They were asked questions on concrete recycling and their answers have been included to complement the survey responses.

Table 3.1: Survey distribution and returns

Region	Distributed	Returned	%
Sydney	38	27	71
Melbourne	54	40	74
Brisbane	8	5	63
Perth	26	17	65
Adelaide	30	17	57
Total	**156**	**106**	**68**

The survey was distributed in May 1992, with the following aims:

1. To establish contacts and exchange knowledge with municipalities currently engaged in the recycling of concrete.

2. To determine the extent of concrete recycling, how the concrete is being recycled, and what it is being used for.

3. To evaluate the current level of technical data available and establish areas in which future research is required.

4. To estimate the current and future markets for recycled concrete.

3.2 SURVEY RESPONSES

Question One: Is concrete recycled in your municipality ?

Table 3.2 shows the percentage of municipalities in the major cities of Australia which are engaged in concrete recycling. Quite clearly, Melbourne and Sydney municipalities are the most active, with the remaining cities relatively uninvolved. The high participation from Melbourne and Sydney is primarily due to the substantial recent increases in landfill disposal costs, which reflect the higher cost of replacement facilities and the relatively short lifespan of existing sites.

Table 3.2: Municipalities engaged in concrete recycling

Region	Responses	Yes (%)	No (%)
Melbourne	40	58	42
Sydney	26	65	35
Brisbane	5	0	100
Perth	16	12	88
Adelaide	15	7	93
Overall	**102**	**42**	**58**

Question Two: How is waste concrete disposed of?

Table 3.3 shows the methods of waste concrete disposal used by councils. Recycling is popular in both Melbourne and Sydney, but landfill is the major source of disposal in the other regions. As alluded to earlier, concrete recycling will only tend to occur in regions where either the cost of disposal or of virgin crushed rock has become prohibitive. Until landfill charges increase in the other capital cities, it is unlikely that concrete recycling will occur in these regions, given that they presently have a ready supply of virgin crushed rock capable of meeting existing demands.

Table 3.3: Methods of waste concrete disposal

Region	Responses	Recycled (%)	Landfill (%)	Stockpiled (%)
Melbourne	41	46	52	2
Sydney	27	63	33	4
Brisbane	5	0	80	20
Perth	16	12	88	0
Adelaide	16	6	94	0
Overall	**105**	**38**	**60**	**2**

Question Three: How is the material crushed ?

Municipalities which undertake recycling dispose of their waste concrete as shown diagrammatically in Figure 3.1. The most popular method is sending the waste concrete to a central crushing plant (62%), followed by the use of private contractors with mobile crushing plants (30%) who crush waste at the demolition site. Eight percent is crushed by municipalities that have their own crushing plants. The method of processing can significantly influence the quality of RCA. When concrete recycling began in Australia a mobile crushing plant, containing a single crusher was commonly used. Scrap steel was sometimes removed using an electro-magnet, but materials such as brick, asphalt, timber and plastic were not removed, resulting in an inferior product. The central plants have the advantages of using primary and secondary crushing processes, which improves aggregate properties such as particle size distribution, water absorption and specific gravity (Kakizaki et al, 1988). Steel is removed automatically and other unsuitable materials are manually removed. Pre-selection of the incoming waste concrete ensures a higher-quality product.

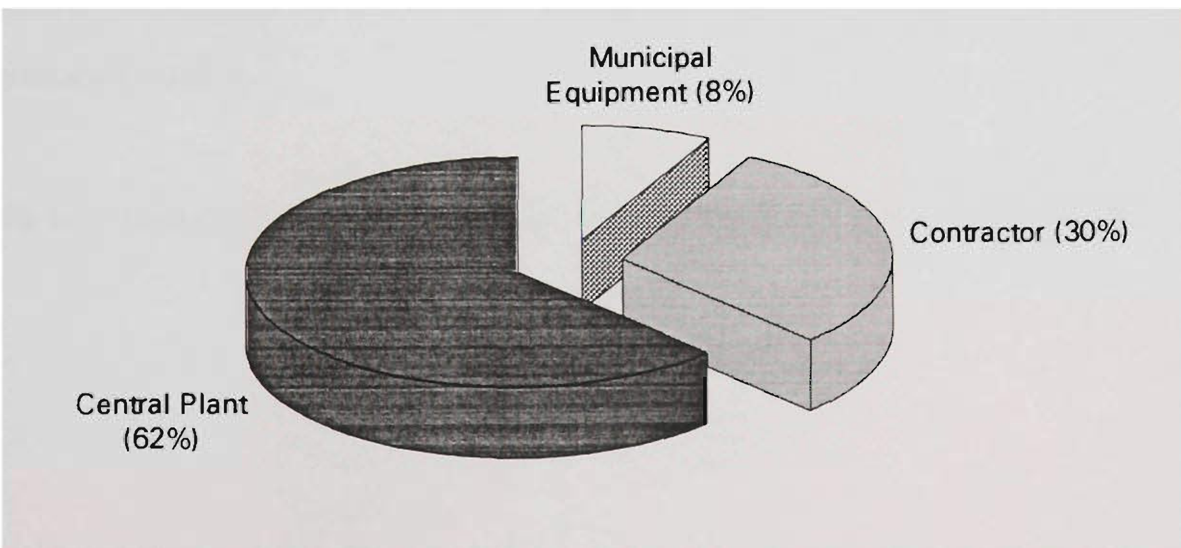


Figure 3.1: Current methods of concrete recycling

Question Four: Approximately how much material is produced per annum ?

The survey results in Table 3.4 show that a total of 132,000 tonnes of concrete was reported to be recycled by the municipalities in 1991, which represents only approximately five percent of the total waste concrete generated in Australia, based on Industry Commission (1991a) discussed in section 1.1. This is a conservative figure given that many of the municipalities that do recycle their waste concrete were unable to give an estimate of the amount. It should also be noted that a large but unknown quantity of building rubble is disposed of by private demolition companies. This material is sometimes used for earthworks or may be disposed of to a commercial concrete recycler. Demolition companies will generally find alternative places or uses for the material rather than dumping at expensive municipal landfills.

The Industry Commission (1991a) estimated that approximately 400,000 tonnes of concrete is recycled in Sydney annually. Alex Fraser Pty. Ltd. estimate that a similar amount is recycled in Melbourne, of which 60% is obtained from private demolition contractors and the 40% remaining supplied by local and state government authorities.

Table 3.4: Amount of concrete currently recycled by responding municipalities

Region	Total (Tonnes)	
Melbourne	43 024	33%
Sydney	69 160	52
Brisbane	-	0
Perth	2 000	2%
Adelaide	6 000	5%
Total	**132 184**	

Question Five: What is the crushed material used for ?

Table 3.5 details the current uses for recycled concrete by the respondents, and shows that the material has been used in a fairly wide range of applications. However, in the majority of cases it has been used in low-level applications requiring limited, if any, technical information. Use in carparks, as fill, in paths, in crossovers and as a trench base account for a total of 74% of responses, whereas the higher end-uses in road construction and concrete production account for only 26%. However it should be noted that these percentages relate to the number of respones and not the amount of material used.

Table 3.5: Current uses of recycled concrete by municipalities

Region	Responses	Carparks	Fill	Paths	Cross-overs	Trench Bases	Road ubbase	Road Base	Concrete Agg.
Melbourne	48	7	6	10	5	8	7	4	1
Sydney	32	5	4	3	4	8	2	2	4
Perth	2	0	0	0	0	0	0	0	2
Adelaide	3	1	1	1	0	0	0	0	0
Overall	85	13(15%)	11(13%)	4(16%)	9(11%)	16(19%)	9(11%)	6(7%)	7(8%)

Note: Figures indicate a positive response to the use of recycled concrete in the above applications, with some municipalities using the material in more than one application. The bracketed figure is the percentage of the total responses.

Alex Fraser Pty. Ltd. report that the majority (approximately 75%) of their material is used by private civil engineering contractors as a roadbase and subbase material. The remaining 25% is sold to various government authorities who tend to use the material for a wider range of low-level applications, such as paths and unsealed carparks.

Question Six: Do you believe that the current use of recycled concrete is limited by a lack of technical data ?

Table 3.6 shows that 71% of respondents believe the use of recycled concrete has been limited by a lack of technical data. This view is also shared by Alex Fraser Pty.

Ltd. Contracts to supply RCA have been lost because contractors have requested technical information which had not yet been produced. They also believe that the conservative nature of the engineering profession in general has inhibited further usage.

Table 3.6: Is the use of recycled concrete limited by a lack of technical data ?

Region	Yes %	No %
Melbourne	71	29
Sydney	65	35
Perth	100	0
Brisbane	73	27
Adelaide	71	29
Overall	**71**	**29**

Question Seven: Examination of proposed areas of research into recycled concrete as an aggregate for use in roadbases.

As part of the survey, respondents were required to assess the level of importance for each of the following areas of research. The results have been summarized in Figure 3.2, where 100 (on the y-axis) represents the highest possible level of importance. The approach used to determine the importance values is given in appendix A. Only the results for Melbourne and Sydney have been included as they are the only two cities in which RCA is used on a large scale.

In general, the Melbourne respondents attached a 10 to 15 points higher level of importance to the first eight areas of research than their Sydney counterparts, possibly indicating greater concerns about the material. In the remaining areas both responses were relatively similar. In Melbourne the most important area was quality control guidelines (1), while in Sydney the major concern was with cracking (3).

Areas of research

1. Quality control guidelines.

2. Material performance on a test section of road, including deflection data.

3. Pavement cracking.

4. Particle breakdown under compaction.

5. Design guidelines.

6. Ease of placement and workability.

7. Repeated load triaxial tests to evaluate loss of stiffness and strength, and the degree of particle breakdown.

8. Stabilisation using cement and lime.

9. Permeability.

10. Determination of a modulus of the material.

11. Strength increase due to residual setting of the mortar.

12. Mineralogical investigations of rock types and harmful minerals present within the waste concrete aggregate.

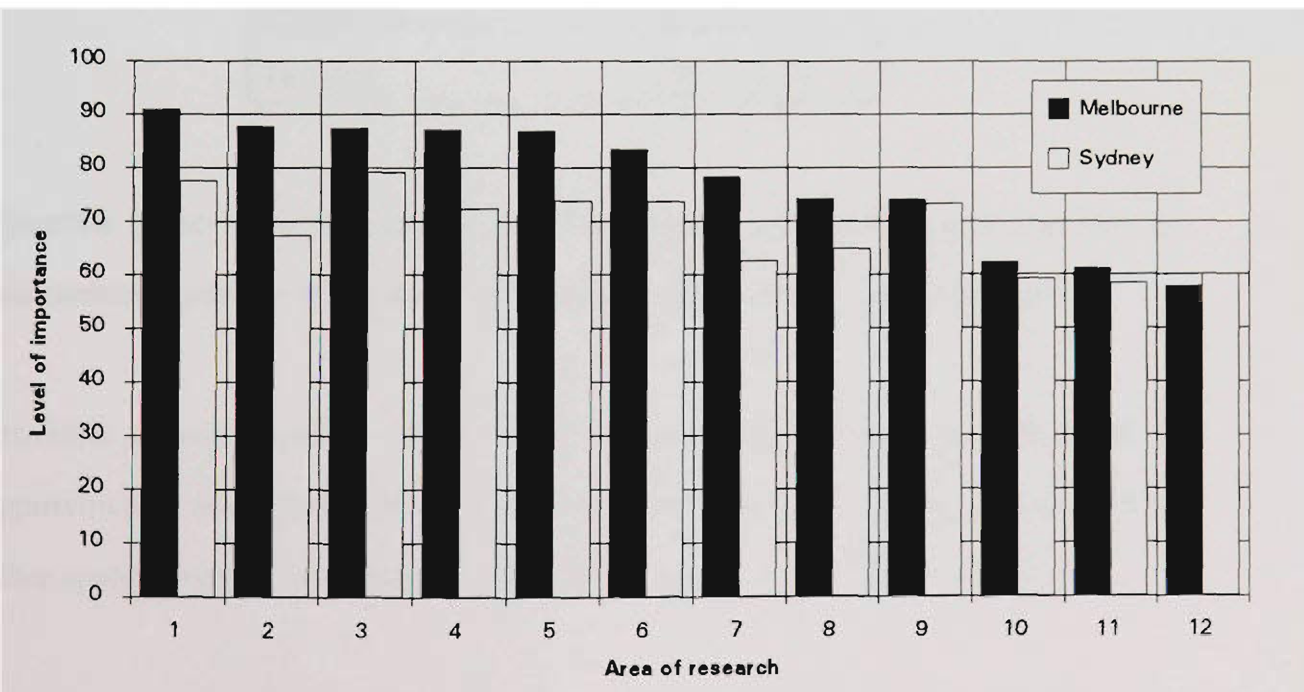


Figure 3.2: Importance levels for the initial areas of proposed research.

Unfortunately, due to time constraints, a lack of funding and the availability of suitable testing equipment, some of the areas surveyed were not researched in this investigation. Further discussion on future areas of research is given in Section 6.3.

Question Eight: Given that present uncertainties about, or objections to, the use of recycled concrete could be overcome by this research, would you be likely to use, or increase the use of, recycled concrete in your municipality ?

As shown in Table 3.7, 87% of respondents indicated that further research into recycled concrete would result in a greater use of the material.

Table 3.7: Influence of research data on the use of RCA

Region	Yes %	No %
Melbourne	85	15
Sydney	92	8
Perth	88	12
Brisbane	67	33
Adelaide	88	12
Overall	**87**	**13**

Question Nine: Provided that a constant supply of recycled concrete can be maintained, estimate the amount of the material you could use per annum ?

Provided a good quality supply of RCA was available, an annual demand of approximately 600,000 tonnes for use in road pavements and over 160,000 tonnes for other applications is estimated from the survey responses, as shown in Table 3.8.

If an upper limit of 3 million tonnes of waste concrete per annum in Australia is assumed, approximately 25% of this total could be consumed by the municipalities.

The remaining 75% would be used by private contractors as was estimated by Alex Fraser Pty. Ltd. (see Question 5), indicating that a demand exists for all reprocessed waste concrete.

Table 3.8: Estimated demand for RCA

Region	Road Pavement (t)	Other Uses (t)
Melbourne	55 813	40 610
Sydney	160 570	39 420
Perth	116 793	5 404
Brisbane	180 000	62 000
Adelaide	88 500	12 000
Total	601 676	159 434

Question Ten: Estimated amount of aggregate used within the municipality per annum for all types of works, including roads, carparks, paths, etc, and the cost of this material.

The most interesting piece of information from Table 3.9 is the relative cost of aggregate in Sydney, which is twice that of the other capital cities. This further emphasizes the fact that concrete recycling in Sydney is currently a more attractive proposition than in other parts of the country.

Table 3.9: Current estimates of virgin aggregate usage and cost

Region	Total Mass (tonnes)	Total Cost ($)	Cost ($/tonne)
Melbourne	441 969	4 489 179	10.16
Sydney	694 800	14 644 800	21.08
Perth	263 697	2 052 414	9.93
Brisbane	632 000	6 274 000	7.78
Adelaide	180 406	2 173 000	12.05
Total	**2 212 872**	**29 633 393**	**13.39**

3.3 GENERAL COMMENTS FROM RESPONDENTS

As part of the survey, respondents were asked to provide any additional comments on the survey or any other issues related to the use of recycled concrete. The following is a sample of the responses received.

Need the crushers to produce a material that is useable without extensive secondary work of mixing other material to obtain a reasonable grading spread.

City of Berwick, VIC.

Discussions with personnel from other municipalities would indicate that recycled concrete material would be used if proper standards were formulated. It would obviously be in the community interest to use recycled material and all municipalities are committed to waste minimization and use of recycled material if the recycled material was at a known specification.

City of Richmond, VIC.

Council does have a contract with a recycle company to deliver this product. However, until VicRoads approve the material extensive use cannot be made.

City of Ringwood, VIC.

Considering that production of a cement stabilised product would overcome variability of source material and be ideal for as a pavement base course.

City of Malvern, VIC.

Would need to buy on stockpile basis rather than crusher run basis. Would only use as road sub base not for basecourse because of grading of recycled material, Macadam type grading with few if any fines.

Blacktown City Council, NSW.

Owing to wide variations in the age and composition of the base concrete material, it is expected that there may be a marked variation in the physical properties of the finished product, and its use on pavement construction should generally be confined to the subgrade or lower third of the pavement.

City of Frankston, VIC.

Wider use of recycled concrete is being greatly inhibited by a lack of proper data and especially data relating to durability. Most organizations are progressing slowly with the use of recycled concrete due to the lack of data. Usage of recycled concrete will increase greatly if proper data indicates that it can be used as a dense graded base complying with RTA (NSW) specifications.

City of Ryde, NSW.

Sutherland Council's materials lab began trailing recycled concrete approximately 18 months ago. We have used recycled concrete roadbase in all works for the last 15 months and recycled concrete aggregate for subsoil filters for 12 months. Our test results, including max deflection and curvature results indicate that this material is performing as well as the equivalent quarried products.

Sutherland Shire Council, NSW.

Crushed concrete to a maximum size of 60mm has been mixed with sandstone in a ratio of 3:1 and 4:1. It was found that this small amount of sandstone gives the crushed concrete the required amount of fines, and thus, resulting in a smoother surface when used as a base for flexible pavements.

Auburn Municipal Council, NSW.

A greater use of recycled concrete could be utilized if fines were mixed with the crushed aggregate, i.e: to form a rubble type product.

City of Kensingston and Norwood, SA.

These comments outline some of the concerns about recycled concrete, and it was considered important that they be properly addressed within the testing program. The points raised have been broadly classified into three areas:

1. Can RCA be produced with a grading suitable for use in road construction ? The inference from the comments made is that RCA generally produces a coarse grading, and that additional fines need to be imported in order to make the material more workable. It was therefore necessary to determine if RCA could be produced with a favorable grading curve, and what type of crushing process is required to achieve this.

2. Does the large variation in source concrete strength and quality lead to variations in the engineering properties of the material ?

3. There is a need to produce a specification and determine the basic engineering properties of the material.

All of these concerns were taken into consideration during the development of the testing program.

3.4 DISCUSSIONS WITH RECYCLED CONCRETE PRODUCERS

As mentioned previously, landfill charge increases is the primary reason for the development of concrete recycling within Australia. The variation in landfill charges between Melbourne and Sydney has resulted in a different attitude to concrete recycling. In Melbourne, landfill charges are lower, the concrete recycling industry is more competitive, and there are also more locations willing to accept clean fill material than in Sydney. Consequently, concrete is disposed of at Alex Fraser Pty. Ltd. in Melbourne free of charge, whereas at Concrete Recyclers in Sydney the cost is $10/m^3$ (Charges as at February, 1994).

The philosophy of Concrete Recyclers in Sydney is to produce the material as a relatively low grade fill, with no secondary crushing. Steel is separated magnetically from the concrete and other unsuitables are manually removed. As the material is generally used as a fill it does not have to meet any specification requirements, and gradings are carried out only to ensure correct operation of the plant. As a significant return has already been made from the disposal charges the material is priced very competitively. No attempt is made to compete against quarry crushed rock.

Alex Fraser Pty. Ltd. takes the opposite approach, competing directly with the quarries for the same markets, and enjoying only a moderate price advantage. Before processing rock, quarries must first blast it free, then transport it to the crushing facility, and also pay a fee to the land owner for each tonne removed. The concrete recycler has lower pre-crushing costs as all material is delivered to the plant free of charge. Competing against quarry products means conforming to the same specifications and therefore carrying out extensive quality control tests on the material, all of which adds to the final cost per tonne.

3.5 CONCLUSIONS

This chapter has shown that concrete is recycled on a large scale only in Melbourne and Sydney, primarily due to the high cost of waste disposal. The other capital cities deposit waste concrete in landfills and will probably continue to do so until the cost becomes prohibitive. In addition to this, the availability of natural aggregates does not encourage concrete recycling.

The vast majority of concrete is recycled at permanent crushing plants, which should ensure a higher quality material. Industry figures estimate the amount of concrete recycled in Australia per annum at 800,000 tonnes, which conservatively approximates to 25% of all waste concrete. Private civil engineering contractors use three times more recycled material than government authorities. Common uses for the material are in carparks, fill, trench bases and as a road pavement material. The survey respondents and both RCA producers who were interviewed firmly believed that use of the material is limited by a lack of technical information. It is also estimated that if all waste concrete in Australia produced per annum was recycled, a ready market for all material would exist.

In terms of recycled concrete production, different circumstances in Melbourne and Sydney have resulted in a differing approach to the marketing of the material. In Sydney, high landfill charges and the relatively high crushed rock prices have combined to form an ideal environment for concrete recycling. In Melbourne, fees are not charged for waste disposal, which helps reduce the cost of production and allows the material to be sold at a cheaper rate. Instead, the concrete recyclers are competing directly against the quarries, using favorable engineering properties of RCA as their marketing edge.

CHAPTER FOUR: MATERIALS AND TESTING PROCEDURES

4.1 TESTING PROGRAM

The testing program for this investigation was developed in conjunction with VicRoads Materials Technology Department and Alex Fraser Pty. Ltd., the major producer of RCA in Melbourne. Close consultation with these two bodies ensured that the testing program was relevant to the regulators and producers of RCA. Responses from the potential users of RCA obtained in the recycled concrete survey and examination of overseas literature also contributed to the final direction of the testing program, which was divided into the following three categories.

4.1.1 Monthly testing

The aim of this section of the test program was to sample RCA produced at the commercial concrete recycling plant of Alex Fraser Pty. Ltd. over a six month period. A range of tests was carried out at monthly intervals to establish any variability of the material. The perception that RCA will be of variable quality is to be expected, given the variety of concrete used to produce it, and this question was raised by some respondents within the recycled concrete survey.

The tests performed within this section of the investigation were used to establish some basic engineering properties relevant to the use of RCA as a road pavement material. The tests included particle size distribution, plasticity index, Los Angeles (LA) abrasion loss, compaction, flakiness index and unsuitable materials content.

Specific gravity, moisture absorption and cement paste content determinations were carried out on the first of the six monthly samples.

4.1.2 Laboratory produced sample testing

The age, quality and strength of the concrete used to produce recycled concrete aggregates is generally unknown. It may come from an old footpath with a strength of 15MPa or from a precast panel with a strength of 70MPa. Because of this, the question has been raised whether a consistently uniform product can be produced.

To examine the influences of source concrete strength on various engineering properties, two RCA samples with compressive strengths of 32MPa and 80MPa were produced and subjected to the following tests - particle size distribution, particle shape, LA abrasion loss, particle breakdown under modified compaction, specific gravity, moisture absorption and cement paste content.

4.1.3 Repeated triaxial loading (RTL) tests.

The performance of RCA on a test section of road was considered the second most important area for research in the recycled concrete survey. The use of RTL tests to evaluate stiffness and strength was ranked only seventh. However, due to a lack of resources it was not possible to construct a test section of pavement. The use of RTL was considered to be the next best way to simulate the performance of RCA under dynamic loading conditions.

The use of a mechanistic design procedure for the determination of pavement design was adopted by the National Association of Australian State Road Authorities (NAASRA) in 1987. The RTL test provides the necessary stiffness data for this method, which is now preferred over the traditional empirical approach, which commonly used the CBR test.

The RTL testing was divided into two sections. The first examined resilient modulus values for a variety of stress states and material variables and the second evaluated permanent strain characteristics of commercially produced RCA over 120,000 load pulses.

4.2 PRODUCTION OF SAMPLES

4.2.1 Commercial samples

RCA was sampled from the commercial concrete recycler, Alex Fraser Pty. Ltd., at their Port Melbourne plant. The following describes the plant and processes used to produce the material. A flow chart of the crushing process is shown in Figure 4.1.

1. All incoming material is initially assessed at the weighbridge. The weighbridge operator can look down on the waste concrete from his higher vantage point and determine its quality based on a visual assessment, having regard to the following considerations:

1. Brick content.
2. Asphalt content.
3. Timber and plastic content.
4. Soil or earth content, particularly with slabs and footings.
5. Concrete appearance.

2. Material is then unloaded at either the high quality or low quality waste concrete stockpiles, depending on the assessment of the weighbridge operator. Both types of material are processed through the same plant, but are crushed separately as this allows greater quality control of the final product.

3. A mobile concrete jaw crusher attached to a Kato excavator is then used to reduce the size of the concrete slabs to enable loading into the primary jaw crusher. All slabs are reduced in size until a maximum dimension of approximately 800 mm is reached. At this point the operator also removes as much reinforcing steel as possible, which is bundled ready for scrap.

4. The pre-processed material is then loaded by a front-end loader into a hopper with a vibrating base adjacent to the crusher .

5. The vibrating base feeds the concrete into the jaw crusher at the rate required. Any material under 100mm in diameter passes through the grizzly bars and does not go through the primary crusher. At this point sprinklers above the feeding tray are used to wet the concrete. This reduces the loss of fines during the crushing process as they tend to stick to the larger aggregate pieces and are not blown away by the wind as readily. The material is then choke fed (the jaw remains full at all times and is not allowed to empty) into the crusher and reduced in size to less than 100mm.

6. The 100mm minus material is then conveyed beneath a self-cleaning electromagnet that removes all steel that has been separated from the concrete during the primary crushing process. The steel is then deposited into a storage bin from which it is later removed for scrap.

7. The material is then transferred to another conveyor passing through a manual picker station where all other unsuitable material, primarily timber and plastic, is removed.

8. The product is then passed over a triple deck vibrating screen and material passing the 20mm screen is directed to the production stockpile without further processing.

Oversized material, between 20mm and 100mm, is transferred via a separate conveyor belt for secondary crushing.

9. This material is then crushed in an impactor and a secondary magnet removes any additional steel contained within the larger concrete pieces. All material is then transferred back to the screen for further sorting.

This process constitutes a closed loop system, as all material receives additional crushing until a specified size is reached.

All sampling of the material was carried out in accordance with AS1141.3(1986). A front end loader was used following the guidelines specified in section 6.1.10.5 (AS1141.3, 1986) - Sampling aided by power equipment.

4.2.2 Laboratory samples

Two concrete mixes were prepared (see Table 4.1 for the mix components). After a 28 day curing period five 100mm diameter by 200mm high specimens for each of the batches were tested. The average compressive strength for the lower strength mix was 31.6MPa and 78.9MPa for the higher strength sample. These two samples are hence referred to as 32MPa and 80MPa.

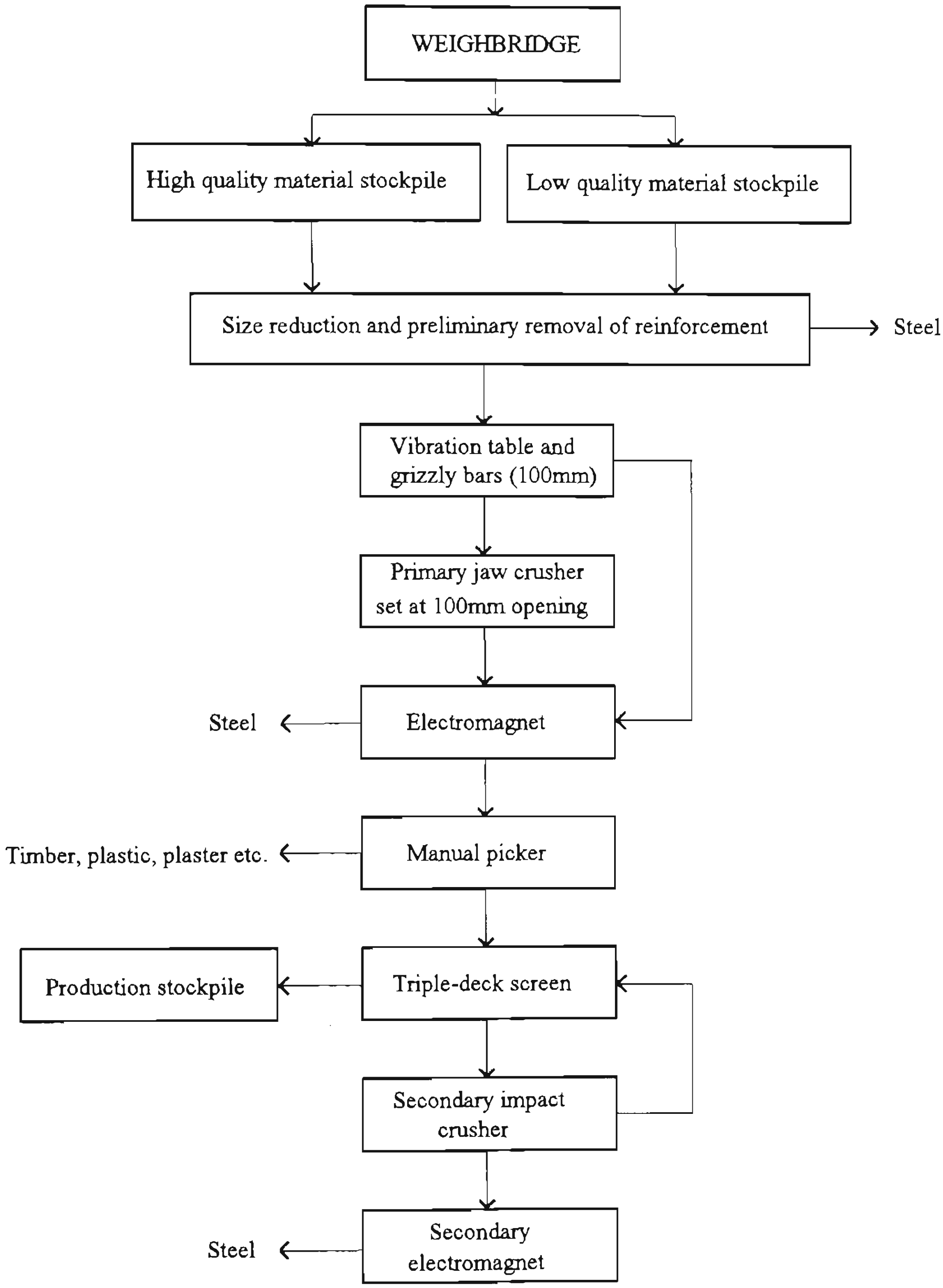


Figure 4.1 : RCA commercial production process

The average strength of waste concrete deposited at the Port Melbourne plant of Alex Fraser Pty. Ltd. was found to be approximately 28MPa, and was obtained by testing ten different concrete slabs per day over a five day period using a Schmidt rebound hammer in accordance with SAA HB34 (1992). A strength of 28.4MPa with a standard deviation of 4.6MPa was found.

Accuracy of the rebound hammer is affected by elastic deformations for concrete sections less than 100mm, therefore all slabs tested were greater than 100mm thick. In order to determine the accuracy of the Schmidt hammer a large slab was rebound tested and its strength estimated to be 31MPa, with a standard deviation of 6MPa. The slab was then reduced in size and three 100x100x100mm cubes cut and compression tested giving an average strength of 34.4MPa with a standard deviation of 1.2MPa.

The higher strength value of 80MPa was selected to represent the concrete now being used to construct multistorey buildings in Melbourne. In the next 20 to 30 years this concrete may be recycled.

The mixes used to produce the concrete are shown in Table 4.1. At the end of the 28 day curing period the concrete cylinders were crushed through a small laboratory jaw crusher set at an opening of 20mm. In order to create additional fines and to simulate the introduction of a secondary crusher, half of the crushed material was then passed through a laboratory cone crusher set to a maximum opening of 10mm.

As the crushing process created only a small percentage of fines smaller than 0.075mm, additional fine material was created using a ring mill.

Table 4.1 : Concrete mix components

Mix components (kg/m³)	80MPa	28MPa
Cement	600	280
Water	180	170
Sand	610	860
20mm Aggregate	700	700
10mm Aggregate	300	300
Slump (mm)	80	80
Average Compressive Strength (MPa)*	78.9	31.6

*Cylinders tested at 28 days after fog room curing at 24°C and RH 100%. Strength is the average of 5 test samples.

The influence of crushed masonry on some engineering properties was also examined. Clifton Red clay house bricks of an unknown age and origin were used. The bricks were crushed down using the same process described above.

4.3 TESTING TO AUSTRALIAN STANDARDS

Australian Standards (AS) test methods were preferred over other international test methods, so that comparisons with local virgin aggregates, tested under similar conditions, could be made.

4.3.1 Particle size distribution

Particle size distribution (PSD) is the most frequently performed test on any crushed rock, recycled concrete included. The performance of any pavement material is greatly influenced by its PSD. A well-graded material is one with a range of particle sizes which allows smaller particles to fit into the void spaces between the larger particles, reducing voids to a minimum and allowing the maximum possible density of the material to be achieved under compaction. A poorly graded material, containing a small range of particle sizes will exhibit a low density, as it is difficult to fill the additional void spaces created without excessive compaction. Such materials have a high permeability which can lead to subgrade damage due to excessive moisture penetration. On the other hand a grading with an excess of fines reduces the potential for direct contact between the larger particles and therefore reduces the stiffness and strength of the pavement.

The tests for this investigation were carried out in accordance with AS1141.11 (1980). The sieve shaker used was a pendulum type and set for 5 minutes of operation. This was enough to ensure that the mass passing the sieve in a subsequent minute was less than 1% of the mass of material retained on any sieve.

4.3.2 Plasticity

The damage caused by plastic fines to a road pavement has been well documented by numerous researchers throughout the world. Empirical information shows that materials with low plasticity make the best subgrades and basecourse (Lay,1990). The plasticity index is a measure of the moisture range within which a soil will remain plastic and relates to the activity of the clay component of the material. Inclusion of the plasticity index tests is standard within any road pavement material specification.

The liquid limit was determined in accordance with AS1289.C1.1(1977) and the plastic limit in accordance with AS1289.C2.1(1977). The plastcity index (PI) is defined as the liquid limit less the plastic limit.

4.3.3 Compaction

Compaction is the process of reducing the air voids ratio in a material. A poorly compacted material will deform under loading, as its particles adopt a closer arrangement. A well-compacted material has a denser particle arrangement, and will therefore deform less under loading.

For this investigation compaction tests were carried out in accordance with AS1289.E2.2(1977). Modified compaction was selected over standard compaction after discussions with the local producers of RCA, Alex Fraser Pty. Ltd. and major contractors using the material, who all reported that the material was compacted to a level comparable with modified energy.

All samples were dried to constant mass at 105°C and allowed to cool for a minimum of 4 hours, after which all material retained on the 19mm was discarded. The samples were then mixed at the appropriate moisture content and allowed to equilibrate for a minimum of 24 hours. All tests were performed manually.

4.3.4 Los Angeles abrasion loss

The Los Angeles (LA) test is widely used in crushed rock specifications to classify materials and to determine a suitable optimum grading envelope. It is an empirical test traditionally used to classify the hardness of source rocks. For road pavement materials to perform in a high stress situation they must be of a hardness sufficient to provide strength and stability under stresses created by road traffic. Materials with a higher LA loss are generally specified with a coarser grading, as additional fines will be created during compaction and placement.

The Los Angeles test was performed in accordance with AS1141.23(1980). The test charge adopted was 'J', as this is generally used for softer source rock and was recommended by VicRoads. For the test 5000g±10g of material between 13.2mm and 9.5mm sieves is used. Ten steel balls are used, with a total mass of 4165g±25g.

4.3.5 Determination of moisture content

Where a moisture content was required for a sample it was carried out in accordance with AS1289.B1.1 (1977). All samples were dried at 105°C for a minimum of 24 hours.

4.3.6 Moisture absorption and specific gravity

Examination of the literature revealed that moisture absorption and specific gravity of RCA can vary significantly from that of natural aggregate (NA). It is necessary that these two characteristics are examined, as they influence other properties of the material, such as compaction.

The tests were carried out on fine aggregate in accordance with AS1141.5(1974) and on the coarse aggregate in accordance with AS1141.6(1974), where fine aggregate is defined as any material passing the 4.75mm sieve. The coarse aggregate was washed in a wire basket to remove any dust particles.

Additional tests were later carried out on the same samples to determine the specific gravity and moisture absorption for aggregate particles retained on the 19mm, 13.2mm, 9.5mm, 4.75mm, 2.36mm and 0.425mm sieves. These tests were done in accordance with AS1141.5(1974) and AS1141.6(1974).

4.3.7 Flakiness Index

In order to determine the shape of RCA, flakiness index tests were carried out in accordance with AS1141.15 'Flakiness Index' (1988). The index is used to determine the percentage by mass of flat particles which have a least dimension less than 0.6 times their average dimension. This test was performed on the laboratory-produced 32MPa and 80MPa samples and then compared with the commercially produced RCA to examine the effect of concrete strength on the aggregate shape.

4.4 REPEATED TRIAXIAL LOAD TEST

The RTL test using a cylindrical specimen has become a popular method of material characterization and is fundamental to the mechanistic design procedure. It should be noted that the apparatus used in this research approximates a 2-D stress field, using only vertical and radial loads. In an actual pavement the transition of a wheel load creates a 3-D stress field and a rotation of the principal stresses. The RTL tests are not designed to replicate precisely insitu conditions of a road pavement material under dynamic wheel loading. They are seen as an indicator of likely performance and can be used to compare RCA with other crushed rock materials tested under similar conditions.

4.4.1 Description of the apparatus

All tests were carried out on a system produced by Industrial Process Controls Ltd. of Melbourne. A diagram of the apparatus is shown in Figure 4.2.

The machine is based on a reaction frame consisting of a heavy, flat, stainless steel base plate supported on four levelling screws. Two vertical threaded rods support the cross-head beam, which can be adjusted for height. The heavy construction of the frame helps limit deflections and vibrations, which can influence the accuracy of the testing.

Vertical load is applied to a 100mm diameter by 207mm high sample by a low-friction pneumatic actuator mounted centrally on the cross-head. An electronically operated, air-assisted solenoid valve controls the air supply for both vertical and confining stresses. The perspex load cell was filled with silicone oil, which was used to prevent rusting of the on-sample linear voltage displacement transducers (LVDT), although the on-sample LVDT's were not operational at the time of testing. A strain gauged force transducer measures the force applied to the specimen.

Longitudinal deformations are measured by a LVDT mounted externally on the cell, between the loading ram and the base platen, as shown in Figure 4.2.

All data acquisition and control mechanisms are performed automatically by the apparatus, which includes signalling, signal conditioning, electrical power and communication facilities. A detailed description of the hardware and data acquisition of the apparatus is given in Tritt (1991).

4.4.1.1 On-sample versus off-sample measurement.

Linear displacements in this investigation were taken off-sample. This method has been deemed to be suitable by the AUSTROADS Pavement Research Group (APRG, 1991) for the determination of routine modulus values, although on-sample measurement is preferred.

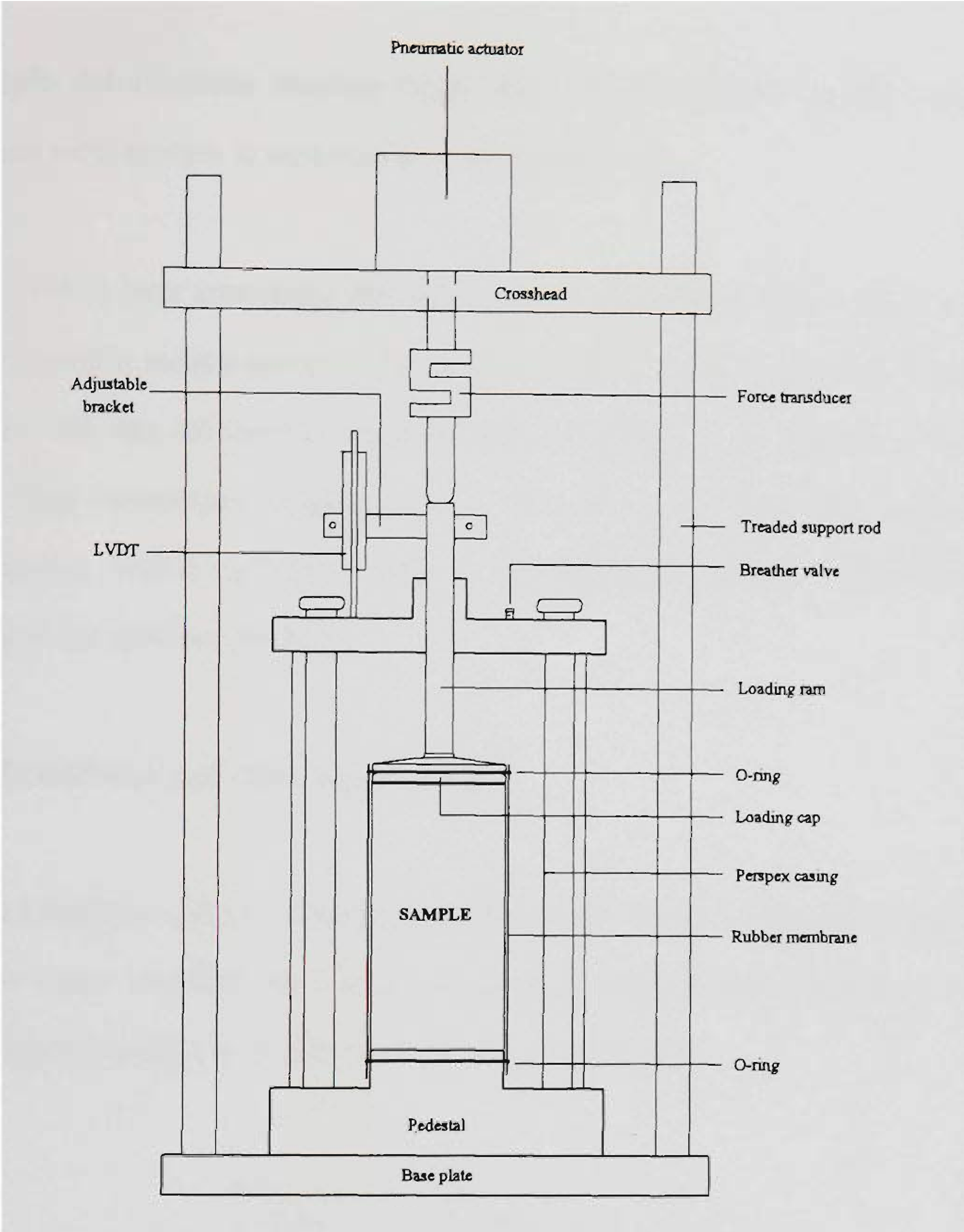


Figure 4.2 Repeated Triaxial Load test apparatus

Vuong (1985) postulated a deformation mechanism for cylindrical, non-cohesive materials under RTL, and related this to the variation in on-sample and off-sample measurement. In the early stages of loading the loose end zones of the sample collapse more rapidly, giving higher strains than those recorded on-sample. As the sample is compressed the collapse rate of the loose end zones decreases, and at this time the accumulated axial compression is accompanied by a lateral expansion due to Poisson's effect. Lateral expansion is prevented at the ends of the sample due to friction with the end caps and lateral deformation occurs in the middle of the sample. As the compression of the sample increases, it becomes more barrel-shaped and the on-sample deformations become larger than the off-sample measurements. This continues until the test is terminated or the sample fails.

Vuong (1991) later concluded that the on-sample measurements were more reliable than off-sample measurements. For materials which have a permanent deformation less than 2%, the off-sample measurements are likely to be between 10% to 30% higher than on-sample measurements. If this is so, then the results in this investigation would therefore tend to overestimate pavement deflections and underestimate resilient modulus.

4.4.2 Definitions and other relationships

Resilient modulus (M_r) is a stress-strain parameter which is defined as the repeated deviator stress imposed on a soil specimen divided by the resilient or recovered strain when the stress is released, as shown in Figure 4.3.

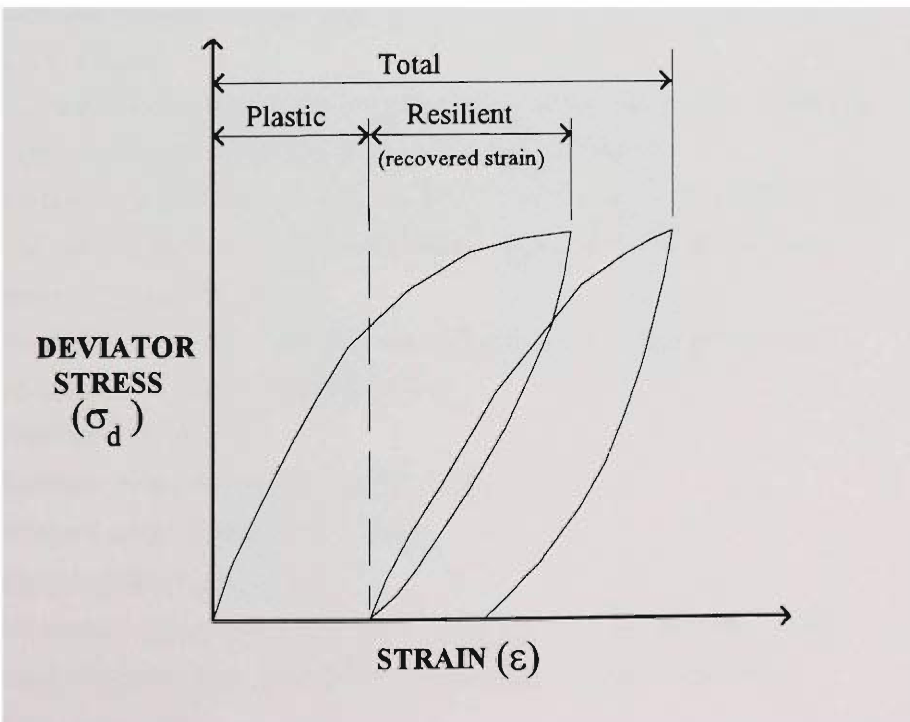


Figure 4.3 Stress versus strain relationships for two cycles of RTL loading

$$\sigma_{d(n)} = \sigma_{3(n)} = \left(\frac{F_v}{A}\right) - \sigma_{3(n)}\left(1 - \frac{A - a}{A}\right) \tag{4.1}$$

$$I_{g(n)} = I_i - \left(\delta_{4(n-1)} - \delta_1\right) \tag{4.2}$$

$$\varepsilon_{r(n)} = \left(\frac{\delta_{3(n)} - \delta_{4(n)}}{I_{g(n)}}\right) \text{ x } 100 \tag{4.3}$$

$$M_{r(n)} = \frac{\sigma_{d(n)}}{\varepsilon_{r(n)}} \text{ x } 10^{-1} \tag{4.4}$$

$$\varepsilon_{p(n)} = \left(\frac{\delta_{4(n)} - \delta_2}{I_i}\right) \text{ x } 100 \tag{4.5}$$

$$\sigma_{m(n)} = \left(\frac{2\sigma_{3(n)} + \sigma_{3(n)}}{3}\right) \tag{4.6}$$

$$\theta_{(n)} = 2\sigma_{3(n)} + \sigma_{3(n)} \tag{4.7}$$

Where;

a = Cross sectional area of the loading ram (m^2)
A = Cross sectional area of specimen (m^2)
F_v = Vertical force applied to the loading ram (kN)
$I_{g(n)}$ = Gauge length over which the deformation is measured for that cycle (mm)
I_i = Initial gauge length, the height of the specimen, for external displacement measurement (mm)
$M_{r(n)}$ = Resilient modulus at that cycle (MPa)
n = Cycle number
δ_1 = Vertical displacement at the commencement of the test with no confining stress(σ_3) and no deviator stress (σ_d) applied (mm)
δ_2 = Vertical displacement when the confining stress (σ_3) is first applied (mm)
$\delta_{3(n)}$ = Vertical displacement with the confining stress (σ_3) and the deviator stress (σ_d) applied (mm)
$\delta_{4(n)}$ = Vertical displacement with the confining stress (σ_3) applied and the deviator stress (σ_d) released (mm)
$\varepsilon_{p(n)}$ = Permanent strain (%)
$\varepsilon_{r(n)}$ = Resilient vertical strain at that cycle (%)
$\sigma_{d(n)}$ = Deviator stress at that cycle (kPa)
$\sigma_{m(n)}$ = Mean normal stress (kPa)
$\sigma_{1(n)}$ = Maximum vertical stress applied to the specimen for that cycle (kPa)
$\sigma_{3(n)}$ = Static confining stress applied to the specimen for that cycle (kPa)
θ_n = Bulk stress (kPa)

4.4.3 Sample preparation and testing

All samples were compacted dynamically into a 100mm diameter by 207mm high steel split mould, in 10 uniform layers using Modified energy. Initial trials with five compaction layers gave unsuitable specimens which contained air voids clearly visible between the layers.

After compaction, samples were placed into rubber membranes and tested within 30 minutes of preparation, except for samples that required curing. Those samples were sealed in a plastic bag and placed in a controlled environment of 24°C and 100% relative humidity for the duration of the curing period.

Each of the samples tested had a target grading as shown in Table 4.2. In order to obtain the target grading each sample was sieved down into graduated aggregate sizes and remixed in the required proportion. For the two specimens to which crushed brick was added, the added brick was also graded according to Table 4.2

Table 4.2: Target grading of all samples used for RTL testing

Sieve Size (mm)	% Passing
26.5	100
19.0	96.1
13.2	78.9
9.5	66.1
4.75	49.4
2.36	40.2
0.425	20.3
0.075	6.9

All RTL tests were carried out in undrained conditions. It is well documented that high moisture contents in RTL testing reduce resilient modulus (Vuong, 1992). Litwinowicz and Wijeyakulasuriya (1991) concluded that premature failures of road pavements constructed with sound aggregate were influenced by excessive pore pressures developed during trafficking. A grading which has been designed to give a maximum density has fewer air-voids than a 'open-graded' material. The reduction in air-voids decreases the permeability of the pavement, resulting in the development of pore pressure when loaded. RTL testing in an undrained state rather than a drained state simulates a pavement with a low permeability, likely to develop pore pressure when loaded. This will ensure that the material is examined in a worst case scenario. The APRG (1991) recommends that routine testing may be done in the undrained condition without the measurement of pore pressure.

Vertical and confining stresses were both applied cyclically in the form of a square top waveform.

A detailed description of the procedures followed for sample preparation and compaction, and running of the RTL test, is given in Appendix B.

4.4.4 Stage modulus tests

In order to use a mechanistic approach, information is required on the response of a material to various combinations of vertical and confining stresses under cyclic loading. The magnitude of these stresses is on the location of the material within the pavement structure and the load applied, which in turn influences the resilient modulus of the material.

In order to assess some variables associated with the production of RCA, the following factors were examined to determine their influence on the resilient modulus.

4.4.4.1 Addition of brick

Two samples of commercially produced recycled concrete aggregate had 15% and 30% by mass of brick masonry added. Occasionally, masonry can represent up to 10% by mass of a recycled concrete aggregate production run. VicRoads Specification 820 limits the amount of high density material, such as brick, to 3% for upper subbase and 5% for lower subbase materials, based on the assumption that large amounts of this material may reduce pavement strength.

4.4.4.2 Effect of source concrete strength

As previously discussed the strength of recycled concrete prior to crushing is generally unknown. In order to determine the effect, if any, which variations in strength have on the resilient modulus were tested, two laboratory-produced RCA samples, one with a source concrete strength of 32MPa and the other of 80MPa.

4.4.4.3 Effect of curing

The literature review briefly outlined that road pavements constructed using recycled concrete aggregates generally exhibit a form of residual setting. In order to determine the magnitude of this setting three cylinders were compacted, using the commercial RCA, and tested after 0, 7 and 28 days of curing.

4.4.4.4 Effect of moisture content

The moisture content of a sample is known to greatly influence the M_r of granular materials in that, as the degree of saturation increases, M_r decreases. Two tests were performed using commercial RCA, the first with a moisture content at 71.6% of optimum moisture content and the second at 80% of optimum (OMC=12%). The selected moisture contents are within the guidelines of the National Workshop on Elastic Characterization of Unbound Pavement Materials and Subgrades (APRG, 1991), which recommended for material characterization that the moulding moisture contents be between 60% and 80% of OMC. Due a limited amount of testing time further tests with different moisture contents could not be performed. For a complete moisture sensitivity analysis, testing of samples compacted at up to 95% of OMC would be necessary.

Table 4.3 summarises the tests carried out and the nomenclature used to describe them.

Table 4.3: Summary of stage modulus sample and nomenclature

Sample description	Nomenclature
Commercially produced RCA tested without curing	RCA
Commercially produced RCA tested without curing, at 71.6% of OMC	72%OMC
Laboratory produced RCA, tested without curing, made from concrete with a strength of 32MPa	32MPa
Laboratory produced RCA, tested without curing, made from concrete with a strength of 80MPa	80MPa
Commercially produced RCA, tested without curing, with 15% of graded brick masonry (BR)added	15%BR
Commercially produced RCA, tested without curing, with 30% of graded brick masonry (BR) added	30%BR
Commercially produced RCA tested after 7 days of curing	7Day
Commercially produced RCA tested after 28 days of curing	28Day

4.4.4.5 Determination of stage modulus stress values.

The stress states used in this investigation were designed to simulate those likely to occur in a typical unbound granular pavement at various depths, subjected to a variety vehicle configurations.

All stage modulus tests were commenced at inverse stress ratio $\sigma_h/\sigma_v = 0.1$ and bulk stress $\sigma_m = 50$ kPa. While the stress ratio was kept constant σ_m was then increased at intervals of 50 kPa until the maximum of 300 kPa was reached. A stress ratio of 0.2 was then selected and the same stress cycle as indicated above was followed. This continued until all of the stress ratios were covered. It should be noted that the combination $\sigma_h/\sigma_v = 0.1$ and $\sigma_m = 300$ kPa was not tested on any sample as the apparatus was unable to supply the vertical stress required. This resulted in a total of 29 stress states as shown in Table 4.4.

4.4.4.6 Stage modulus testing procedures

Prior to the testing for modulus the samples were preconditioned. The purpose of preconditioning is to eliminate strains that result from disturbances of sampling, specimen preparation and seating of the end caps. 1500 cycles at a vertical stress of 630 kPa and a confining stress of 315 kPa were applied. No specimen failed during the preconditioning phase. Graphs of the preconditioning process are shown in Appendix C. Each graph shows the load pulse count versus resilient modulus, permanent strain and resilient strain. The preconditioning was deemed to be effective once a repeatable modulus for the material was obtainable after 1500 load pulses. All tests were terminated at 1500 load pulses with a steady modulus being achieved for each of the samples.

Table 4.4: Stage modulus stresses

Stage	Vertical Stress (kPa) (σ_1)	Confining Stress (kPa) (σ_3)	Mean Normal Stress (kPa) (σ_m)	Inverse Stress ratio (σ_3/σ_1)	Bulk Stress (kPa) (θ)
1	125	13	50	0.1	151
2	250	25	100	0.1	300
3	375	38	150	0.1	451
4	500	50	200	0.1	600
5	625	63	250	0.1	751
6	108	21	50	0.2	150
7	214	43	100	0.2	300
8	321	64	150	0.2	449
9	427	86	200	0.2	599
10	534	108	250	0.2	750
11	640	130	300	0.2	900
12	94	28	50	0.3	150
13	187	56	100	0.3	299
14	281	84	150	0.3	449
15	375	112	200	0.3	599
16	470	140	250	0.3	750
17	564	168	300	0.3	900
18	83	33	50	0.4	149
19	167	67	100	0.4	301
20	250	100	150	0.4	450
21	333	133	200	0.4	599
22	416	166	250	0.4	748
23	500	200	300	0.4	900
24	75	38	50	0.5	151
25	150	75	100	0.5	300
26	225	113	150	0.5	451
27	300	150	200	0.5	600
28	375	188	250	0.5	751
29	450	225	300	0.5	900

After the preconditioning phase was completed, the stage modulus test was automatically started and controlled automatically by the computer software. Each stress stage consisted of a minimum of 50 cycles, and was continued until the resilient modulus values from the last six results varied by less than 10% of the mean value of those six results, or until 250 cycles had been completed, whichever was the lesser. Once these criteria were achieved the next stage was automatically started. Each load pulse was applied for one second and unloaded for a total of three seconds. This loading cycle allowed full specimen recovery, enabling an accurate value for resilient vertical strain to be obtained. The specimen recovery was monitored via a computer screen.

The apparatus applied the load in the form of an approximate square-top pulse, which could also be monitored on the computer screen. The application of the confining stress was cyclic and the vertical load was applied in accordance with Australian Pavement Research Group recommendations (APRG, 1991). Details of the loading configurations for both the stage modulus and permanent strain tests are given in Table 4.5 and Figure 4.4.

Table 4.5: Load cycling times

Test	Loading interval (ms)	Lead time (ms)	Lag time (ms)	ulse width (ms)
Stage modulus	4000	500	500	1000
Permanent strain	3000	200	0	300

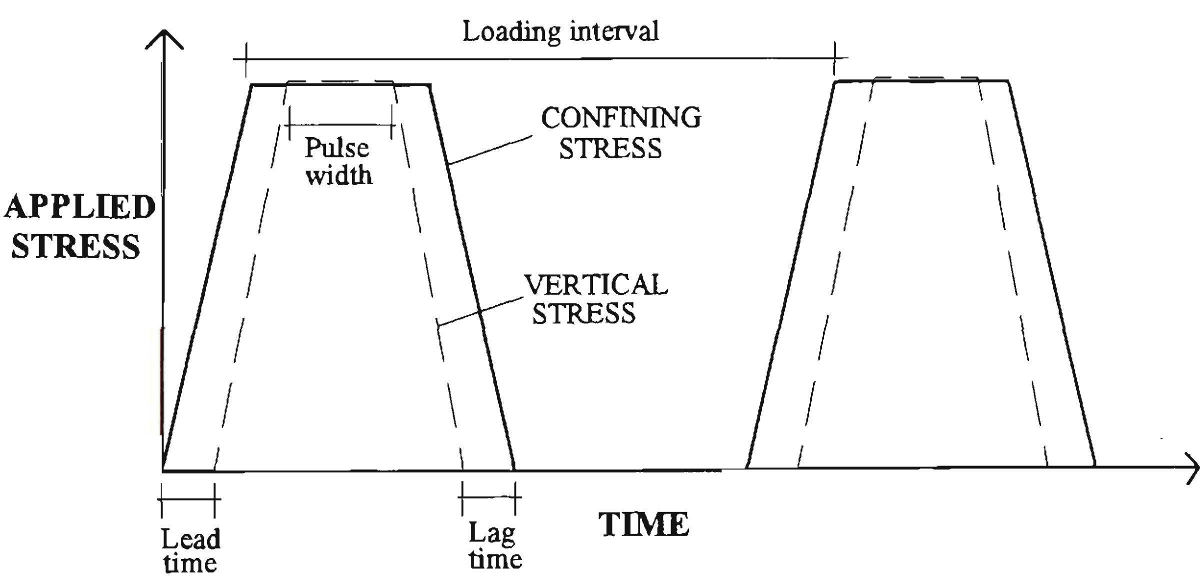


Figure 4.4: Loading cycles

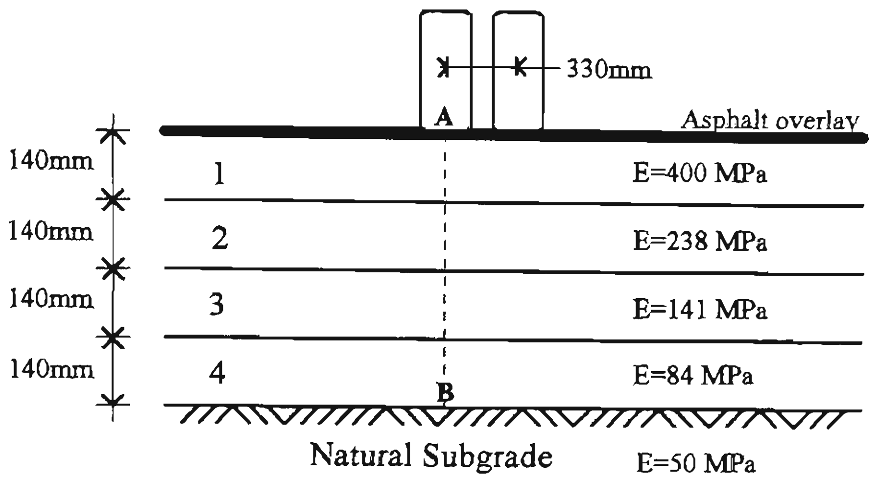
4.4.5 120,000 Pulse permanent strain test

The 120,000 pulse RTL test is used to measure the long term permanent strain characteristics of a road pavement material. The 120,000 pulse test has been used by the CSIRO Division of Building, Construction and Engineering over a number of years to determine the comparative performance of road pavement materials (Shayan and Westgate, 1988 and Cole, 1982).

One specimen of commercial RCA was prepared in the manner described within Appendix B and tested without curing.

4.4.5.1 Experimental techniques

The specimen was preconditioned for 1500 pulses at a vertical stress of 630 kPa and a confining stress of 315 kPa. At the completion of the preconditioning the permanent strain test commenced. The specimen was subjected to 120,000 load pulses at a vertical stress of 500 kPa and confining stress of 70 kPa, which typically represents stresses found near the top of a base course pavement with a sealed overlay. Figure 4.5 shows a typical granular pavement with an asphalt overlay loaded with an equivalent standard axle. The stresses created by the loading along the vertical line A-B are shown in Figure 4.6 and have been calculated using the computer program CIRCLY (Wardle, 1977). It is the experience of the CSIRO that lower stress levels produce small permanent deformations, whereas higher levels produce excessive initial deformations, leading to an early failure of the specimen (Shayan and Westgate, 1988). The loading occurred at three second intervals, with a duration of 0.3 seconds, which represents a relatively slow moving vehicle (approximately 15 kilometres per hour). Kalcheff and Hicks (1973) and Allen and Thompson (1974) found that load duration's between 0.1 and 1.0 second had only a small effect on resilient modulus.



Tyre contact stress=700kPa

Tyre radius=95mm

Total load mass = 8.2t.

Figure 4.5: Typical pavement design

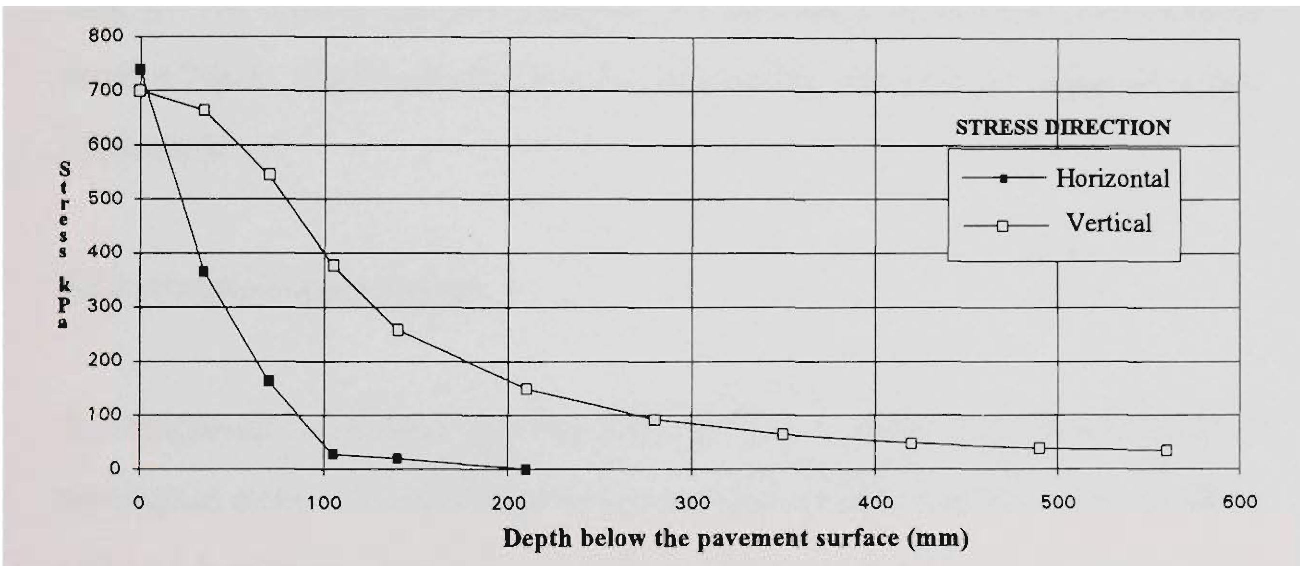


Figure 4.6: Stress distributions along a vertical line A-B under a standard axle load

4.5 NON-STANDARD AND DEVELOPED TEST METHODS.

4.5.1 Foreign material content

During the demolition process concrete is often contaminated with other less desirable building material, such as timber, plastic, plaster or glass. As no Australian or international method was found to determine the quality of these 'unsuitable materials', one was developed.

The test is used essentially as quality control and is performed rapidly at the production plant. Typically it is carried out in conjunction with a grading test and only material retained above the 4.75mm sieve is assessed as it is difficult to accurately sort smaller material. The unsuitable materials are classified as either 'high' or 'low' density and are expressed as a percentage of the total mass retained above 4.75mm. Details of the procedure followed for the tests are contained within Appendix B.

4.5.2 Attached cement paste

The fundamental difference between RCA and NA is the cement paste attached to the original stone. Determination of its quantity enables other properties of RCA, such as LA abrasion loss, specific gravity and moisture absorption, to be more fully explained.

The method adopted to determine the amount of cement paste adhering to recycled aggregates was based on a Japanese investigation reported by BCSJ (1978). It involves immersing a sample of RCA in a dilute solution of hydrochloric acid and dissolving the attached cement paste, leaving only the original stone. A full description of the procedure adopted for this method is given in Appendix B.

4.5.3 Cement paste coverage

The amount of cement paste visible on RCA particles can be used assess the mode of crushing of the original waste concrete. In general weaker and old concrete tends to crush through the concrete, exposing little of the original natural aggregate. Whereas a stronger cement matrix tends to result in a higher amount of crushing of the original natural aggregate.

The method of crushing waste concrete also may influence the amount of cement paste coverage. Impact crushers tend to crush more readily through both the waste concrete and natural aggregate alike. Jaw crushers, using predominantly pressure as the crushing action fracture the material more through the cement paste, leaving the natural coarse aggregate relatively undamaged when compared to impact crushed material.

The method used to determine the amount of cement paste coverage is discussed in Appendix B.

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 MONTHLY TESTING PROGRAM

5.1.1 Crushing characteristics, surface texture and shape

The observed particle shape of crushed concrete in the six monthly samples was cubical to angular. The flakiness index value for each of the samples is shown at the bottom of Table 5.1 and ranges between 12% and 15%, indicating that relatively few flat particles are present. The shape of an aggregate is influenced by the crushing process. In the case of the commercial samples, primary-jaw and secondary-impact crushing, along with the use of a closed loop system, tended to reduce the number of flat particles because of the additional processing.

Coarse RCA particles have a rough surface texture, caused by the cement paste attached to the original stone. A detailed visual examination of 100 20mm aggregate pieces showed that on average the surface of each stone had 80% coverage of cement paste, with relatively little shearing of the source stone. This indicates that the crushing of the waste concrete generally occurred through the cement paste. Hansen (1992) proposed that the use of impact crushers may produce an inferior product as both the cement paste and original aggregate are crushed alike. This was not observed in this investigation where an impactor was used as a secondary crusher.

The fine RCA particles (less than 5mm) consist mainly of cement paste with relatively little natural aggregate present. The particles are angular in shape, and have a rough surface texture.

5.1.2 Particle size distribution

The results of the six PSD tests carried out are shown in Table 5.1 and graphically displayed in Figure 5.1, which also shows the current VicRoads specification 820 grading limits.

Table 5.1: Particle size distribution and flakiness index for the Six Monthly Samples

Sieve Aperture (mm)	SAMPLE					
	MS1	MS2	MS3	MS4	MS5	MS6
	Percentage passing					
26.5	100	100	100	100	100	100
19.0	97	99	99	100	100	100
13.2	80	83	83	85	88	86
9.5	66	69	70	72	76	74
6.7	57	60	61	62	66	65
4.75	49	52	53	54	58	56
2.36	37	40	40	43	45	43
1.18	28	30	31	32	34	34
0.600	23	24	25	26	27	25
0.425	19	21	21	22	24	22
0.300	15	17	18	19	20	18
0.150	10	11	12	13	14	14
0.075	7	8	7	8	9	9
Flakiness Index	11	13	14	12	11	14

From Figure 5.1 it can be seen that all six samples fall well within the VicRoads class 3 grading limits and have a relatively low variability. In general the gradings fall more or less centrally between the limits, but are finer than the Fuller optimum grading curve.

Clearly a grading suitable for use as a road pavement material can be obtained, provided appropriate plant, and layouts are selected, as previously discussed in section 2.5.1. The creation of sufficient fines below 75μm is sometimes a problem, particularly with a hard source rock, such as fine grained basalt's (Fielding and McHaffie, 1992). The problem does not occur with recycled concrete aggregate as the majority of fines are made up of the old cement paste which crushes readily.

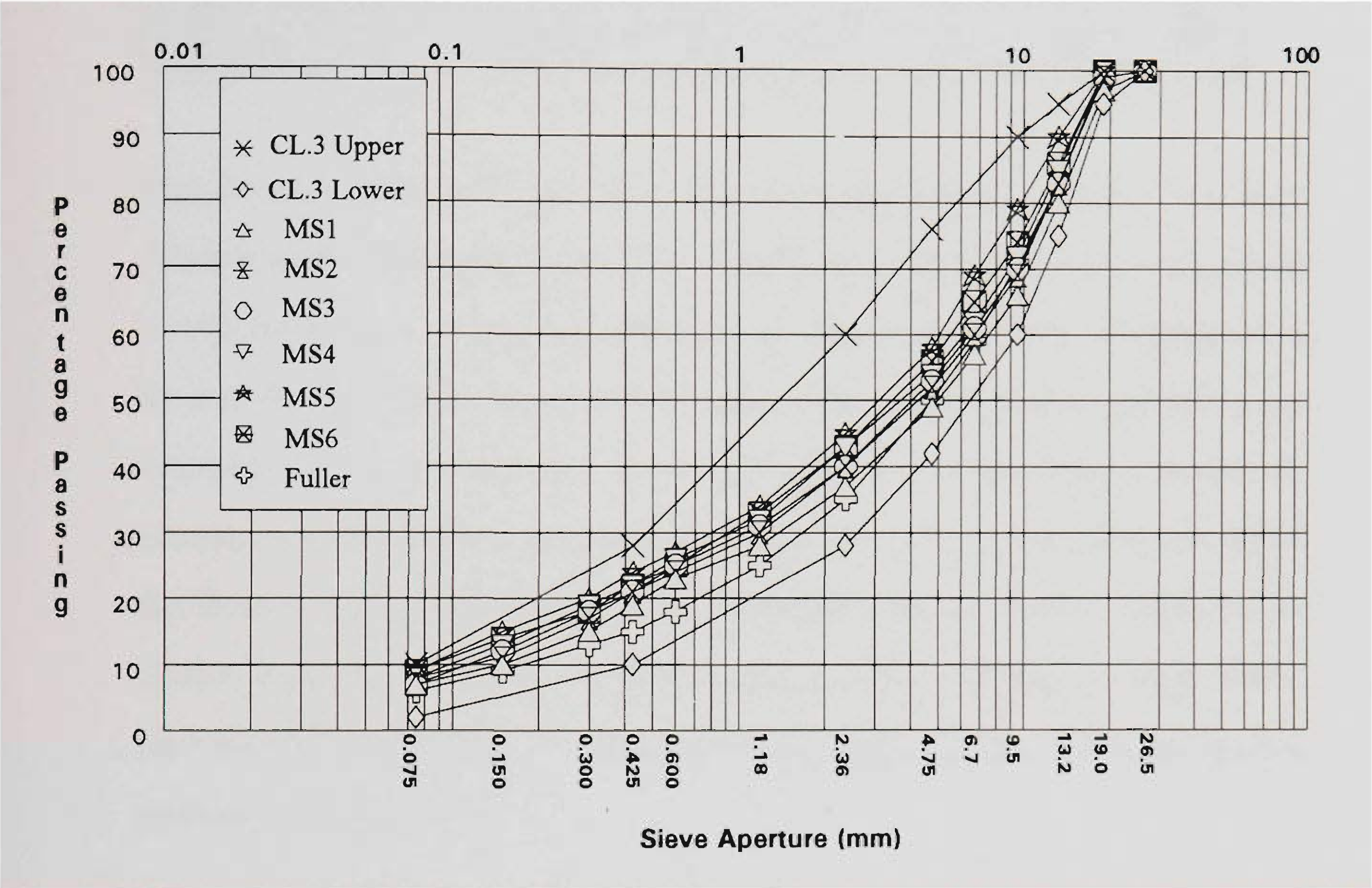


Figure 5.1: Particle size distributions of monthly samples

5.1.3 Plasticity

The results displayed in Table 5.2 show that RCA is a non-plastic material. Plasticity index is obtained by subtracting the plastic limit from the liquid limit. If a plastic limit is not obtainable the material is considered non-plastic. The liquid limit values range from 29 to 33 and are relatively consistent. The plastic limit could not be obtained as the RCA fines, below 0.425mm, continually crumbled before reaching the requirement under AS1289.C2.1 of a 3mm mm thick thread, the point at which the material is considered to be in the plastic limit.

Table 5.2: Atterberg limits

TEST	Sample					
	MS1	MS2	MS3	MS4	MS5	MS6
Liquid Limit (LL)	29	30	30	33	30	31
Plastic Limit (PL)	NO	NO	NO	NO	NO	NO
Plasticity Index	NP	NP	NP	NP	NP	NP

Clay particles within RCA can come from two possible sources - either secondary minerals within the original stone used to produce the concrete or from soil mixed in with the concrete during the demolition or excavation process. Contamination by soil can be reduced provided that appropriate quality control guidelines are followed. These are discussed later. The influence of secondary minerals on plasticity has been a source of discussion within Melbourne, particularly as some of the Western suburbs' basalt's have high secondary mineral counts. However, an opinion expressed is that any secondary minerals present within the stone would have reacted long before it is recycled into an aggregate, and should not pose a problem (Fielding, 1994).

The primary reason that RCA fines are non-plastic is that they contain approximately 4% calcium hydroxide $Ca(OH)_2$, i.e. hydrated lime (Hansen and Narud, 1983b), depending on the amount of cement used to produce the original concrete. Hydrated, quick and dolomitic limes have all been used to improve the workability and strength of clayey soils. The lime present within RCA fines promotes the dissolution of the clay, particularly at the edges of the clay plates, allowing the formation of silicates and aluminates at these sites. This has the immediate effect of improving the materials granulation and handling properties and in the long term increases strength (NAASRA, 1986). The presence of $Ca(OH)_2$, within the crusher fines should react with any clay particles present and reduce the plasticity of RCA.

5.1.4 Compaction

RCA compacted at either Standard or Modified energy has a dry density lower than that of compacted virgin aggregate, because of the low-density cement paste attached to the source stone. Crushed rock from Western suburbs' basalt's typically has a maximum dry density between 2.35t/m^3 and 2.5t/m^3 with an optimum moisture content of 7-8%, using Modified compaction (Cole, 1982) and Shayan and Westgate, 1988). Table 5.3 shows the maximum dry density (MDD) and optimum moisture content (OMC) for RCA for the tests on the six monthly samples, performed in accordance with AS1289.E2.2 (1977). The compaction results in Table 5.3 indicate a consistent MDD between 2.01t/m^3 and 2.07t/m^3, with an average of 2.04t/m^3 and standard deviation of 0.02t/m^3. The OMC is slightly more variable between 10.9% and 12.5%, with an average of 11.8% and standard deviation of 0.55%. Sherwood and Pike (1984) reported on 30 compaction tests performed on subbase materials. They also found that OMC was more variable than the MDD.

Table 5.3: Maximum dry density and optimum moisture content results

SAMPLE	MDD (t/m^3)	OMC (%)
MS1	2.02	10.9
MS2	2.05	11.5
MS3	2.01	12.0
MS4	2.05	11.8
MS5	2.07	12.1
MS6	2.02	12.5

RCA has a MDD approximately 15% lower than the basalt crushed rock and an OMC of up to 80% higher. Figure 5.2 shows a compaction curve for recycled concrete aggregate sample MS1, which is typical of the compaction curves obtained. The remaining compaction curves are given in Appendix C.

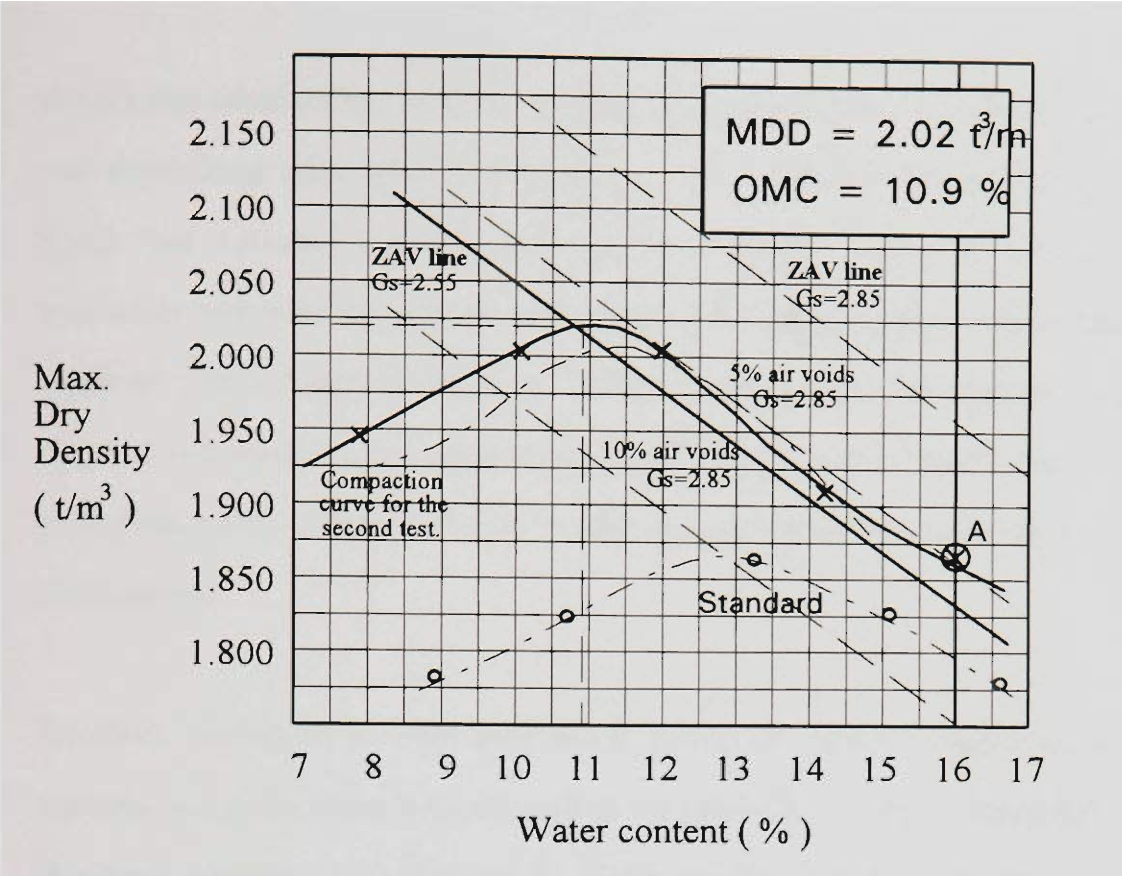


Figure 5.2: Modified compaction curve for MS1

The most significant feature of the graph is that the compaction curve intersects the original zero air void (ZAV) line, indicating an error in the computations as it is not possible to compact any material beyond a point where all of the air voids removed. O'Mahony and Milligan (1991) also compacted an RCA sample to a point where the compaction curve and ZAV line intersected. They concluded that the error was probably due to the difficulty in accurately determining a specific gravity value for the material. No other explanation for the error was proposed, and it appears that the sample was not re-tested.

As there is no published literature to compare the compaction values obtained in this investigation, an examination of the independent testing commissioned by Alex Fraser Pty. Ltd. was examined. Compaction tests were carried out by Geotech Pty. Ltd., a NATA registered, Geotechnical engineering consultancy in Melbourne. The material tested was a 20mm RCA produced from the Port Melbourne plant. The sample was taken on the 12/1/94. Under Modified compaction an MMD of 1.98t/m^3 was determined with OMC occurring at 11.9%. Under Standard compaction the MDD was 1.91t/m^3 and the OMC 12.8%. Earlier testing (13/7/93) had been previously had been carried out on a 40mm RCA, with similar results obtained, an MDD of 2.04t/m^3 and an OMC of 11.9%. Based on this information Alex Fraser Pty. Ltd. recommends to contractors an OMC of 12%, which should result in a MDD of approximately 2.0t/m^3. These results compare favorably with the those in this investigation.

To check that errors had not been made during the initial compaction test, it was repeated using the same procedures and sample (MS1). The compaction curve for this test is also shown in Figure 5.2. Clearly the two compaction curves are similar, indicating the repeatability of the test. It was therefore considered that the use of an incorrect specific gravity was the most likely cause of the compaction curve and ZAV line intersecting.

As previously stated O'Mahony and Milligan (1991) experienced problems in obtaining an accurate specific gravity. The standard method to determine specific gravity is by immersing the sample in water for a period of time and then drying it back to a SSD condition. Other researchers (Hansen and Marga, 1988 and Puckman and Henrichsen, 1988) have expressed doubts about the suitability of this test on RCA. This is because it is difficult to determine when surface dryness has occurred with a material that is highly porous and has a rough surface texture. Until a specific test method for RCA is developed this remains the only method. It was reported in the literature review (section 2.5.3) that Puckman and Henrichsen (1988) had developed an alternative test method to determine specific gravity and moisture absorption, but further work was still required.

A specific gravity of 2.55t/m^3 was initially calculated for MS1 and this value was used to determine the original ZAV line shown in Figure 5.2. The test was repeated at a later stage using a sample from the same bulk sample (MS1) and a value of 2.52t/m^3 was obtained. Although the results obtained are consistent, they may both be erroneous due to the difficulties, as discussed previously, in determining the correct SSD condition.

Assuming that the compaction curve is correct and the specific gravity is incorrect, it is possible to determine the value required to bring the ZAV line to the right of the compaction curve.

Shown in Figure 5.2 is a point 'A'. This is the last of the compaction points and has a MDD of 1.87t/m^3 at an OMC of 15.9%. By rearranging equation 5.1 it was possible to determine the specific gravity value required for the ZAV line to pass through point 'A'. A value of 2.67t/m^3 was obtained, assuming that the material has been compacted until all air voids are eliminated, an impossible situation. It is likely that the material compacted using modified energy will have between 5% and 10% air voids. At the same point 'A' the RCA would need to have a specific gravity of 2.85t/m^3 and 3.1t/m^3, for 5% and 10% air voids respectively, for the ZAV line to pass to the right of the compaction curve. Also shown on Figure 5.2 are the ZAV, 5% and 10% air void lines, assuming a specific gravity of 2.85t/m^3.

By examining the individual components of RCA it is possible to estimate the theoretical maximum specific gravity of the material. Based on concrete mix designs contained within the Basic Guide to Concrete Construction (Cement and Concrete Association, 1980) it can be approximated that concrete with compressive strengths ranging between 15MPa and 50MPa are composed of 50% cement paste and 50% coarse aggregate. In order to determine the specific gravity of cement mix a mortar was designed. The components of the mix were the same as those used for the

32MPa sample (See Table 4.1), with the exception that no coarse aggregate was used. The sample was cured, tested and crushed using the procedures outlined in Section 4.2.2. The mortar samples had an average compressive strength of 29.6MPa.

$$\rho_d = \frac{\rho_w(1 - \frac{V_a}{100})}{\frac{\rho_w}{G_s} - \frac{w}{100}} \qquad (5.1)$$

where:

ρ_d = Dry density (t / m^3)

ρ_w = Density of water (t / m^3)

V_a = Air voids (%)

w = water content (%)

G_s = Specific gravity (t / m^3)

A specific gravity of 2.23t/m^3 for the cement paste was obtained, using AS1141.5 (1974) and AS1141.6 (1974). As a comparison Hansen and Narud (1983b) reported mortar densities between 2.04t/m^3 and 2.15t/m^3 for water-cement ratios between 0.40 and 1.20.

Based on the following assumptions an estimate of the specific gravity for the NA component of RCA can be made:

1. RCA is made up of 50% cement paste and 50% original natural aggregate.
2. Cement paste has a specific gravity of approximately 2.23t/m^3.
3. A specific gravity of 2.85 is required to stop the intersection of the ZAV line and compaction curve, assuming 5% air voids.

Based on these assumptions a specific gravity of 3.47t/m^3 for the NA component is required to ensure the compaction curves do not intersect. The most common source of concrete aggregate in the Western suburbs of Melbourne is the Newer Volcanic basalt's, which typically has a specific gravity between 2.63t/m^3 and 2.96t/m^3. This is significantly lower than the value of 3.47 t/m^3 required to correctly position the ZAV line to the right of the compaction curve.

Clearly problems exist in accurately obtaining complete compaction characteristics for the material. It is likely that the testing procedures used to determine specific gravity are not ideal for use on RCA, however they do not totally explain the results obtained. Further work is required to understand behaviour of RCA when compacted and accurately determine its specific gravity.

5.1.5 Foreign material content

The amounts and type of foreign material found during the six-monthly testing period is shown in Table 5.4.

Table 5.4: Foreign Material Content

(Percentage by mass of total sample)

MATERIAL	Sample					
	MS1	**MS2**	**MS3**	**MS4**	**MS5**	**MS6**
Brick (%)	2.3	0.5	1.8	1.7	2.6	1.3
Asphalt (%)	1.2	0.8	0	1.1	0	0
Glass (%)	0	0	0	0.3	0	0
Total High Density (%)	3.5	1.3	1.8	3.1	2.6	1.3
Total Low Density (%)	0	0*	0	0	0*	0
Total Timber & Vegetable Matter (%)	0	0	0.1	0.1	0	0

* Denotes that the material was observed but the percentage of total mass was under 0.05%.

The two non-concrete materials that were most commonly encountered during the processing of demolition are brick and asphalt. Typically, the brick comes from the demolition of buildings and the asphalt from the removal of kerb and channel. The VicRoads specification section 820 limits the amount of 'high density' material, which includes brick, metal, asphalt and glass to 3% for the upper subbase and 5% in the lower subbase. Test samples MS1 and MS4 exceeded the requirements for upper subbase materials in the high density range by 0.5% and 0.1% respectively.

As the majority of waste concrete is obtained from building demolition many other materials, such as timber, plastic and plaster might be expected. An examination of Table 5.4 shows that low density materials, timber and vegetable matter are occurring in very limited quantities. This can be attributed to the quality control procedures built into the processing of the material, which have been discussed in section 4.2.1.

5.1.6 Hardness

5.1.6.1 Los Angeles abrasion loss

The results for all the samples tested for Los Angeles (LA) abrasion loss are shown in Table 5.5. The results for the six monthly samples show a consistent LA value of 29% and one value of 30% for MS3. The consistency of values is interesting to note, given the wide range in both strength and quality of the concrete used to produce the RCA. The six monthly samples are all well within the current VicRoads specification limits of 35% and 40% respectively for use as a lower and upper subbase material. Fielding and McHaffie (1992) reported that the LA abrasion loss of a typical Western Victorian aggregate, the major area of supply for the original concrete, is between 10 and 30%.

Table 5.5: Los Angeles abrasion loss values

Sample	LA Abrasion Loss %
MS1	29
MS2	29
MS3	30
MS4	29
MS5	29
MS6	29

5.1.6.2 Particle breakdown under compaction

When an aggregate is compacted it is important that an excessive amount of fines is not created as this can reduce the amount of direct contact between the larger particles and thereby reduce the stiffness and strength of the pavement. Permeability of the material will also decrease with an increase of the fine particles, which may cause problems in some applications.

The particle breakdown under Modified and Standard compaction of RCA is shown in Table 5.6. The results shown are for a single test performed on a material taken from bulk sample (MS1), separate gradings were performed on the two samples before compaction. As expected, the greater breakdown occurs when Modified energy is used. An average breakdown across all particle sizes (26mm not included) of 5.63% occurred using Modified energy, compared to 1.73% for standard energy. The amount of breakdown for both compaction energies is comparable with a high quality sandstone material (Low, 1994). After compaction, both samples are still fall between the VicRoads upper and lower grading limits for a class 3 RCA (see Figure 5.3).

Table 5.6: RCA particle breakdown under Modified and Standard compaction

Particle Size (mm)	Modified Compaction			Standard Compaction		
	Pre-Compaction Grading (%)	Post-Compaction Grading (%)	Change in Grading (%)	Pre-Compaction Grading (%)	Post-Compaction Grading (%)	Change in Grading (%)
26.5	100	100	0	100	100	0
19	97	100	3	96	98	2
13.2	80	88	8	81	82	1
9.5	66	72	6	66	68	2
4.75	49	56	7	47	49	2
2.36	37	45	8	36	37	1
1.18	28	34	6	27	29	2
0.600	23	29	6	21	23	2
0.425	19	25	6	17	19	2
0.300	15	21	6	13	16	3
0.150	10	14	4	9	10	1
0.075	7	10	3	6	7	1
	Average increase in particle breakdown (%)		5.63	Average increase in particle breakdown (%)		1.73

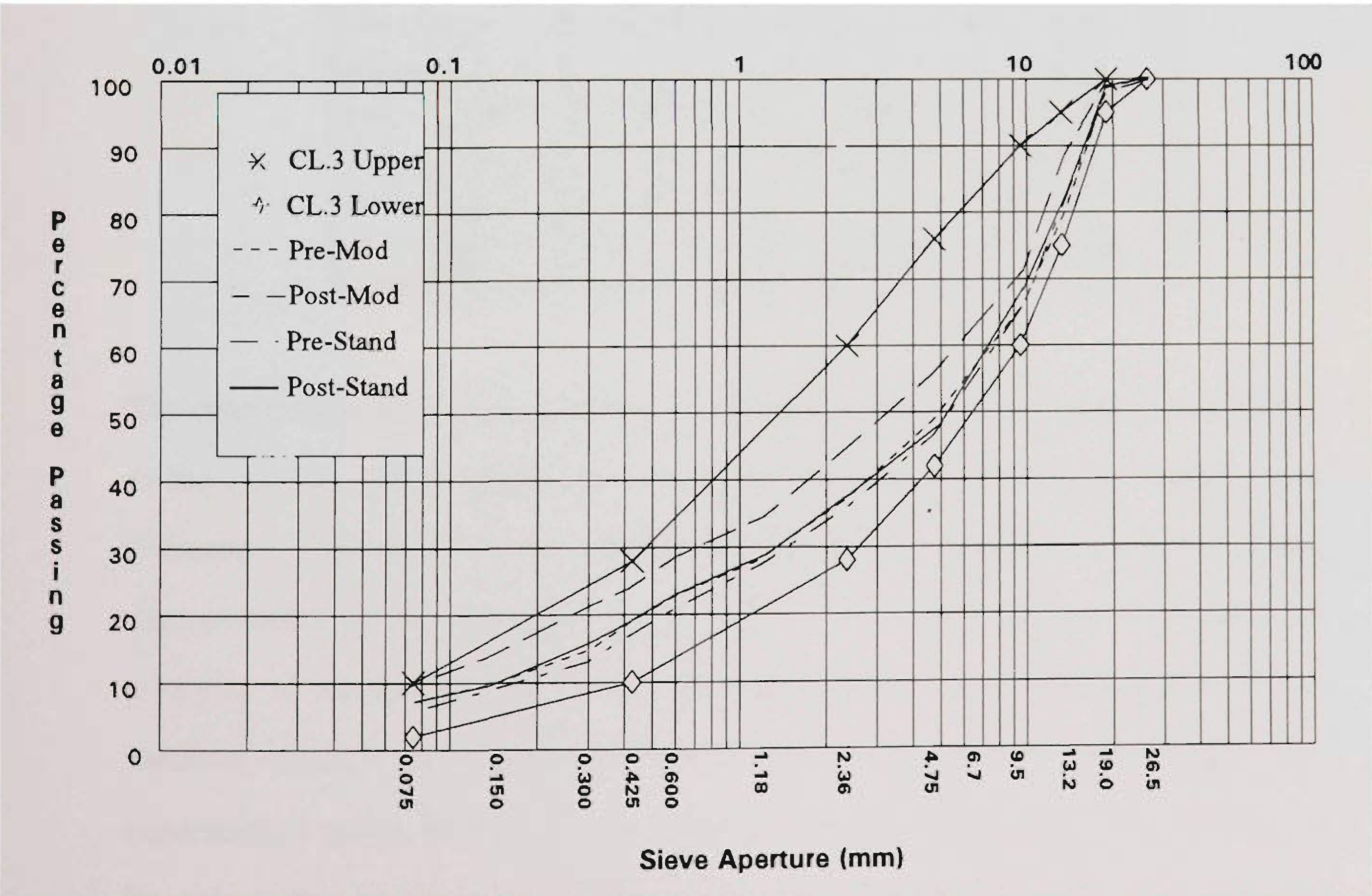


Figure 5.3: Particle breakdown under compaction

5.1.7 Attached cement paste (ACP), specific gravity and moisture absorption

When waste concrete is recycled into an aggregate cement paste remains attached to the original NA. It is this attached cement paste which gives RCA engineering properties that vary from NA and is the fundamental difference between the two materials. Table 5.7 shows the results for attached cement paste, specific gravity and moisture absorption carried out on the first of the commercial RCA samples (MS1), for a range of particle sizes.

Table 5.7: Attached cement paste, moisture absorption and specific gravity of RCA

Particle Size (mm)	Attached Cement Paste (%) (By mass)	Moisture Absorption (%)	Specific Gravity (t/m^3)
19.0	21.8	2.72	2.68
13.2	24.0	4.10	2.67
9.5	31.1	4.85	2.65
4.75	38.8	6.31	2.62
2.36	48.6	8.43	2.58
1.18	55.5	10.25	2.51

The relationship between particle size and attached is shown in Figure 5.4. Clearly, as the particle size increases the percentage by weight of attached cement paste decreases. This is to be expected given the earlier discussion on the crushing characteristics of the material (section 5.1.1). The coarse aggregate is made up primarily of natural aggregate, only 21.8% of cement paste is attached to 19mm particles, whereas the 1.18mm particles have 55.5% of attached cement paste. The experimental values for particle sizes between 2.36mm and 19.0mm are plotted on a log axis against the percentage by weight of attached cement paste. From this the following expression was obtained by straight-line regression analysis:

$$\text{Attached cement paste} = -12.766\ \mathrm{Ln}(x) + 58.703 \qquad (5.2)$$

where, x = particle size (mm)

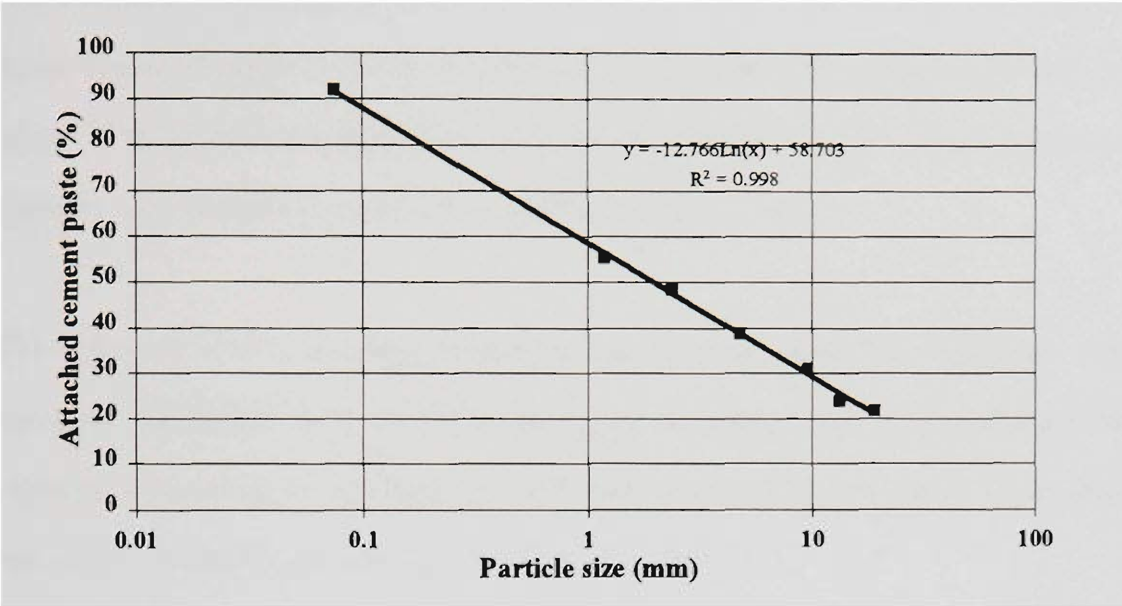


Figure 5.4: Relationship between particle size and attached cement paste

The examination of particles under 1mm was not practical using the hydrochloric acid method, although it was attempted. The problem was in separating and sorting accurately the very small natural aggregate particles from the cement paste. Instead, an alternative approach was used to determine whether the regression equation (5.2) could be used for particles smaller than 1.18mm.

The particle sizes (column A) shown in Table 5.8 has been used in equation 5.1 to estimate the percentage of attached cement paste, shown in column B. The original grading of the material (C) is also included, from this the percentage of material retained on each of the individual sieves has been calculated (D). In order to determine the total quantity of attached cement paste for each of the particle sizes, columns B and D are multiplied , giving the amount of attached cement paste for the particle expressed as a percentage of the total sample mass (E). A summation of column E gives a final percentage of attached cement paste for the entire sample of 50.9%. As all of the waste concrete deposited at the commercial concrete recycler is of an unknown mix design, an estimate of the amount of cement paste within a typical concrete mix is required. Based on mix designs contained within the Cement and Concrete Associations 'Guide to Concrete Construction' (1982), concrete with a compressive strength between 15MPa and 50MPa, has approximately 49.5% cement paste. The typical strength of waste concrete deposited at the commercial concrete recycler was earlier estimated to be 28MPa (section 4.2.2).

The value of 50.9% attached cement paste obtained using the regression equation compares favorably with 49.5% for a typical concrete mix. This indicates that the regression equation (5.1) could be used with reasonable confidence to estimate the amount of cement paste attached to RCA particles.

Table 5.8: Determination of attached cement paste (ACP) for RCA fines

(A) Particle Size (mm)	**(B) Estimated ACP** (By mass) (Equation 5.1)	**(C) Original Grading** % Passing	**(D) Percentage retained on sieve**	**(E)=(B)x(D) Percentage of the total ACP** (By mass)
19	21.1	97	3	0.6
13.2	25.8	80	17	4.4
9.5	30.0	66	14	4.2
4.75	38.8	49	17	6.6
2.36	47.7	37	12	5.7
1.18	56.6	28	9	5.1
0.425	69.6	19	9	6.3
0.075	91.8	7	12	11.0
Pan	100.0	-	7	7
Estimated ACP as a percentage of total sample mass				**50.9%**

The attached cement paste values obtained in this investigation are higher than those of the BSCJ (1978), who used the hydrochloric acid method but lower than those by Hansen and Narud (1983b) using microscopical examination. Both of these investigations were reported in greater detail in section 2.5.2.

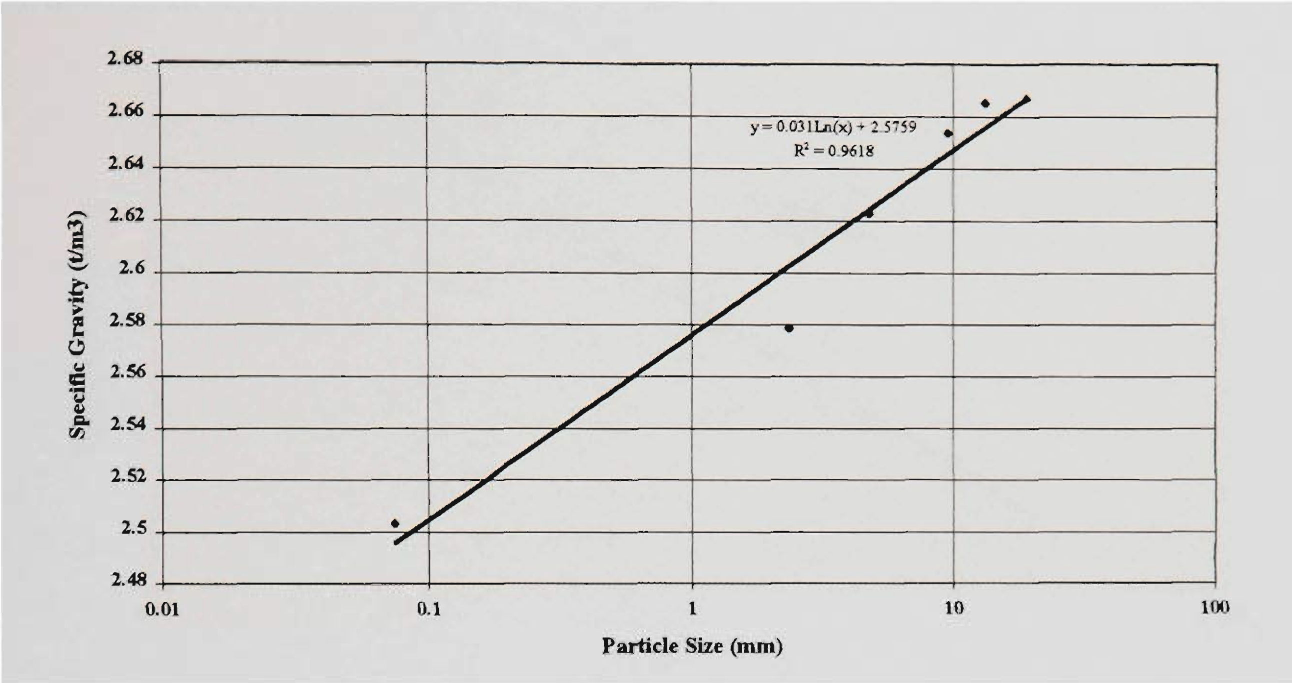


Figure 5.5: Relationship between particle size and specific gravity

The moisture absorption and specific gravity of RCA are directly related to the quantity of attached cement paste, which in turn is influenced by particle size. This can clearly be observed in Table 5.7. The attached cement paste has a lower specific gravity and is also more moisture absorbent than NA. Figure 5.5 clearly shows the relationship between particle size and specific gravity. As particle size decreases, the amount of attached cement paste increases. The greater the quantity of low-density cement paste, specific gravity is reduced. The same effect can be observed in the relationship between particle size and moisture absorption. Cement paste is significantly more moisture absorbent than NA, as the amount of attached cement paste increases, so to does the overall moisture absorption of the material. This is shown in Figure 5.6.

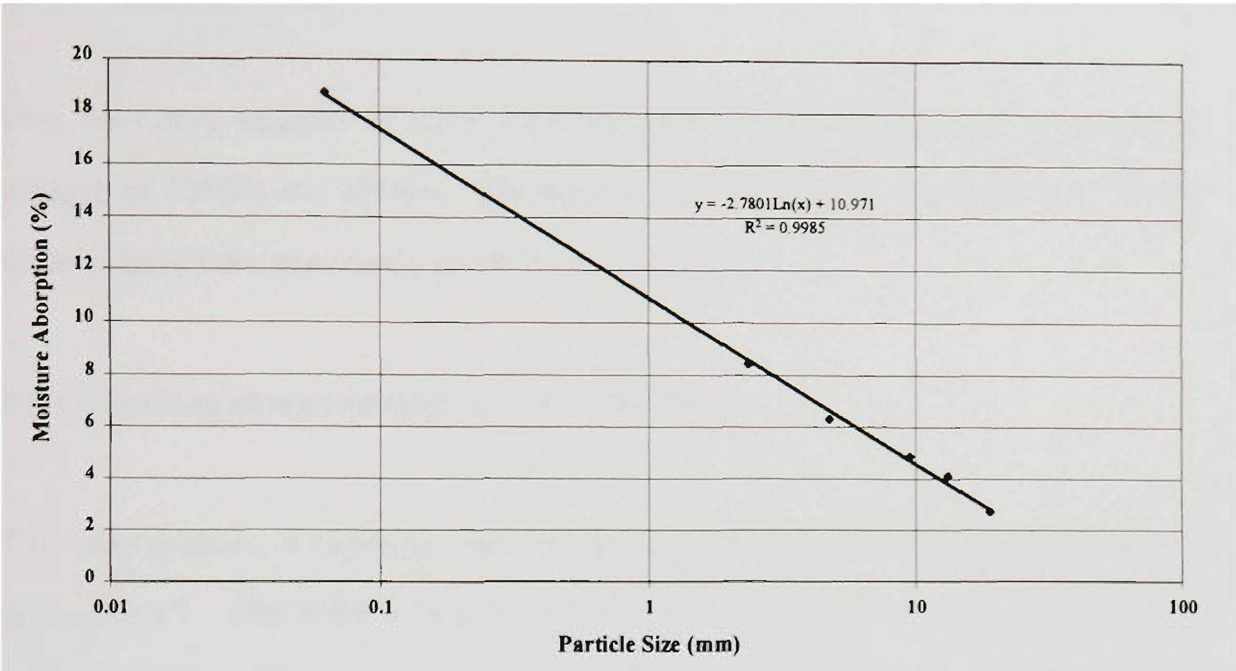


Figure 5.6: Relationship between particle size and moisture absorption

Under the reporting provisions of AS1141.5(1974) and AS1141.6(1974) coarse RCA particles tested (≥ 4.75mm) had an SG of 2.66 t/m^3 and a moisture absorption of 5.7%. The fine RCA (particles < 4.75mm) had an SG of 2.40 t/m^3 and a moisture absorption of 11.3%. By combining the two fractions an overall SG of 2.55 t/m^3 and a moisture absorption of 8.5% was obtained.

These values do vary from the most common crushed rock in the Western Suburbs of Melbourne, basalt. The ACP has the effect of lowering the SG and raising the moisture absorption properties of RCA, when compared to virgin crushed rock. Older and Newer volcanic basalts have SG values between 2.63 t/m^3 and 3.07 t/m^3. The moisture absorption values range between 0.2% and 3.7% (Fielding and McHaffie, 1992).

5.2 LABORATORY-PRODUCED RCA.

Two laboratory samples of RCA were produced from concretes with compressive strength of 32MPa and 80MPa. The procedures followed for the production of this material have been previously given in Section 4.2.2.

5.2.1 Crushing characteristics, texture and shape

The general mode of crushing observed in the 80MPa and 32MPa sample is shown in Figure 5.7. The 80MPa sample tended to crush through the cement paste and basalt aggregate alike, with shear planes through the natural aggregate more visible. The 32MPa sample tended to shear through the cement paste leaving the natural aggregate relatively undamaged. The 32MPa sample has approximately 74% cement paste coverage of the original aggregate particles, compared to 68% for the 80MPa sample. This tends to support the theory that harder concrete has more shearing through the original aggregate than weaker concrete. It was previously discussed in section 5.1.1 that the commercial-RCA has approximately 80% cement paste coverage and a relatively low amount of shearing through the original aggregate.

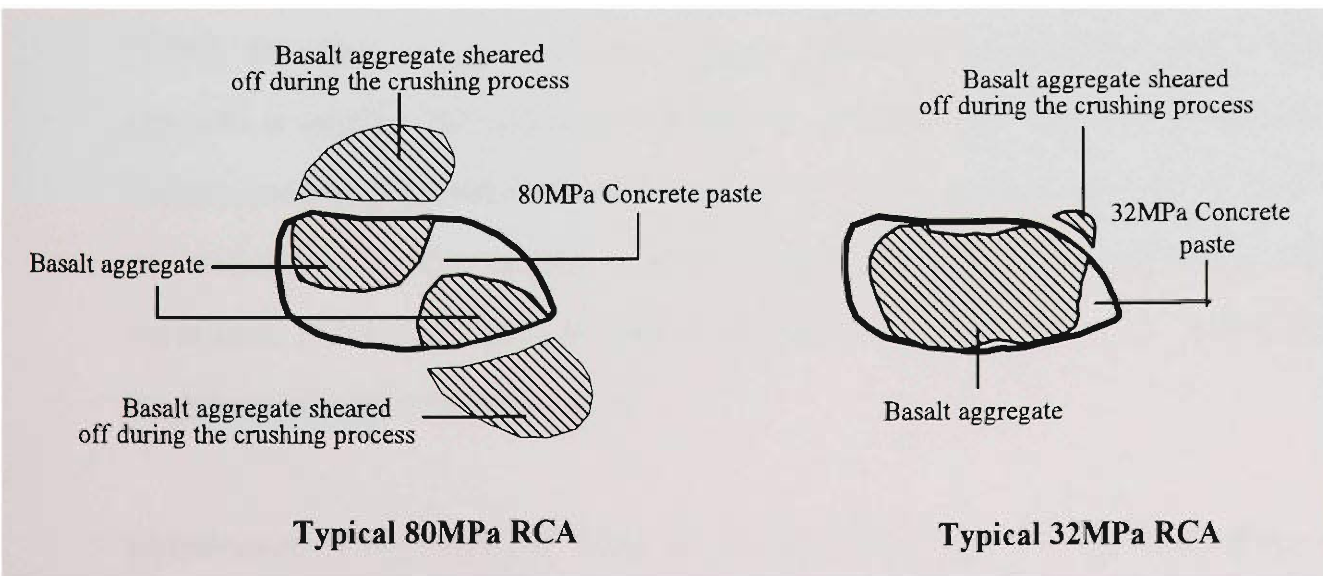


Figure 5.7: Crushing behaviour of laboratory-produced RCA samples

The 80MPa sample has a smoother texture than the 32MPa sample, which in turn is smoother than the commercially produced RCA. The smoothness of the 80MPa sample is probably due to a tendency to shatter when crushed, creating clear shear faces. The 32MPa and commercial RCA seem to be crushed more by a grinding process, which will more than likely to produce a rougher surface texture

The most obvious difference between the two aggregates is the particle shape. The 80MPa sample had a flakiness index (AS1141.15, 1988) of 25 compared with 18 for the 32MPa sample. The 80MPa sample appeared to have more angular and flat particles than the 32MPa sample. Neither samples had the cubical shape of material produced by Alex Fraser Pty.Ltd., although this may be attributed to the different crushing processes used.

5.2.2 Particle size distribution

The particle size distributions of the two aggregates are shown in Table 5.9. Both aggregates are very coarse with relatively few fines and are not within the grading requirements of VicRoads specification 820 'Crushed concrete for subbase pavement' (1992), for either an upper or lower subbase material. This generally occurs when concrete is crushed through small laboratory crushers, and has been reported by Hansen and Narud (1983b) and the BCSJ (1978). These small crushers do not give a true indication of what can be achieved by full scale production plants. Practical experience has shown that any desired grading can be achieved with appropriate modification to the production plant.

Examination of the results in Table 5.9 clearly shows that the 32MPa produces a finer grading than the 80MPa sample. The 32MPa sample has a greater percentage passing for all of the particle sizes examined, with the exception of the 19mm particles. This is to be expected as the 32MPa cement paste is more readily broken down than the 80MPa material. Work carried out by Ravindrarajah and Tam (1985) showed that the percentage of material less than 5mm in size increased as the strength decreased for three concrete mixes of 22MPa, 30MPa and 37MPa processed through a laboratory crusher.

Table 5.9: Particle size distributions for 80MPa and 32MPa samples

Particle size (mm)	80MPa Grading	32MPa Grading
	Percentage passing	
26.5	100	100
19.0	100	98.5
13.2	74.3	75.9
9.5	53.3	59.8
4.75	32.5	40.3
2.36	21.0	27.0
0.425	6.1	9.3
0.075	0.9	4.6

5.2.3 Hardness

5.2.3 1 Los Angeles abrasion test

The 80MPa sample had a LA loss of 26% and the 32MPa of 27%. The difference between the two samples of only 1% is less than expected considering the large difference in the strength of concretes. The basalt aggregate used to produce the two concretes had a LA loss of 17%. This indicates that the cement paste attached to the original stone is the major source of the breakdown and causes a significant rise in the LA In section 5.1.7.1 of this thesis the typical LA loss for a commercially produced recycled concrete aggregate was shown to be 29%. The commercial RCA was made from a concrete of unknown strength and age yet the LA loss varies only slightly with the 32 and 80MPa samples

The relatively small variation in LA loss between the 32MPa, 80MPa and commercial RCA, maybe partly explained by variations in particle shape. The 80MPa sample as previously discussed is relatively flat in shape, as indicated by the flakiness index of 25%. This compares to a flakiness index of 18% for the 32MPa and an average of 12.5% for the 6 commercial RCA samples.

5.2.3.2 Particle breakdown under compaction

When an aggregate is compacted it is important that an excessive amount of fines not be created as these can reduce the amount of direct contact between the larger particles and therefore reduce the stiffness and strength of the pavement. Permeability of the material will also be reduced, which may cause problems in some applications.

Due to a shortage of material, the particle breakdown under compaction test was carried out in conjunction with a 3000 pulse repeated triaxial loading test. The two samples were graded as shown in Table 5.10 and then compacted using Modified compaction (2703kJ/m^3 of energy). Ten layers were used to ensure uniform compaction of the material throughout the specimen. It had been previously observed that five compaction layers for a 200mm high sample resulted in poor compaction at the layer interfaces, where air voids were clearly visible. The use of ten compaction layers and a 3000 pulse triaxial test has produced a more severe test than would normally be the case with a five layer Modified compaction procedure and no load pulses.

Examination of Table 5.10 shows that the two samples had a similar particle breakdown under compaction. The average breakdown across all particles for the 80MPa sample was 5.8% and 5.5% for the 32MPa respectively. These values compare with the 5.63% breakdown for the commercial sample discussed in section 5.1.7.2, although the testing method differs slightly. Figure 5.8 shows that after compaction both samples still remain within the grading limits of VicRoads specification 820.

Table 5.10: Particle breakdown under compaction

		80 MPa sample		32 MPa sample	
Particle size (mm)	**Pre-compaction Grading**	**Post-compaction Grading**	**Change in Grading**	**Post-compaction Grading**	**Change in Grading**
26.5	100	100	0	100	0
19.0	96.1	98.4	2.3	99.0	2.9
13.2	78.9	87.0	7.1	86.4	6.5
9.5	66.1	76.4	10.3	72.2	6.1
4.75	49.4	57.7	8.3	58.4	9.0
2.36	40.2	47.1	6.9	47.5	7.3
0.425	20.3	24.7	4.4	25.0	4.7
0.075	6.9	8.2	1.3	8.8	1.9

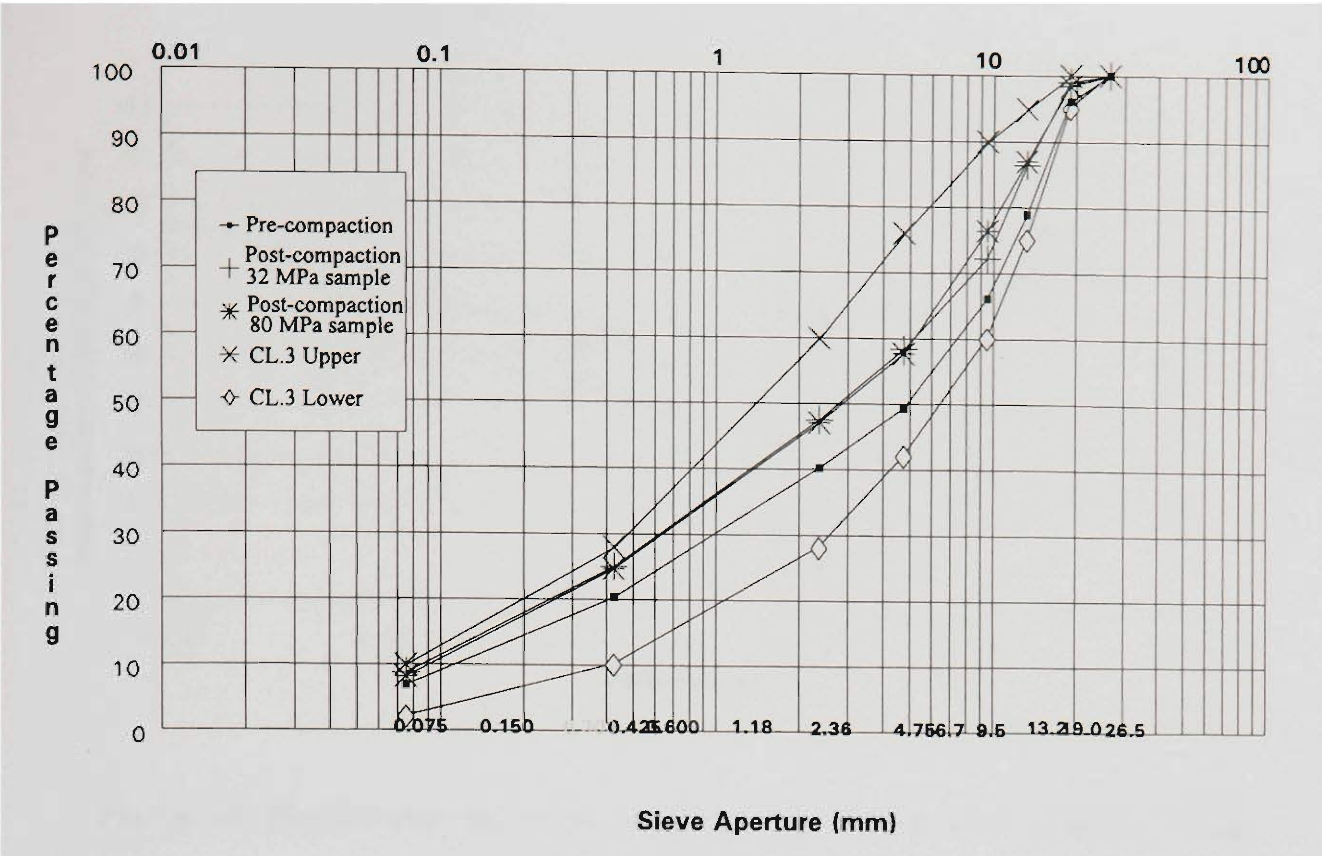


Figure 5.8: Influence of source strength on particle breakdown under compaction.

5.2.4 Attached cement paste, specific gravity and moisture absorption

As with the commercial RCA the amount of attached cement paste is dependent on the particle size, as shown in Table 5.10 and Figure 5.9. As the particle size increases the amount of attached cement paste decreases.

Table 5.11: Percentage of attached cement paste (by mass)

Particle Size (mm)	32MPa sample	80MPa sample	Commercial RCA sample
19.0	31.5	36.7	21.1
13.2	34.2	41.6	25.8
9.5	40.9	54.1	30.0
4.75	53.4	56.4	28.8
2.36	67.2	61.5	47.7
< 2.36	76.6	65.8	92.0

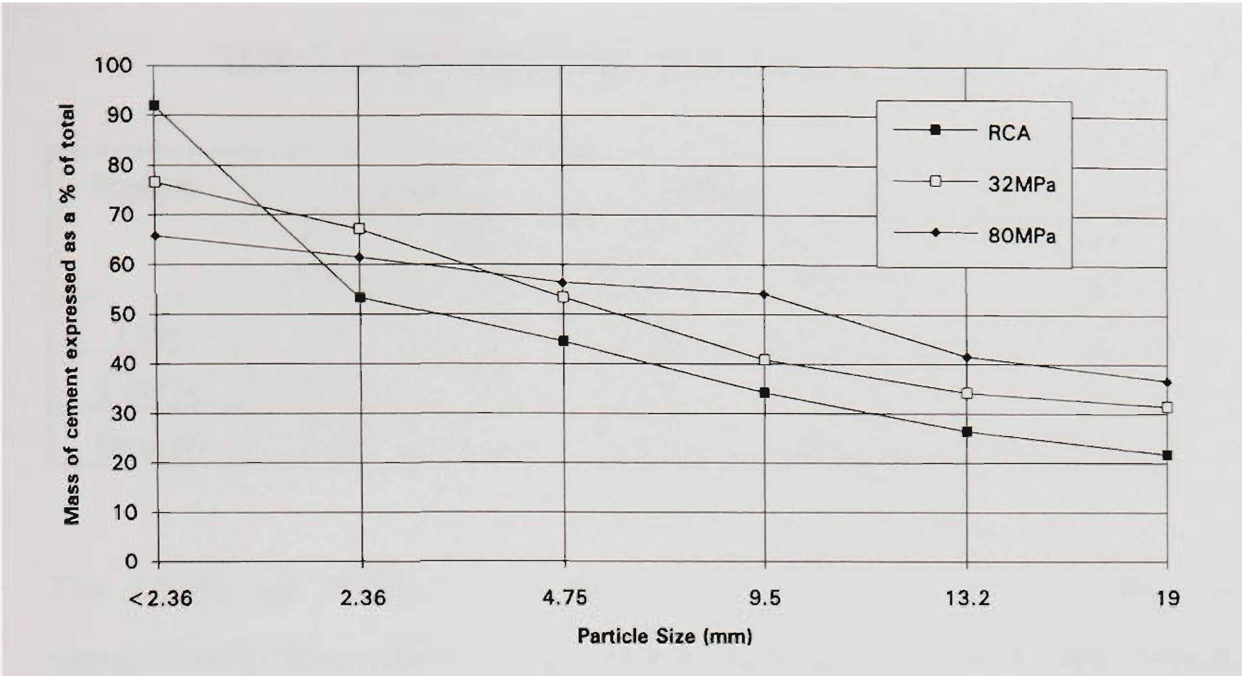


Figure 5.9: Particle size versus percentage of attached cement paste for RCA, 32MPa and 80MPa samples.

As the source concrete becomes stronger, 32MPa up to 80MPa, the distribution of cement paste becomes more even across the range of particle sizes. Earlier observations on the crushing characteristics (see 5.2.1) of the 80MPa sample were that the material crushed through cement paste and stone alike. Shear planes through the source aggregate were common, whereas this did not occur to the same extent in the 32MPa and RCA samples. It seems possible that, if a cement paste with the same strength as the source rock was used to make the concrete, the distribution of attached cement paste may be equal across all particle sizes.

Table 5.12 summaries the specific gravity and moisture absorption characteristics of the 32MPa and 80MPa samples. The values for the RCA sample are also included for comparative purposes.

Table 5.12: Specific gravity and moisture absorption

Sample	32MPa		80MPa		RCA	
	S.G (t/m^3)	M.A (%)	S.G (t/m^3)	M.A (%)	S.G (t/m^3)	M.A (%)
Fine	2.48	10.8	2.52	9.7	2.40	11.3
Coarse	2.69	3.84	2.72	4.51	2.66	5.7
Overall	2.62	8.16	2.64	7.42	2.55	8.53

The 32MPa and 80MPa have similar specific gravity and moisture absorption characteristics. The concrete density of the 80MPa sample is 50kg/m^3 higher than the 32MPa sample, due to the higher cement content. This maybe the cause of the slight variation in SG between the two samples. Both laboratory samples have specific gravity values slightly higher than the RCA sample. The 80MPa sample has the least moisture absorption of the three samples probably because it is the least porous of the three samples. In addition, it also has the coarsest grading (see Table 5.9), therefore yielding the lowest surface area to mass ratio of the three samples. As moisture absorption is a function of surface area a lower rate would be expected for the 80MPa sample and a higher value for the RCA, as it has the greatest quantity of fine material.

5.3 PRELIMINARY EXAMINATION OF THE BEHAVIOUR OF RCA UNDER REPEATED TRIAXIAL LOADING (RTL).

The RTL test provides data for the use of a mechanistic procedure in the design of road pavements. This method of design was adopted by the National Association of Australian State Road Authorities (NAASRA) in 1987. The tests carried out in this investigation give only preliminary data on the resilient modulus characteristics of RCA under repeated loading. The information presented should enable a RCA pavement to be designed in accordance with the procedure presented in the NAASRA Pavement Design manual. It is acknowledged that further more detailed testing of the material is required to gain a greater appreciation of its behaviour under repeated loading.

In addition to the resilient modulus work, a test was also carried out to determine the permanent strain characteristics of RCA over 120,000 load pulses. The performance of the material was then compared to earlier work carried out by the CSIRO on two basalt aggregates, using the same test equipment and procedures.

5.3.1 Compaction details

The compaction details for the eight, stage modulus tests are given in Table 5.13. The details of the compaction procedure are given in Appendix B. In general, the samples were compacted to 95% of maximum dry density (MDD) at approximately 80% of the optimum moisture content (OMC). A comparison is also given within Table 5.13 of the relative density of all the samples compared with test 1 (RCA).

Table 5.13: Compaction details

Test No.	1	2	3	4	5	6	7	8
Description	RCA No-cure	RCA 72% OMC	80MPa	32MPa	RCA + 15% Brick	RCA + 30% Brick	RCA 7Day	RCA 28Day
Water (%)	9.53	8.59	8.78	9.28	9.88	10.51	9.99	9.79
OMC	12.0	12.0	10.8	11.3	12.4	13.3	12.0	12.0
MDD (t/m^3)	2.03	2.03	2.11	2.18	1.94	1.86	2.03	2.03
% of OMC	79.4	71.6	81.3	82.1	79.7	79.0	83.2	81.6
% of MDD	95.8	95.6	96.4	96.2	95.6	95.3	95.5	96.3
MDD relative to Test 1 (%)	100.0	99.8	104.6	107.8	95.4	91.1	99.7	100.5

5.3.2 Stage modulus tests

5.3.2.1 RCA with added brick

Before the brick was added it was sieved down into separate proportions and recombined into the same grading as the RCA, which had undergone similar processing to ensure that all samples had an identical grading.

Figure 5.10 shows the which the addition of 15% and 30% brick had on the resilient modulus of RCA. Resilient modulus has been plotted versus the 29 stress stages which are detailed in Table 4.4. For comparative purposes the RCA (Test 1) sample has also been included.

The RCA sample is clearly higher than the 30% added brick across all 29 stress stages. In general the 15%BR has lower values then the RCA sample, with the exception of stages 7, 18, 24, 25 and 28, but always exceeds the modulus values of the 30%BR sample. From these results it can be stated that an increase in the amount of brick has lowered the resilient modulus. Table 5.12 shows that the three samples were compacted using a similar percentage of the . This indicates that variations in modulus are not due to differences in compaction.

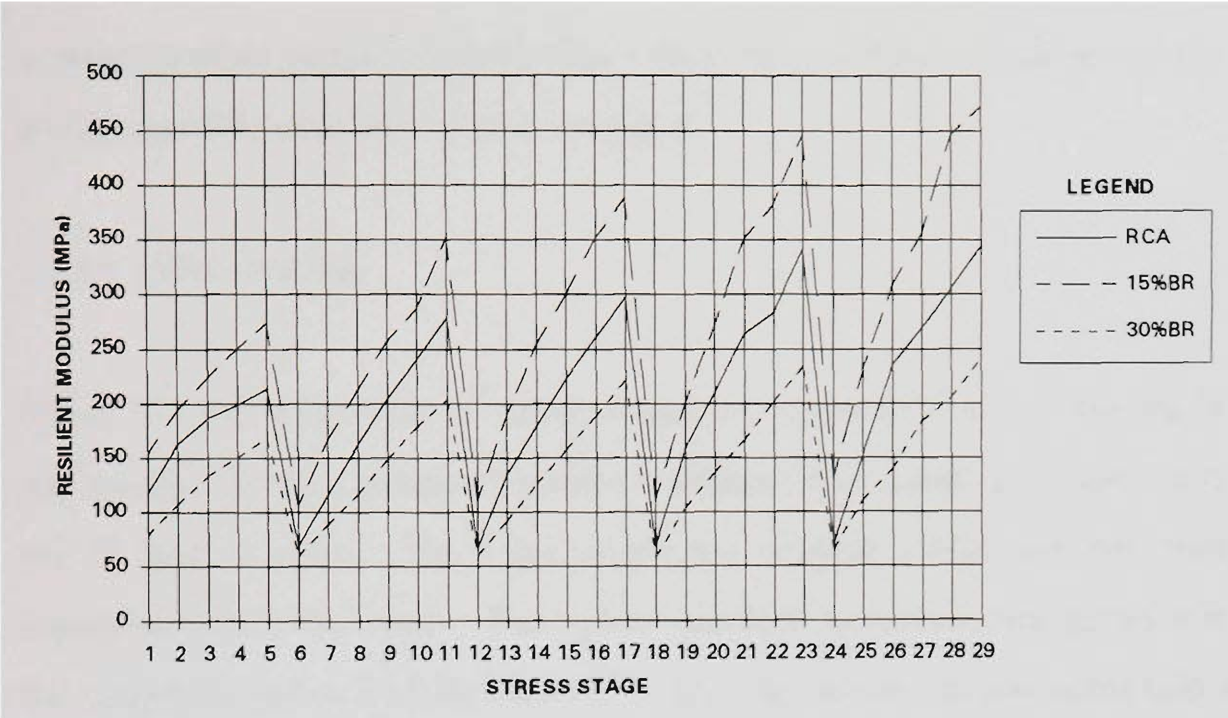


Figure 5.10: Effect of added brick on resilient modulus

The reduction of resilient modulus due to the addition of brick is most likely caused by a combination of the following two factors. Firstly, the addition of brick has led to a lower MDD relative to the MDD for the RCA sample. Examination of Table 5.12 shows that addition of 15% and 30% of brick to the RCA has reduced the MDD by 4.6% and 8.9% receptively. Vuong (1991) reported that the resilient modulus of a material decreases as the density of the sample is lowered. The second consideration is that brick is a slightly softer material than RCA. An LA abrasion loss of 40% was obtained for a 100% brick sample compared to 29% for the RCA sample. Being a softer material an increase in particle breakdown under compaction and during the test is expected. This would reduce the interparticle contact between the larger aggregate particles, reducing the stiffness of the material.

This preliminary investigation indicates the addition of brick to RCA reduces stiffness. Based on the average resilient modulus obtained across the 29 stress stages a reduction of six percent occurred when 15% by mass of brick was added and this increased to 29% when 30% of brick was added.

5.3.2.2 Effect of curing

Figure 5.11 shows the effect on resilient modulus of curing RCA over 7 day and 28 day periods. Clearly a significant increase in stiffness has occurred, particularly after the 28 days of curing. The 7 day sample has recorded a slight increase when compared to the RCA sample. This increase should be assessed in conjunction with the compaction details given in Table 5.12. The 7Day sample was compacted with a higher percentage of the OMC (83.2%) compared to the RCA (79.4%) and 28Day (81.6%) samples. The increase in the amount of moisture used may explain why only a small increase in stiffness has occurred after the initial seven days of curing. The percentage of MDD of the three samples was similar and would not have been a cause of variations in the results.

The large increase in modulus between the RCA and 28Day samples indicates that some form of 'residual setting' has occurred. The two proposed mechanisms for 'residual setting' previously discussed in section 2.5.10 - resetting of previously unhydrated cement and/or carbonation of the calcium hydroxide within the material. However, it was beyond the scope of this investigation to quantify the effect these two mechanisms had on the resilient modulus values obtained. Further work should be carried out on the long-term 'residual setting' characteristics of RCA when used in an unbound pavement. This is particularly important as the RCA may 'set' over-time resulting in the pavement behaving in a bound state. This potentially could clause problems with cracking as the pavement may have been designed to operate as a flexible one. Further investigation is this area is warranted.

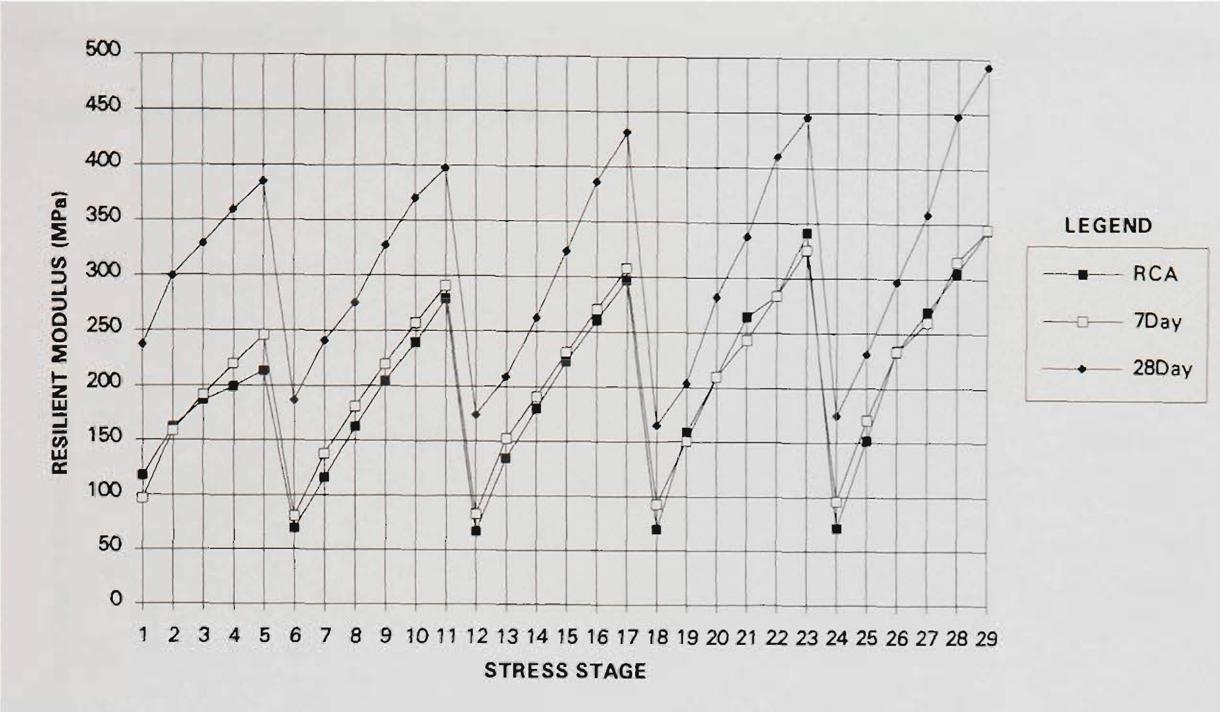


Figure 5.11: Effect of curing on resilient modulus

5.3.2.3 Effect of source concrete strength

Figure 5.11 compares the stage modulus results of the two laboratory produced samples to that of the standard RCA sample. Unfortunately due to a puncturing of the membrane the 80MPa sample was terminated after the 14th stress stage. Table 5.12 shows the compaction details of the three samples. The two laboratory samples have a higher MDD than the RCA sample but have been compacted using a higher percentage of the optimum moisture content.

Figure 5.12 indicates that the 32MPa and 80MPa samples have higher resilient modulus values between stress stages 1 to 9, where the inverse stress ratio is between 0.1 and 0.2. After this point the RCA has the higher modulus values are higher than both the laboratory sample. Taking into account the slight variations in moisture contents between the three samples, the modulus results are comparable. However, before any generalization about the influence of source concrete strength on resilient modulus properties can be made, further testing is required.

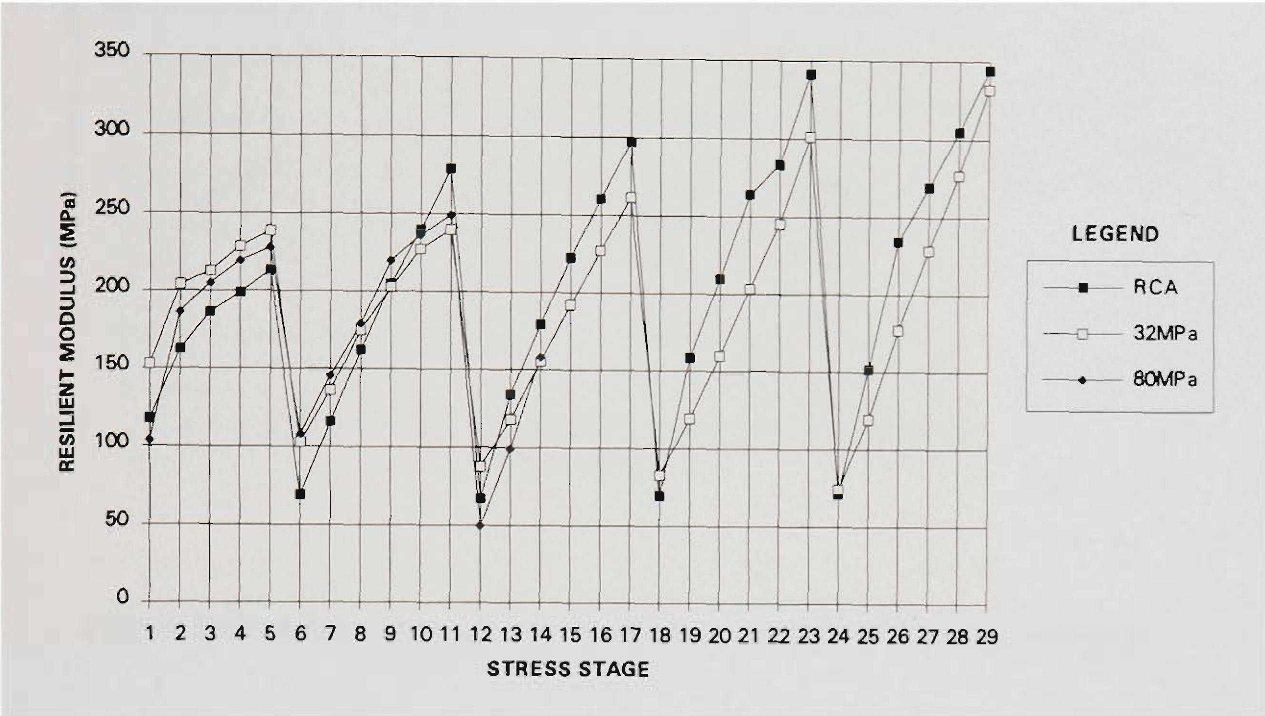


Figure 5.12: Effect of source concrete strength on resilient modulus

5.3.2.4 Effect of compactive moisture content

Figure 5.13 shows the effect of a reduction in the compactive moisture content from approximately 80% of OMC 72% of OMC. Clearly the reduction in the moisture content has resulted in a significant rise in the resilient modulus. It has been universally found (APRG, 1991) that non-cohesive granular materials have an increase in resilient modulus as the compactive moisture content decreases, for a constant MDD. The resilient modulus values obtained with the reduced moisture content were only slightly lower than those for the 28 day cured sample.

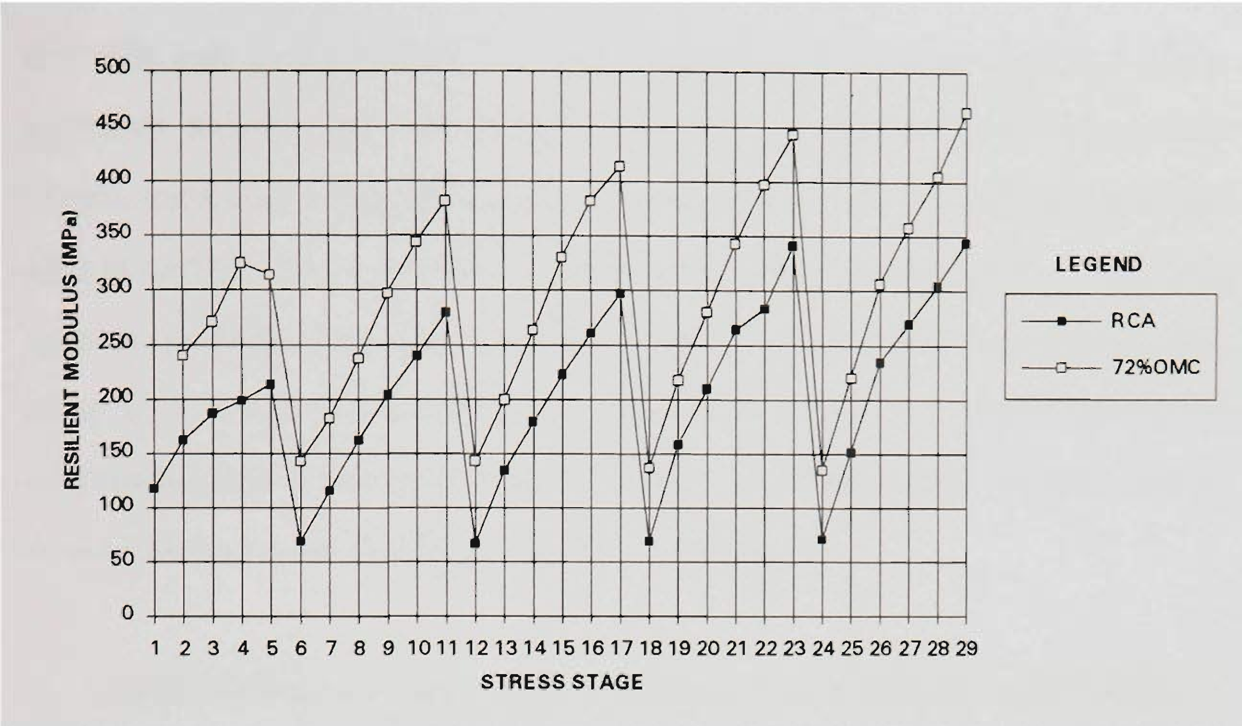


Figure 5.13: Effect of compactive moisture content on resilient modulus

5.3.3 The K- θ Model.

The K- θ model is used to estimate the resilient modulus of a material under loading, based on experimental data. It assumes that the modulus of any granular, unbound material is strongly influenced by the stress levels to which it is subjected and, as the stresses increase, so too does the modulus. The relationship is shown by the following non-linear equation,

$$M_r = K_1\theta^{K_2} \quad (5.3)$$

Where;

K_1, K_2: Experimental test constants.

θ: Bulk Stress (kPa)

M_r: Resilient modulus (MPa)

The experimental constants of the equation (K_1,K_2) were determined by taking the logarithms of both the bulk stress and resilient modulus and then producing a scatter plot with bulk stress on the x-axis and resilient modulus on the y-axis. A linear regression analysis was then performed using the computer spreadsheet package Excel4, producing a regression equation in the form y = mx + c, based on the least squares method. The constant K_1 is equal to the antilog of the y intercept and K_2 is equal to the slope of the line. Table 5.14 shows the experimental constants for each of the tests, as well as the correlation coefficient 'r'. Figure 5.12 shows a plot of the relationship, bulk stress versus resilient modulus. The data used to determine the K-θ relationships for the eight tests is given in Appendix C.

Table 5.14 Experimental constants K_1,K_2 and correlation coefficient (r)

Sample	K_1	K_2	r
RCA	2315	0.720	0.944
7Day	3714	0.652	0.973
28Day	22664	0.429	0.942
15%BR	5996	0.572	0.940
30%BR	4257	0.629	0.971
32MPa	6412	0.550	0.916
75%OMC	7676	0.584	0.965

Rada and Witzak (1981) identified the relationship between K_1 and K_2, that is as K_1 increases, K_2 generally decreases. Higher quality materials were found to have larger K_1 and smaller K_2 values. As K_2 approaches zero the material becomes linear, whereas a larger K_2, based on equation 5.3 results in greater non-linearity. This further implies that a higher K_1 value corresponds to greater shear strength. Further examination of Table 5.14 shows that the 28Day sample has a significantly higher K_2 value than all other samples. This is to be expected given that some 'residual setting' has occurred, which would result in an increase in shear strength. Examination of the RCA sample indicates that before the 'residual setting' has occurred the shear strength is lower and the material behaves in a non-linear fashion.

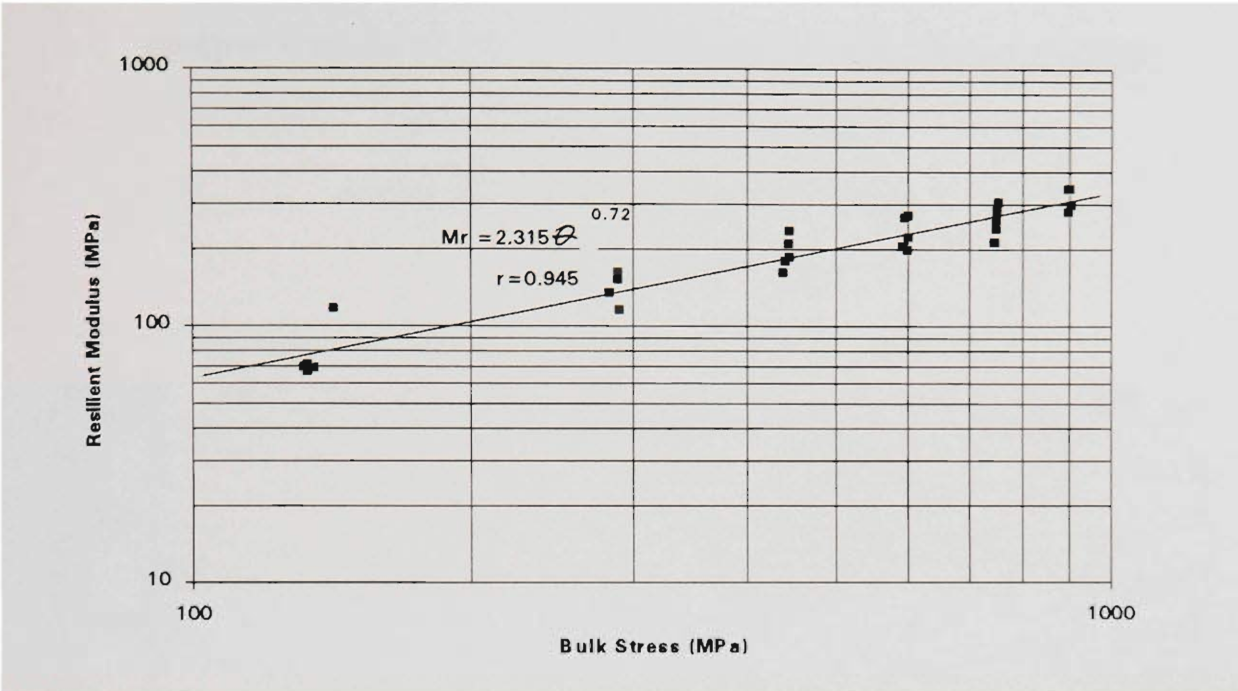


Figure 5.14: Bulk stress versus resilient modulus (RCA)

5.3.4 Resilient Modulus Design Charts.

The use of a design chart to display resilient modulus results has been developed by the Department of Road and Transport, South Australia (MTRD,1989). The charts allow three variables to be displayed simultaneously, vertical stress confining stress and the resilient modulus. Figure 5.15 is the design chart for the RCA sample. It shows contour lines of modulus, or Iso-Moduli, for the various vertical and confining stresses. The design charts are particularly useful when using the mechanistic design procedure in conjunction with a computer pavement stress modelling program, such as CIRCLY. The pavement design is input into CIRCLY which calculates the vertical and horizontal stresses within the pavement at the desired depths. Having estimated the vertical and confining (sum of x and y horizontal stresses components) stresses using CIRCLY, the resilient modulus can be determined using the design chart.

DESIGN CHART 1: RECYCLED CONCRETE AGGREGATE (RCA)

No curing period.- **Linear Model.**

Eq(1): $M_r = 58.04 + 0.166x + 0.9703y$

$r = 0.9702286$

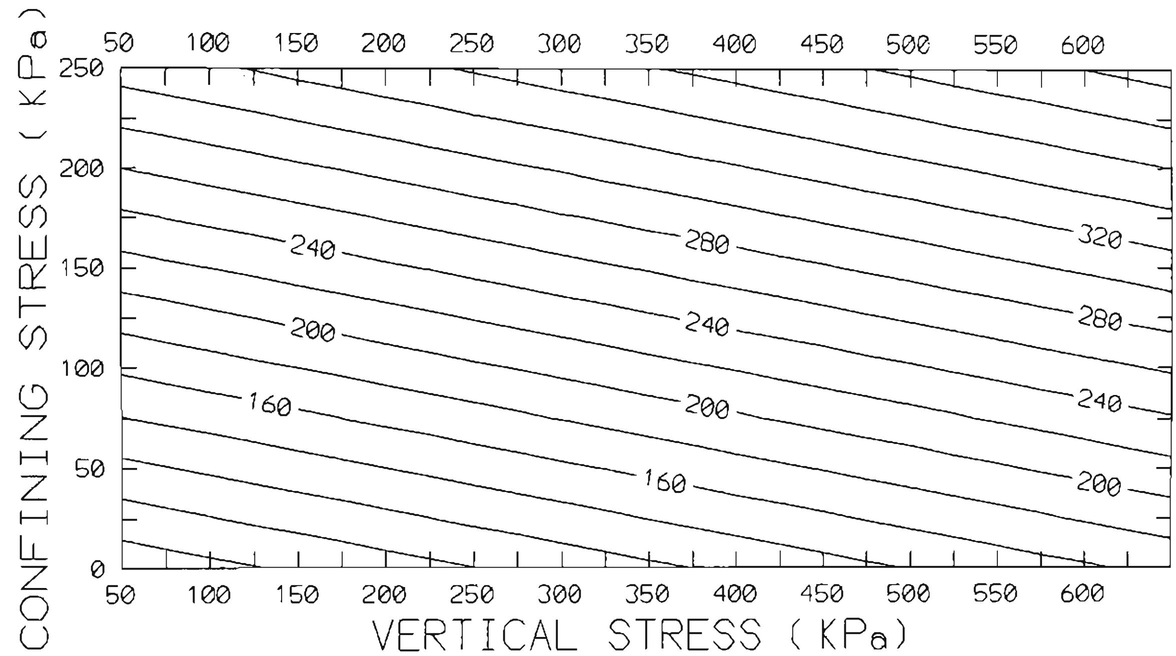


Figure 5.15: Linear Model Design chart for the RCA sample

In Figure 5.15 the contours of resilient modulus have been drawn as straight lines to best fit the experimental data. Appendix C contains the design charts for all stage modulus tests showing both a linear model, as shown in Figure 5.15 and a quadratic model. The use of a quadratic model enables a closer fit of the experimental data. However, it should be noted that for all the linear models a correlation coefficient greater than 0.92 was obtained. Indicating that the relationship between vertical and confining stress versus resilient modulus can be modelled with confidence. The raw data was analyzed using the statistical program Statistica, and a least squares fit criteria was used to produce both models, each design chart also shows the correlation co-efficient 'r' and the equation used to plot the chart. This method of displaying the information was taken to smooth out any irregularities in the results due to a relatively small amount (29) of experimental data points. The South Australian contour plots were calculated using 69 different stress stages and averaged over 3 runs on different samples.

5.3.5 120,000 Pulse permanent strain test

The permanent strain test was carried out over 120,000 load pulses and took approximately five days to complete. The procedures and experimental techniques used have previously been described in section 4.4.5.

In order to assess the relative performance of RCA in the permanent strain test, results for a Deer Park basalt performed by Cole (1982), and on a Ballarat basalt by Shayan and Westgate (1988), have been included. The RCA test was carried out using the same stresses and test conditions as the two basalt's, but some of the material properties of the three samples are different, as shown in Table 5.15.

Table 5.15: RCA and basalt material properties

TEST	RCA	Basalt-1 Cole(1982)	Basalt-2 Shayan(1988)
Grading-Sieve size (mm)			
19	96.1	100	97.9
13.2	78.9	90	87.9
9.5	66.1	80	73.8
4.75	49.4	67	51.2
2.36	40.2	52	36.8
0.425	20.3	21	20.6
0.075	6.9	13	6.9
Plasticity Index	N.P	4	5
O.M.C (%)	12	7.8	7
M.D.D (t/m^3)	2.03	2.34	2.50
% of OMC	95	100	88
% of MDD	98	100	98

5.3.6.1 Results and discussion.

Plots of permanent strain versus the number of loading pulses are given in Figure 5.16. After 100,000 load cycles, the permanent strain for the RCA sample was 0.45%, compared with 4.5% and 5% after 100,000 pulses for the basalt's. The main difference between the curves is that the permanent strain in the RCA remains relatively constant after 10,000 cycles. By contrast, the two basalt samples undergo constantly increasing permanent strain.

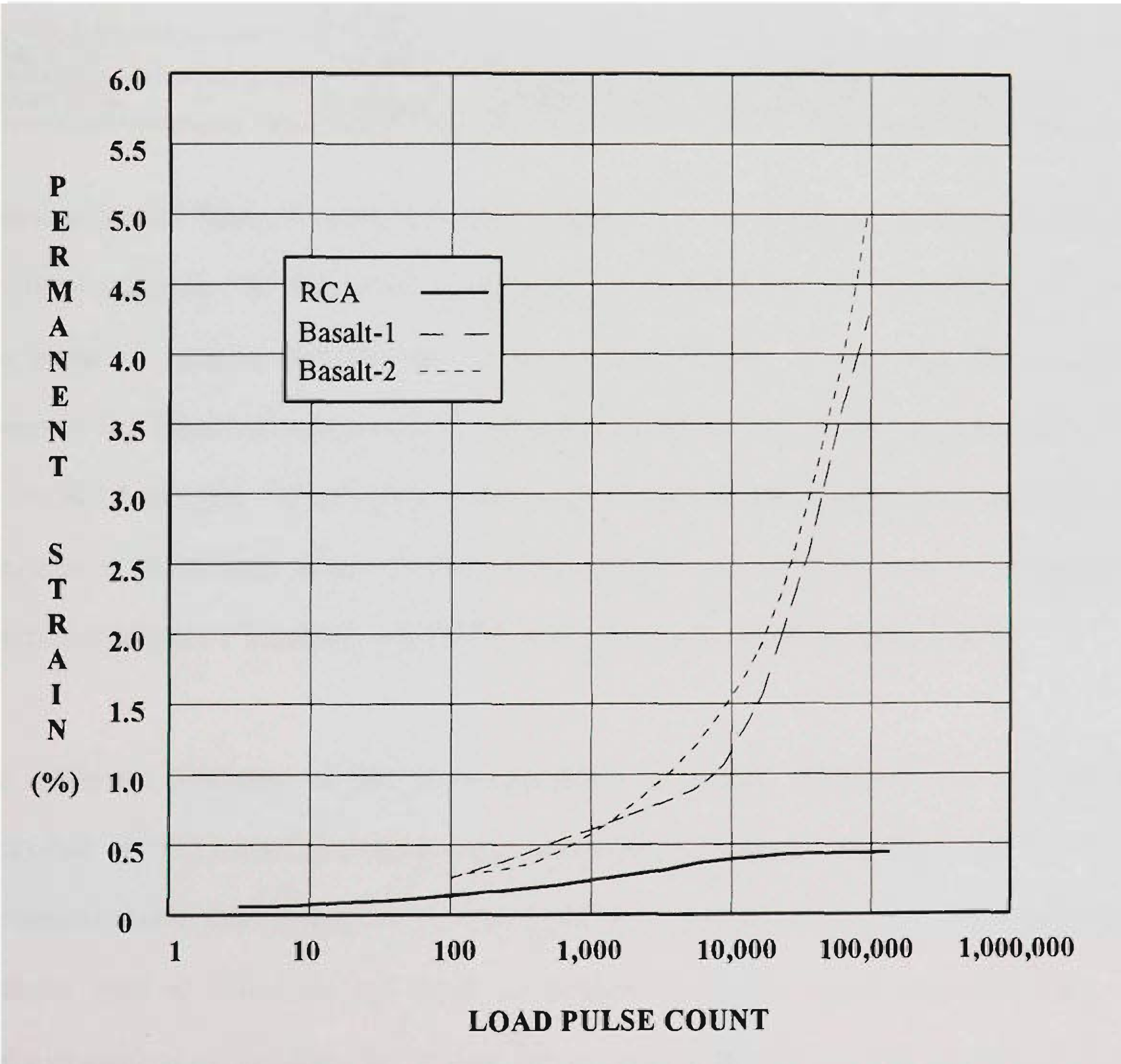


Figure 5.16: 120,000 pulse permanent strain test.

Based on work carried out by CSIRO over many years (Cole,1982 & Shayan and Westgate, 1988) the comparative performance parameters shown in Table 5.16 have been developed to classify road pavement materials based on permanent strain at 100,000 load pulses. Using Table 5.16 as a guide, all indications are that the recycled material would perform well as a road pavement material.

Table 5.16: CSIRO pavement performance parameters

(After Cole, 1982 & Shayan and Westgate, 1988)

Permanent strain at 100000 load pulses.	Probable pavement performance.
Under 2%	An extremely good quality roadbase or subbase material.
2%-5%	A satisfactory roadbase or subbase material.
Over 5%	Likely to produce excessive pavement deformations.

Examination of Table 5.15 shows the variations in the compaction characteristics of the three samples. The Basalt-1 sample was compacted to 100% of MDD at OMC. The Basalt-2 sample was compacted to 98% of MDD, as was the RCA sample. However the Basalt-2 sample was compacted using 88% of OMC compared to 95% for the RCA sample. When assessing the three permanent strain curves the differing compaction conditions must be taken into account. A reduction in the compactive moisture content or increase in density will cause a lower permanent strain.

The differing gradings of the three materials may also influence the test results. Barksdale (1989) found that materials with a coarser grading tended to have a lower permanent strain than those with a finer grading. This is because the large aggregate particles tend to interlock and bridge the load imposed on the test specimen. A finely graded material does not permit as much bridging, resulting in sliding of the particles, which increases permanent strain. The RCA and Basalt-2 samples have similar gradings. The Basalt-1 sample has a finer grading than the other two samples.

A good comparison between the RCA and Basalt-2 sample can be made as they were both compacted to the same percentage of MDD and had similar gradings. The Basalt-2 sample was compacted with a lower percentage of OMC than the RCA sample, his would reduce tend to reduce the permanent strain. Even so the RCA still had a significantly lower permanent strain. Comparison with the Basalt-2 is more difficult because it was compacted to MDD at OMC and had an inferior grading to the over two samples. Regardless of this Basalt-1 had a very similar permanent strain curve to Basalt-2, however both were inferior to the RCA.

Another factor which may help explain the low permanent strain of RCA when compared to the basalt samples is the shape and surface texture of the particles. Busch (1988) hypothesized that RCA gained an increase in strength not only through residual setting of crusher fines, but also from an increased number of contact points (or area of contact) between the particles, as shown in Figure 5.17. The number of contact points is a governing factor in the strength of an unbound pavement. Shear failure of soils and aggregates generally occurs due to a sliding of the particles over each other. This is a function of particle arrangement, the shape of the particles and the coefficient of friction between those particles. The relatively rough texture of RCA suggests that it would have a higher coefficient of friction than the smoother traditional aggregates. When combined with the additional contact points as suggested by Busch, this may lead to an increase in shear strength. Barksdale and Hani (1989) studied in detail the influence of aggregate shape on resilient modulus. They concluded that characteristics such as shape, angularity, surface roughness and roundness all have an important influence on the resilient modulus of an unbound aggregate.

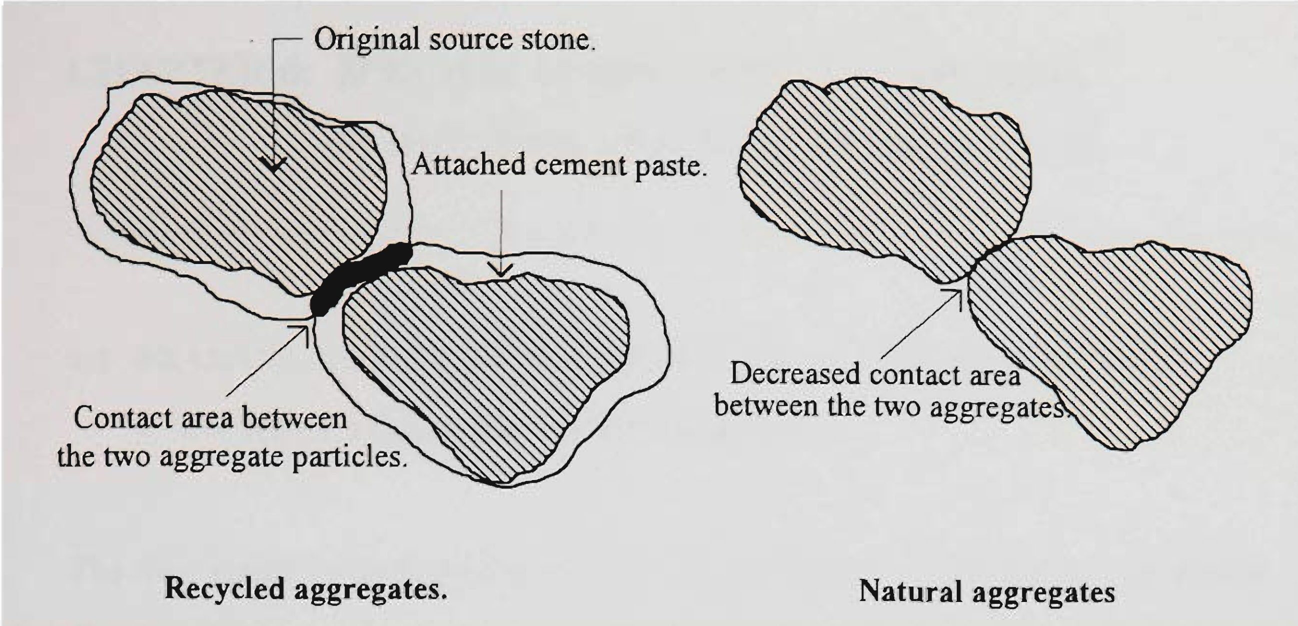


Figure 5.17: Contact points between natural and recycled concrete aggregate particles.

CHAPTER 6: SPECIFICATION, QUALITY CONTROL GUIDELINES AND FUTURE RESEARCH.

6.1 EXAMINATION OF VICROADS SPECIFICATION 820: CRUSHED CONCRETE FOR SUBBASE PAVEMENT.

The first VicRoads draft specification for the use of recycled concrete was written in October 1990. It was developed because of pressure from the emerging concrete recycling industry, which wanted the material to be approved for road construction. The current VicRoads specification is Section 820 Crushed Concrete for Subbase Pavement (July, 1993) and covers the use of 20mm and 40mm RCA in upper and lower subbases. The tests required under the specification are, Grading, Liquid Limit, Plasticity Index, California Bearing Ratio (CBR), Los Angeles (LA) Abrasion Loss, Foreign Material Type and Moisture Content.

6.1.1 Grading

The gradings specified, prior to compaction, for upper and lower subbase materials are shown in Tables 6.1 and 6.2 respectively. They are typical for a softer rock such as a high quality sandstone, and a testing frequency of one per day or every 300 tonnes or part thereof is required. The target gradings adopted have a Talbot grading exponent 'n' equal to approximately 0.4. This represents a grading slightly coarser than Fullers theoretical maximum density curve of 0.5 and will enable RCA to be compacted to a higher density with a lower percentage of air voids. Equation 6.1 defines the Talbot grading exponent as follows:

$$\% \text{ Passing } = \left(\frac{d^x}{D}\right) * 100 \qquad (6.1)$$

Where: x = grading exponent

d = sieve aperture (mm)

D = maximum particle diameter (mm)

The gradings adopted within the specification are easily obtained (as discussed in Section 5.1.2) provided the appropriate plant is selected, which typically would include primary and secondary crushing in a closed loop system.

Table 6.1: Grading requirements for crushed concrete upper subbase

(Table 820.062, VicRoads, 1990)

Sieve Size AS (mm)	**Nominal Size**			
	20mm		**40mm**	
	Target Grading % Passing	**Grading Limits % Passing**	**Target Grading % Passing**	**Grading Limits % Passing**
53.0	-	-	100	100
37.5	-	-	100	95-100
26.5	-	100	85	75-95
19.0	100	95-100	77	64-90
13.2	85	75-95	-	-
9.5	75	60-90	60	42-78
4.75	59	42-76	46	28-64
2.36	44	28-60	35	20-50
0.425	19	10-28	15	7-23
0.075	6	2-10	6	2-9

Table 6.2: Grading requirements for crushed concrete lower subbase

(Table 820.063, VicRoads, 1990)

Sieve Size AS (mm)	Limits of Grading - Test Value before Compaction (% Passing)							
	Nominal Size (mm)							
	50	40	30	25	20	14	10	5
75.0	100							
53.0		100						
37.5			100	100				
26.5					100			
19.0	54-75	64-90				100	100	
9.5			48-70	54-75				100
4.75					42-76	54-75	64-84	
2.36								65-84
0.425	7-21	7-23	9-24	10-26	10-28	15-32	18-35	26-45
0.075	2-10	2-12	2-12	2-13	2-14	6-17	7-18	10-23

6.1.2 Unsuitable material content

Until some specific research is carried out into the effects of unsuitable materials on the performance of RCA as a road pavement material, the specification requirements as outlined in Table 6.3 seem reasonable, with two possible exceptions. The limitation on the amount of high density materials, particularly brick, seems excessive. Brick has been used extensively as a road pavement material in Europe since World War II. RTL tests carried out in this investigation showed that the addition of masonry to a commercial-RCA reduced the resilient modulus by approximately one percent for each one percent of masonry added, over a wide stress range. In relatively low stress areas, such as the lower and upper subbase, an increase in the allowable masonry content up to 15% would seem more suitable. The second concern is the relatively high limit on the amount of wood and vegetable matter. One percent of wood represents a significant amount, given its relatively low density when compared to concrete. During the course of this research wood was detected in stockpiles but the amount, as a percentage of the total material was insignificant.

Table 6.3: Allowable foreign material contents (% by mass)

(Table 820.042, VicRoads, 1990)

Foreign Material Type	Upper Subbase	Lower Subbase
	Max. Allowable (%)	
High density materials such as metal, glass, brick, asphalt, stone, ceramics and slag.	3	5
Low density materials such as plastic, rubber, plaster, lumps and friable material.	2	3
Wood and other vegetable matter	1	1

6.1.3 Plasticity index

The specification sets Plasticity Index limits of 10 for upper subbase and 20 for lower subbase materials, with a testing frequency of one every 5,000 tonnes or part thereof. Plasticity Index tests carried out in this, and overseas investigations clearly show that RCA fines are non-plastic. This was previously discussed in section 5.1.3. It then follows that any specification requirement for the testing of plasticity is superfluous, provided adequate quality control measures for the reduction of soil into the waste concrete stream are taken.

A simpler, cheaper and more rapid solution on the likely quality of the fines may be obtained by a settling method (SAA HB2.1, 1986) to determine the clay and fine-silt content. The current approach of using Atterberg limits gives an unambiguous non-plastic result. This gives little indication as to the amount of clay or fine-silty material present within RCA and there likely variation over-time.

6.1.4 LA abrasion loss

The LA abrasion loss test is not suitable for RCA because RCA is a two-phase material, the outer phase of which (cement paste) is weaker than the inner phase (stone). The action of the steel balls removes the cement paste readily. Additionally, as the test is performed only on the coarse fraction, which has proportionately less cement paste coverage than the fine fraction, the result is not necessarily representative of the whole material. However, the current specification limits of 35% loss for the upper subbase and 40% loss for the lower subbase are easily achievable

6.1.5 Other specification tests

The maximum moisture content of RCA when being sold by the tonne is limited to 3.5%. This is a lower limit than that placed on scoria (5%), a material with similar moisture absorption characteristics (VicRoads, 1984). The value of 3.5% is unrealistic given that RCA is 2 to 2.5 times more moisture absorbent than NA (Fielding and McHaffie, 1992). A more realistic value for minimum moisture content would be 7%, twice that of natural aggregate.

6.2 QUALITY CONTROL GUIDELINES

The aim of any quality control program is to provide a consistent product which complies with a given specification. The variability of the source product used to produce RCA means that more care must be taken to achieve these objectives. The quality control guidelines have been divided into three areas - pre-processing, processing and post-processing. These recommendations relate to the production of RCA at a fixed central processing plant, but similar recommendations could be applied to a mobile crushing plant.

6.2.1 Pre-processing

- Depositors of waste concrete should be made fully aware of material which is considered unsuitable and should separate out such material and dispose of it in another manner.

- Operators on demolition sites must ensure that the least possible amount of soil is mixed in with the waste concrete as it is loaded onto trucks.

- All concrete should be visually assessed before acceptance. When examining the concrete the following factors should be taken into consideration;
  - Brick content
  - Asphalt content
  - Timber and plastic content, as excessive amounts of this material may warrant rejection of the load.
  - Soil, as very high contents of plastic soil may result in the RCA becoming plastic.

- After assessment, the waste concrete should then be directed to one of a number of stockpiles. The stockpiles will hold unprocessed material of different qualities.

- Before processing, the waste concrete at a given stockpile should be mixed to ensure that concrete from different sources is crushed together. This will help equalize any differences between them.

6.2.2 Processing

- A closed loop system is the most effective way of obtaining the required grading of the material. This approach slightly reduces the production capacity per hour but it enables a tighter grading envelope to be achieved, when compared to an open loop system.

- A significant loss of fine material (less than 0.075mm) can occur on windy days. This can be reduced by wetting the concrete prior to and during the crushing process. Large losses of fine material can reduce the workability of the material.

- Where possible, secondary crushing of the concrete should occur. It has been shown repeatedly that many of the fundamental properties of RCA, such as moisture absorption and specific gravity, are improved by secondary crushing. When the concrete is crushed only once it is difficult to obtain a grading suitable for road pavement construction, as the grading is too coarse.

- Regardless of the pre-processing carried out an additional method must be employed to remove unsuitable material which has been processed. This may take the form of a manual picker to remove material directly from the conveyor belt, or other automatic techniques such as air or vacuum sifting.

6.2.3 Post-processing

- The stockpile site should be clean and adequately drained away from the product.

- When stockpiling or loading material onto trucks adequate steps should be taken to ensure that segregation of the material does not occur. This problem is more acute with RCA than with natural crushed rock as the fines have a relatively low density when compared to natural aggregates.

6.3 FUTURE RESEARCH

The basic engineering properties of RCA such as grading, hardness and plasticity, have been determined in this project, as have the reasons for differences between RCA and virgin aggregates. Based on discussions with the producers of RCA and VicRoads, and results from the recycled concrete survey, and the literature review, four major areas for future research into the use of RCA as a road pavement material have been identified.

6.3.1 Mechanisms of residual setting.

Opinions vary as to the mechanisms of so called 'residual setting' of RCA within a pavement layer. As discussed previously the two major causes are thought to be either carbonation of the calcium hydroxide or re-hydration of previously unhydrated cement particles within the cement matrix. Determination of the exact mode and magnitude of residual setting would enable pavements constructed using RCA to be designed in a more efficient manner. For example, thinner pavements maybe specified if the magnitude of residual setting can be accurately predicted because of the greater strength of the material. However, the pavement becomes less flexible with the risk of cracking increasing.

The mode of residual setting may also influence methods of stabilising the material. Typically, a virgin aggregate requiring stabilisation would be treated with cement or lime, but as RCA contains approximately 4% calcium hydroxide (hydrated lime) it may be possible to stabilise it with products such as silica-fume, fly ash or blast furnace slag. These may be a cheaper alternative to cement stabilisation and could also result in less shrinkage. The unhydrated cement content can be determined using powder X-ray diffraction, and the amount of calcium hydroxide by thermo-gravimetric analysis.

In addition to the residual setting, the shape and texture of RCA has been postulated as a cause of strength improvement, and was discussed in detail within section 5.3.6.1. This could be examined by determining the shear strength of RCA and comparing it to virgin aggregates of a similar shape.

Examination of both the chemical and mechanical strength characteristics will ensure a greater understanding of the mechanisms of strength gains in RCA.

Work also needs to be carried on the potential for cracking of the material, particularly due to shrinkage. In addition to this, consideration must be given to the design of pavements using RCA. When designing a flexible pavement using RCA it should be taken into consideration that 'residual setting' may result in a bound or rigid pavement. This may produce further cracking problems.

Further investigation could also be carried out on ways of neutralizing residual setting, for applications where the effect is undesirable, such as, permeable drainage layers or a truly flexible road pavement. Possible solutions may be altering the grading of the RCA and or blending in natural sands.

6.3.2 Further RTL testing

The RTL tests carried out within this investigation should serve as a useful starting point for a more detailed examination of the material. Specifically the following areas require examination:

- Sensitivity of RCA to variations in moisture content and maximum dry density, with respect to their effect on resilient modulus and permanent strain characteristics.

- The influence of unsuitable or marginal materials on the performance of RCA under RTL. The current specification limits the amount of materials such as brick, slag, timber and asphalt, but these limitations are not based on experimental data.

6.3.3 Construction of a test pavement

The construction of a test pavement was considered to be the best method of evaluating RCA as a road pavement material by those who responded to the recycled concrete survey. However, lack of funds for this investigation made that impossible. Ideally, the test pavement would be used to correlate the RTL tests, and monitor cracking and increases in stiffness due to residual setting.

6.3.4 Compaction characteristics

In section 5.1.4 the problems of determining an accurate value for specific gravity were discussed at length. An alternative test method could be developed specifically for RCA, possibly using the graphical method proposed by Puckman and Henrichsen (1988). The errors encountered with the intersection of the ZAV line and the compaction curve, were not solely caused by an incorrect specific gravity. Further work is therefore required to gain a greater understand of the compaction characteristics of RCA.

6.3.5 Clay and fine-silt content test

As discussed within section 6.1.3 the plasticity index test consistently gives a non-plastic result for RCA, with no indication as to the quality of RCA fines. The test is time consuming, expensive and does not give the rapid answers required for a useful quality control test.

The use of the clay and fine-silt content (settling test) would enable more rapid assessment of the material. The test could be calibrated against the plasticity index test by performing tests on RCA with clay and fine-silt added. The quantity of clay and fine-silt required for a plastic result could be determined. This in turn could be compared to RTL results for RCA with added clay and fine-silt, allowing a qualitative assessment as to the effects of these materials on likely pavement performance.

The use of the clay and fine-silt content (settling test) would enable the producer to RCA to have a same day answer on the quality of the material, rather than having to wait up to three days for a plasticity index test, by which time the stockpile of production material may have been sold.

CHAPTER SEVEN: CONCLUSIONS

This study has investigated the use of RCA as a road pavement material. Based on results from the testing program, the survey of local government authorities, discussions with RCA producers and a thorough review of all relevant literature, the following conclusions can be drawn:

1. The recycling of waste concrete in Australia will continue to increase in regions where the cost of waste disposal and of new aggregate increases. The recycled concrete survey clearly showed that Melbourne and Sydney are the only capital cities which recycle waste concrete on a large scale because of the relatively high cost of waste disposal. A lack of suitable natural material is not as yet a major consideration in the development of concrete recycling in Australia, as is the case in many European countries and also Japan. In 1992 it is estimated that 25% of waste concrete in Australia was recycled and being used in a wide range of civil engineering applications. This means, however, that a significant proportion of waste concrete is not being utilised. In the opinion of both producers and users of RCA, further use will not increase until a greater body of technical knowledge is obtained which will enable the material to be used in other applications.

2. Detailed examination of literature from around the world has shown that RCA can be used as a road pavement material in either a bound or unbound state. This is based on a wide variety of empirical laboratory tests such as CBR and plasticity index, through to the modern mechanistic procedure of repeated triaxial loading tests. In addition to this, the construction of test pavements made using RCA has shown the material to be equal and, in some instances, superior to the equivalent natural aggregate. In the course of this investigation no reports were found of failure of a pavement constructed using RCA.

3. RCA can clearly be produced to the required specification grading using standard crushing and screening equipment. In addition to this, electro-magnets are required to remove steel reinforcement from the crushed concrete and manual labour to remove unwanted demolition materials such as timber and plastic, although mechanical techniques have been used overseas to remove such materials. When processing waste concrete for use as a road pavement material, primary and secondary crushing is preferable. Primary crushing only, generally with the use of a jaw crusher, will produce a coarse, unworkable grading. Secondary crushing has also been shown in the literature to improve material properties such as specific gravity and moisture absorption. In addition to this, where a tight grading envelope is required (which can be the case in Australia), a closed system should be adopted. However, it should be noted that this will reduce production when compared to an open system.

4. The fundamental difference between RCA and a natural aggregate is the cement paste which remains attached to the original aggregate particles. The basic properties of a commercially-produced RCA were examined at six monthly intervals. The following outlines the test results and the likely effect that the attached cement paste has on them:

- The surface texture of RCA is rough and the exterior surface is covered by up to 80% cement paste. In general the particle is cubical to angular.

- The RCA fine particles contain between 2 to 4% of calcium hydroxide (Hydrated Lime), a by-product of the hydration process. This chemical acts to stabilize any clay particles within the waste concrete. In each of the six monthly tests and the reviewed literature RCA has been classified as non-plastic.

- The commercial-RCA investigated had a MDD of between 2.01t/m^3 and 2.07 t/m^3, with OMC ranging between 10.9% and 12.5%. The attached cement paste has the effect of lowering the MDD and raising the OMC because it is less dense and more moisture absorbent when compared to virgin crushed rock. Problems were experienced in plotting the ZAV line, as it tended to intercept the compaction curve. The reason for this could not be fully determined, and is recommended as an area for future research.

- LA abrasion loss and particle breakdown under compaction tests indicate that RCA has hardness and abrasion characteristics similar to a high quality scoria or sandstone, both relatively 'soft' aggregates. This is because the relatively weak cement paste is easily removed from the original harder aggregate particles.

- A clear relationship was found to exist between particle size and the amount of cement paste attached to the original aggregate particle. As the particle size increases the amount of attached cement paste decreases. The SG and moisture absorption of RCA are directly influenced by the amount of attached cement paste. As the amount of attached cement paste, which is related to particle size, increases the moisture absorption increases and SG decreases.

5. The only significant difference between the two laboratory-produced RCA samples was the crushing characteristic. The 80MPa sample had more flat particles and was more angular than the 32MPa sample which could generally be described as cubical. The 32MPa sample produced more fine particles less than 4.75mm in size. The particle breakdown under compaction, and LA abrasion loss, of the 32MPa and 80MPa samples were very similar. The 80MPa sample had a slightly lower specific gravity and higher moisture absorption than the 32MPa sample. The strength of source concrete had very little effect on the properties examined in this investigation.

6. The RTL testing was a preliminary investigation into some of the variables associated with the use of RCA. The influence of brick on resilient modulus was found to be minimal, leading to a reduction of one percent for each one percent of brick added. Significant rises in modulus were recorded over a 28 day curing period and when the compactive moisture content was lowered. The 32MPa and 80MPa laboratory concrete samples tested under the same conditions exhibited no significant variations from the commercial RCA. Permanent strain testing over 120,000 load cycles showed RCA to have a significantly lower permanent strain than two basalts tested under similar conditions.

7. The commercial-RCA samples complied with the VicRoads specification (820) and produced favourable results in the RTL testing, in comparison to local basalt products. All empirical testing in this investigation indicates that RCA is a suitable material for road pavements. Further investigations should examine and correlate these results with performance in actual road pavements, enabling further comparisons with virgin crushed rock to be made.

BIBLIOGRAPHY

AASHTO. (1986) AASHTO Guide for Design of Pavement Structures, *American Association for State Highway and Transportation Official.*

Allen, J.R. and Thompson, M.R. (1974) The Resilient Responses of Granular Materials Subjected to Time-Dependent Lateral Stresses. *Highway Research Record 510*, Highway Research Board.

APRG. (1991) National Workshop on elastic characteristic of unbound pavement materials and subgrades, *Austroads Pavement Research Group Report No.3*, Australian Road Research Board.

AS1141.3 (1986) Sampling of aggregates and rock, *Standards Australia.*

AS1141.5 (1974) Bulk density and water absorption of coarse aggregate, *Standards Australia.*

AS1141.6 (1974) Bulk density and water absorption of fine aggregate, *Standards Australia.*

AS1141.11 (1980) Particle Size Distribution by dry sieving, *Standards Australia.*

AS1141.15 (1988) Flakiness Index, *Standards Australia.*

AS1141.23 (1980) Los Angeles Value, *Standards Australia.*

AS1289.B1.1 (1977) Determination of the moisture content of soil - Oven drying method - (Standard method), *Standards Australia.*

AS1289.C1.1 (1977) Determination of the liquid limit of a soil - oven drying method (Standard method), *Standards Australia.*

AS1289.E2.2 (1977) Part E - Soil compaction and density tests - Determination of the dry density/moisture content relationship of a soil using modified compaction - subsidiary method, *Standards Australia.*

ASTM C 403-77 (1985) Penetration resistance test for concrete, *American Society for Testing and Materials.*

ASTM C 457-71 (1987) Standard recommended practice for microscopical determination or air-void content and parameters of the air-void system in hardened concrete, *American Society for Testing and Materials.*

AUSTROADS. (1992) A Guide to the Structural Design of Road Pavements, *AUSTROADS.*

BCSJ. (1978) Study on recycled aggregate and recycled aggregate concrete, Building Contractors Society of Japan. Committee on Disposal and Reuse of Concrete Construction Waste. Summary in *Concrete Journal*, Japan, 16(7), pp. 18-31.

Barksdale, R.D. (1971) Compressive Stress Pulse Time in Flexible Pavements for Use in Dynamic Testing. Highway Research Record 345, Highway Research Board.

Barksdale, R.D. (1972) Evaluation of Rutting in Base Course Materials. *Proceeding of Third International Conference on the Structural Design of Asphalt Pavements, London.* pp.161-174.

Barksdale, R.D. and Itani, S.Y. (1989) Influence of Aggregate Shape on Base Behavior. *Transport Research Record 1227*, Transport Research Board.

Barksdale, R.D.,Itani,S.Y. and Swor, T.E. (1991) Evaluation of Recycled, Open-Graded Aggregate, and Large Top-size Aggregate Bases. *Transport Research Record 1345*, Transport Research Board.

Bauchard, M. (1988) The use in roads of aggregate made from demolition materials. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 719-725. (Chapman and Hall, London.)

BS5835 (1980) Compactibility Test for Graded Aggregate, *British Standards Institution.*

Buck, A.D. (1973) Recycled Concrete , *Highway Research Record No. 430.*

Busch, J. (1988) Crushed concrete used as base course material on runway 04r-221 at Copenhagen Airport. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 766-774. (Chapman and Hall, London.)

Cement and Concrete Association. (1980) Basic Guide to Concrete Construction, *Cement and Concrete Association of Australia.*

Cole, W.F. (1982) The performance of Deer Park basalt in triaxial testing, *Proceedings of the 11th Australian Road Research Board Conference*, 11(3), pp 52-59.

Collins, R.J. (1993) Reuse of demolition materials in relation to specifications in the UK. In E.K. Lauritzen (ed) *Proceedings of the Third International RILEM Symposium on Demolition and Reuse of Concrete and Masonry*. pp 49-58. (Chapman and Hall: London)

Department of Transport. (1986) Specification for Highway Works. *London, England. Her Majesty's Stationary Office.*

De Pauw, C. (1981) Fragmentation and recycling of reinforced concrete. In P. Kreijger (ed) *Adhesion Problems in the Recycling of Concrete*. pp 311-317. (Plenum Press: New York.)

De Vries, P. (1993) Concrete re-cycled, Crushed concrete as aggregate. May/June, *Concrete*, pp 9-13.

DRTSA. (1989) Resilient modulus characterisation of granular unbound pavement materials report No.1, Report No.16-1., *Department of Road Transport, South Australia.*

Environmental Resources Limited. (1980) Examination of the arising end uses and disposal of demolition waste in Europe and the potential for further recovery of materials from these wastes, *Demolition Waste*.

Fergus, J.S. (1981) Laboratory Investigation and Mix Proportions for Utilizing Recycled Portland Cement Concrete as Aggregate. *Proceedings of the National Seminar on PCC Pavement recycling and Rehabilitation*, St. Loius, Missouri, USA, Federal Highway Administration Report FHWA-TA-82-208, pp140-160.

Fielding, B.J. and McHaffie, I.W. (1992) Crushed rock products, *Engineering Geology of Melbourne*, Edited by Peck, Neilson, Olds and Seddon, (Balkema: Rotterdam.)

Fielding, B.J. (1993) Private discussions with VicRoads Senior Geologist

Frondistou-Yannas, S. (1977) Waste concrete as aggregate for new concrete. *ACI Journal*, pp. 373-376.

Gorle, D. and Saeys, L. (1988) Reuse of crushed concrete as a road base material. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 736-745. (Chapman and Hall, London.)

Gottfredsen, F.R. and Thogersen, F. (1993) Recycling concrete in aggressive environment. In E.K. Lauritzen (ed) *Proceedings of the Third International RILEM Symposium on Demolition and Reuse of Concrete and Masonry.* pp 309-318. (Chapman and Hall: London)

Hansen, T.C. and Narud, H. (1983a) Recycled concrete and silica fume make calcium silicate bricks. *Cement and Concrete Research*, 13(5), pp.507-510.

Hansen, T.C. and Narud, H. (1983b) Strength of recycled concrete made from crushed coarse aggregate. *Concrete International-Design and Construction*, 5(1), pp. 79-83.

Hansen, T.C. and Boegh, E. (1985) Elasticity and drying shrinkage of recycled concrete aggregates. *ACI Journal*, pp. 648-652.

Hansen, T.C. and Angelo, J. (1986) Crushed concrete fines recycled for soil stabilisation purposes. *ACI Journal*, 83, pp.983-987.

Hansen, T.C. and Marga, M. (1988) Strength of recycled concrete made from coarse and fine recycled concrete aggregates. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste*. pp. 605-612. (Chapman and Hall, London.)

Hansen, T.C. (ed) (1992) *Rilem Report 6: Recycling of Demolished Concrete and Masonry* (E & FN Spon, Melbourne.)

Hasaba,S., Kawamura, M. and Toriik, K. (1981) Drying shrinkage and durability of concrete made of recycled concrete aggregates. Translation of the *Japan Concrete Institute*, 3, pp.55-60.

Ikeda, T., Yamane, S. and Sakamoto, A. (1988) Strengths of concrete containing recycled concrete aggregate. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste*. pp. 585-604. (Chapman and Hall, London.)

Industry Commission. (1991a) Recycling , Report No.6, 22 Feb., 2 Vols.,*AGPS*, Canberra.

Industry Commission. (1991b) Waste management and recycling: Survey of Local government practices. Information paper, *AGPS*, Canberra.

Japan Road Association. (1984) Technical Guideline for Recycling and Utilizing Waste Pavement Materials (Draft), *Japan Road Association.*

Kaga, H., Kasai, Y., Takeda, K. and Kemi, T. (1988) Properties of recycled aggregate from concrete. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 690-698. (Chapman and Hall, London.)

Kakizaki, M., Harada, M. and Motoyasu, H. (1988) Manufacturing of recovered aggregate through disposal and recovery of demolished concrete structures. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 699-708. (Chapman and Hall, London.)

Kalcheff, I.V. and Hicks, R.G. (1973) A Test Procedure for Determining the Resilient Properties of Granular Materials, *Journal of Testing and Evaluation*, 6(1) ASTM.

Kasai, Y. (1993) Guidelines and the present state of the reuse of demolished concrete in Japan. In E.K. Lauritzen (ed) *Proceedings of the Third International RILEM Symposium on Demolition and Reuse of Concrete and Masonry.* pp 93-104. (Chapman and Hall: London)

Kawamura, M. and Torii, K. (1988) Reuse of recycled concrete aggregate for pavement. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 726-735. (Chapman and Hall, London.)

Lauritzen, E.K. (1993) Building waste generation and reuse of building waste materials. *International Recycling Congress*, Geneve, Jan. 1993.

Lay, M.G. (1990) Handbook of Road Technology. Vol.1. (Gordon and Breach: Cooper Station, New York.)

Litwinowicz, A. and Wijeyakulasuriya, V. (1991) Laboratory characterisation of the behavior of crushed rock. *Austroads Pavement Research Group Report No.3*, Australian Road Research Board. pp 63-76.

Low, P. (1994) Private discussion with VicRoads Geologist.

McHaffie, W.I. (1992) A review of needs and sources on construction materials for the Melbourne Area. In Peck, Neilson and Olds (eds.) Engineering Geology in Melbourne. (Baulkema: Rotterdam.)

Morel, A., Gallias, J.L., Bauchard, M., Mana, F. and Rousseau, E. (1993) Practical guidelines for the use of recycled aggregate in concrete in France and Spain. In E.K. Lauritzen (ed) *Proceedings of the Third International RILEM Symposium on Demolition and Reuse of Concrete and Masonry.* pp 71-82. (Chapman and Hall: London)

Morlion, D., Venstermans, J. and Vyncke, J. (1988) Demolition waste of the 'Zandvliet' lock as aggregate for concrete. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 709-718. (Chapman and Hall, London.)

Mulheron, M. (1988) The recycling of demolition debris: Current practice, products and standards in the United Kingdom. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 510-519. (Chapman and Hall, London.)

NAASRA. (1986) Guide to Stabilisation in Roadworks *Association of Australian State Road Authorities.*

NAASRA. (1987) Pavement Design: A Guide to the Structural Design of Road Pavements. *National Association of Australian State Road Authorities.*

Nishibayashi, S. and Yamura, K. (1988) Mechanical properties and durability of concrete from recycled coarse aggregate prepared by crushing concrete. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 652-659. (Chapman and Hall, London.)

O'Mahony, M.M. and Milligan, G.W.E (1991) Use of Recycled Materials in Subbase Layers. *Transportation Research Record* 1310, pp. 73-80.

Petrarca, R.W. and Galdiero,V.A.. (1983) Summary of Testing of Recycled Crushed Concrete. *Transport Research Record 989*, pp. 19-26.

Portland Cement Association. (1942) Kansas Salvages Old Road Base. *Soil Cement News*.

Puckman, K. and Henrichsen, A. (1988) Reuse of concrete pavements. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 746-755. (Chapman and Hall, London.)

Rada, G. and Witzak, M.W. (1981) Comprehensive evaluation of laboratory resilient moduli results for granular material. *Transport Research Record 810.*

Ravindrarajah, R. and Tam, C.T. (1985) Properties of concrete made with crushed concrete as coarse aggregate. *Magazine of Concrete Research.* 37(110).

Ravindrarajah, R. and Tam, C.T. (1988) Methods of improving the quality of recycled aggregate concrete. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 575-584. (Chapman and Hall, London.)

RILEM. (1993) TC121 Draft specification Concrete with Recycled Aggregate. *RILEM.*

Robertson, R. (1991) Setting in concrete the business of rubble recycling, *Financial Review*, Dec. 19, p26.

SAA HB2.1 (1986) Section 33: Clay and Fine Silt (Settling Method), *Standards Australia.*

SAA HB34 (1992) Section 2: Test for Rebound Number, *Standards Australia.*

Sherwood, P.T. and Pike D.C. (1984) Errors in the sampling and testing of subbase aggregates, *Transport and Road Research Laboratory*, TRRL Supplementary Report 831.

Schultz, R.R. (1988) Concrete with Recycled Rubble - Developments in West Germany. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 500-509. (Chapman and Hall, London.)

Shayan, A.. and Westgate, P. (1988) Behavior of chemically-treated crushed basalt aggregate under repeated triaxial loading, *Proceedings of the 14th Australian Road Research Board Conference*, 14(7). pp 54-60.

Sweere, G.T.H. (1990) Unbound Granular Bases for Roads, Ph.D. thesis, *Delft Technical University*, Delft, Netherlands.

Transport Research Board. (1989) Recycling of Portland Cement Concrete Pavements., *National Cooperative Highway Research Program Report 154.*

Tritt, B. (1991) Developmental aspects of laboratory apparatus and data acquisition systems, *Austroads Pavement Research Group Report No.3*, Australian Road Research Board. pp 99-111.

VicRoads,(1992) Section 820 - Crushed Concrete for Subbase Pavement, Draft July. *VicRoads.*

VicRoads,(1984) *Section 818* - Crushed scoria for base and subbase pavement. *VicRoads*

Vuong, B. and Kinder, D.F. (1984) A deformation measurement device for use in repeated load triaxial tests. *ARRB Internal Report AIR 403-2*.

Vuong, B. (1985) Permanent deformation and resilient behavior of a Victorian crushed rock using the repeated load triaxial test. *ARRB Internal Report AIR 403-6.*

Vuong, B. (1991) Resilient modulus testing and application at ARRB. *Austroads Pavement Research Group Report No.3*, Australian Road Research Board. pp 27-36.

Wardle, L.J. (1977) Program Circly User's Manual, *CSIRO*.

Yoshikane, T. (1988) The instances of concrete recycled for base course material in Japan. In Y.Kasai (ed.) *Proceedings of the Second International RILEM Symposium on demolition and reuse of concrete and masonry. 2: Reuse of demolition waste.* pp. 756-765. (Chapman and Hall, London.)

APPENDIX A: RECYCLED CONCRETE SURVEY

- Covering letter
- RCA survey
- List of municipalities that participated in the survey
- Determination of importance levels

Ballarat Road
Footscray

PO Box 64
Footscray
Victoria 3011
Australia

Telephone
(03) 688 4200

Facsimile
(03) 689 4069

Footscray Campus

VICTORIA UNIVERSITY OF TECHNOLOGY

Dear Sir/Madam,

RE: RECYCLED CONCRETE SURVEY.

Please find enclosed a survey document on the use of recycled concrete. This survey forms an integral part of an extensive research program on the use of recycled concrete as road pavement material, presently being conducted by this department.

The survey has been formulated to determine the views and practises of Municipal Engineers regarding the use of recycled concrete and has been distributed to every metropolitan council within the country.

The results from this survey will help guide future research into the uses of recycled concrete. Currently a lack of Australian knowledge about the material is hampering its wider use and acceptance.

Your participation in this survey is greatly appreciated. Any problems relating to it can be directed to Mr Brian Richardson on (03) 688 4983. Could you please return the survey form in the stamped self-addressed envelope or fax through on (03) 688 4806 by the 1st June 1992.

[redacted]

Brian Richardson
Post-graduate Research Student
Department of Civil and Building Engineering

Campuses at
Footscray, Melton,

VICTORIA UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF CIVIL AND BUILDING ENGINEERING

RECYCLED CONCRETE SURVEY 1992.

MUNICIPALITY: ....

CONTACT PERSON: ....

TELEPHONE NUMBER: ....

QUESTION ONE: IS CONCRETE RECYCLED IN YOUR MUNICIPALITY ?

YES ☐ GOTO Q3

NO ☐

QUESTION TWO: HOW IS WASTE CONCRETE DISPOSED OF ?

.... GOTO Q6

QUESTION THREE: HOW IS THE MATERIAL CRUSHED ?

COUNCIL'S MOBILE CRUSHER ☐

CONTRACT CRUSHING ☐

TRANSPORTED TO A CENTRAL CRUSHING PLANT ☐

OTHER: ....

QUESTION FOUR: APPROXIMATELY HOW MUCH MATERIAL IS PRODUCED PER ANNUM ?

.... TONNES

QUESTION FIVE: WHAT IS THE CRUSHED MATERIAL USED FOR ?

CARPARKS ☐

FILL ☐

PATHS ☐

CROSSOVERS ☐

TRENCH BASES ☐

ROAD SUBBASE ☐

ROAD BASE ☐

CONCRETE AGGREGATE ☐

OTHER: ....

QUESTION SIX: DO YOU BELIEVE THAT THE CURRENT USE OF RECYCLED CONCRETE IS LIMITED BY A LACK OF TECHNICAL DATA ?

YES ☐

NO ☐

QUESTION SEVEN: THE FOLLOWING ARE PROPOSED AREAS OF RESEARCH INTO RECYCLED CONCRETE AS AN AGGREGATE FOR USE IN ROAD BASES.

MARK OFF THE RELEVANT BOX TO SHOW THE IMPORTANCE TO YOU OF SUCH INFORMATION. WHERE 1 IS HIGH IMPORTANCE AND 5 IS OF LOW IMPORTANCE

DETERMINATION OF A MODULUS OF THE MATERIAL.	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
STRENGTH INCREASE DUE TO RESIDUAL SETTING OF THE MORTAR.	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
PAVEMENT CRACKING	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
PARTICLE BREAKDOWN UNDER COMPACTION	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
PERMEABILITY	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
MATERIAL PERFORMANCE ON A TEST SECTION OF ROAD,INCLUDING DEFLECTION DATA.	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
REPEATED LOAD TRIAXIAL TESTS TO EVALUATE LOSS OF STIFFNESS AND STRENGTH. AND THE DEGREE OF PARTICLE BREAKDOWN.	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
MINERALOGICAL INVESTIGATIONS OF ROCK TYPES AND HARMFUL MINERALS	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
STABILIZATION USING CEMENT AND LIME	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
EASE OF PLACEMENT AND WORKABILITY	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
QUALITY CONTROL GUIDELINES	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5
DESIGN GUIDELINES	☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5

OTHER AREAS NOT SPECIFIED: ....

....

....

QUESTION EIGHT: GIVEN THAT PRESENT UNCERTAINITIES OR OBJECTIONS TO THE USE OF RECYCLED CONCRETE COULD BE OVERCOME BY THIS RESEARCH WOULD YOU BE LIKELY TO USE, OR INCREASE THE USE OF, RECYCLED CONCRETE IN YOUR MUNICIPALTY ?

YES ☐

NO ☐ GOTO Q10

QUESTION NINE: PROVIDED THAT A CONSTANT SUPPLY OF RECYCLED CONCRETE CAN BE MAINTAINED, ESTIMATE THE AMOUNT OF THE MATERIAL YOU. COULD USE PER ANNUM, FOR THE FOLLOWING WORKS.

ROAD PAVEMENTS .... TONNES

OTHER USES .... TONNES

QUESTION TEN: ESTIMATED VOLUME IN TONNES OF AGGREGATE USED WITHIN THE MUNICIPALITY PER ANNUM FOR ALL TYPES OF WORKS, INCLUDING ROADS, CARPARKS, PATHS ETC.

.... TONNES

ESTIMATED COST OF THIS MATERIAL

$ ....

ANY ADDITIONAL COMMENTS RELATING TO THIS SURVEY OR THE USE OF RECYCLED CONCRETE WOULD BE GREATLY APPRECIATED.

....
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WOULD YOU PLEASE RETURN THE SURVEY FORM IN THE STAMPED ADDRESSED ENVELOPE BY THE 1st JUNE.1992. OR FAX THROUGH ON (03) 688 4806 MARKED TO THE ATTENTION OF MR.BRIAN RICHARDSON.

List of municipalities

Listed below are the municipalities which were sent a recycled concrete survey.

Melbourne

Altona	City	Footscray	City
Berwick	City	Frankston	City
Box Hill	City	Hawthorn	City
Brighton	City	Healesville	Shire
Broadmeadows	City	Keilor	City
Brunswick	City	Kew	City
Bulla	Shire	Know	City
Camberwell	City	Lillydale	Shire
Caulfield	City	Malvern	City
Chelsea	City	Melbourne	City
Coburg	City	Melton	Shire
Collingwood	City	Moorabbin	City
Cranbourne	Shire	Mordiallic	City
Croydon	City	Mornington	Shire
Dandenong	City	Northcote	City
Diamond Valley	Shire	Nunawading	City
Doncaster and Templestowe	City	Oakleigh	City
Eltham	Shire	Port Melbourne	City
Essendon	City	Prahran	City
Fitzroy	City	Preston	City
Flinders	City	Richmond	City
		Ringwood	City

Melbourne (cont.)

Sandringham	City
Sherbrooke	Shire
South Melbourne	City
Springvale	City
St Kilda	City
Sunshine	City
Waverley	City
Werribee	City
Whittlesea	City
Williamstown	City

Sydney

Ashfield	Municipality
Auburn	Municipality
Bankstown	City
Baulkham Hills	Shire
Blacktown	City
Botany	Municipality
Burwood	Municipality
Campbelltown	City
Canterbury	Municipality
Concord	Municipality
Drummoyne	Municipality
Fairfield	City
Hawkesbury	Shire
Holroyd	Municipality
Hornsby	Shire
Hunters Hill	Municipality

Sydney (cont.)

Hurstville	City
Kogarah	Municipality
Ku-ring-gai	Municipality
Lane Cove	Municipality
Leichardt	Municipality
Liverpool	City
Manly	Municipality
Marrickvile	Municipality
Mosman	Municipality
North Sydney	Municipality
Parramatta	City
Penrith	City
Randwick	Municipality
Rockdale	Municipality
Ryde	Municipality
South Sydney	City
Strathfield	Municipality
Sutherland	Shire
Sydney	City
Warringah	Shire
Waverley	Municipality
Willoughby	Municipality
Woollahra	Municipality

Perth

Armadale	City
Bassendean	Town
Bayswater	Shire
Belmont	City
Canning	City
Claremont	Town
Cockburn	City
Cottesloe	Town
East Fremantle	Town
Fremantle	City
Gosnells	City
Kalamunda	Shire
Kwinana	Town
Melville	City
Mosman Park	Town
Mundaring	Shire
Nedlands	City
Peppermint Grove	Shire
Perth	City
Rockingham	Shire
Serpentine-Jarrahdale	Shire
South Perth	City
Stirling	City
Subiaco	City
Swan	Shire
Wanneroo	City

Brisbane

Brisbane	City
Caboolture	Shire
Ipswich	City
Logan	City
Moreton	Shire
Pine Rivers	Shire
Redcliffe	City
Redland	Shire

Adelaide

Adelaide	City
Brighton	City
Burnside	City
Campbelltown	City
East Torrens	District Council
Elizabeth	City
Enfield	City
Gawler	Municipality
Glenelg	City
Happy Valley	City
Henley and Grange	City
Hindmarsh	Municipality
Kensington and Norwood	City
Marion	City
Mitcham	City
Munno Para	City
Noarlunga	City
Payneham	City
Port Adelaide	City

Adelaide (cont.)

Prospect	City
Salisbury	City
St Peters	Municipality
Stirling	District Council
Tea Tree Gully	City
Thebarton	Municipality
Unley	City
Walkerville	Municipality
West Torrens	City
Willunga	District Council
Woodville	City

Determination of importance levels

Question seven of the Recycled Concrete asked respondents to indicate the relevant importance they attached to 12 areas of proposed research (see p.39). A scale of one to five was provided. A rating of one indicated that the proposed area of research was of a high importance and a rating of five represented a low importance.

In order to simplify the presentation of the results into a single graph, Figure 3.2, the following procedure was adopted:

1. Each level of importance is assigned a points value. High importance, rating one = 5points, rating two = 4points, rating three = 3points, rating four = 2 points and, finally, the lowest importance rating five = 1point.

2. The total number of points (P_t) for each area of research was determined.

3. The maximum possible points (P_m) for each area of research was calculated by multiplying the number of responses by five points.

4. The level of importance was determined using the following relationship:

Level of importance = $P_t / P_m \times 100$

APPENDIX B: DEVELOPED TEST METHODS AND RTL TESTING PROCEDURES

- Determination of the amount of attached cement
- Estimation of cement paste coverage
- Foreign material content
- RTL testing procedures

DETERMINATION OF THE AMOUNT OF ATTACHED CEMENT PASTE

Scope

This test method covers the determination of the amount of attached cement paste, expressed as a percentage of the total RCA sample mass. Hydrochloric acid is used to remove the cement paste from the original aggregate.

Apparatus

The following apparatus is required for this procedure:

1. Balance of at least 2 kg capacity, accuracy to 0.1 g.
2. Australian Standard sieves.
3. Wire basket or washing sieve.
4. Thermostatically controlled drying oven capable of maintaining a temperature of 105-110°C.
5. 20mm riffle box.
6. Sealable container, minimum capacity 2 litres.

Procedure

1. Obtain a representative 20 kg unwashed sample of RCA, in accordance with the procedures detailed in AS1141.3.
2. Sieve the material until a minimum mass of 1 kg of the desired size range is obtained. Ensure that the sample is made up entirely of sound concrete. Remove all brick, asphalt or any other contaminants.
3. Wash the sub-sample in water using a suitable wire mesh basket or other appropriate device.
4. Oven-dry the material at 105°C to 110°C for a period of 24 hours.

5. Allow the material to cool for a minimum of 4 hours.

6. Take the cooled material and obtained a test sample of 500±10g, by splitting and record the mass as M_1.

7. Prepare a 500ml solution of diluted hydrochloric acid, at one part hydrochloric acid to three parts water. When preparing the solution always add the acid to the water.

8. Place the sample in a sealable container and add the diluted acid, ensuring that the entire sample is immersed in the solution and allow to stand for 48 hours.

9. Wash the sample as described in part (3) making sure that no source rock is lost during the process. Check that as much cement paste as possible has been removed from the source rock.

10. Oven dry the material at 105°C to 110°C for a period of 24 hours.

11. After a 4 hour cooling period re-examine the sample and remove by brushing any cement paste still attached to the source rock.

12. Weigh the remaining source rock and record the mass as M_2.

Calculations

The mass of attached cement paste shall be calculated as follows:

$$\% \text{ of attached cement paste } = \left(\frac{M_1 - M_2}{M_1}\right) x\ 100$$

The result should be expressed to the nearest whole number.

ESTIMATION OF CEMENT PASTE COVERAGE

Scope

This test method covers the estimation of the amount of cement paste covering the surface of coarse RCA particles.

Apparatus

The following apparatus is required for this procedure:

1. Australian Standard sieves of 19mm and 13.2mm apertures.
2. Wire basket or washing sieve.
3. Inspection light.
4. Magnifying glass.

Procedure

1. Obtain a 10 kg representative sample of the material, in accordance with the procedures detailed in AS1141.3.

2. Sieve the material over the 19mm and 13.2mm sieves, discarding all material retained on the 19mm and passing the 13.2mm.

3. Count out 100 particles of RCA from the sieved sample.

4. Wash the 100 particles in a wire basket or washing sieve.

5. Carefully inspect each of the aggregate particles using the magnifying glass and inspection light.

6. Estimate the percentage of cement paste covering the total surface area of the RCA particle to the nearest 5%.

7. Record the estimated cement paste coverage for each particle.

Calculations

Determine the average percentage of cement paste coverage for the 100 RCA particles and the express the result to the nearest whole number.

FOREIGN MATERIAL CONTENT

Scope

This test method covers the determination of the amount of foreign material within a sample of RCA.

Apparatus

The following apparatus is required for this procedure:

1. Australian Standard sieves.
2. Washing sieve.
3. Inspection light.
4. Magnifying glass.
5. Balance of at least 2 kg capacity and accuracy of 0.1 g.
6. Thermostatically-controlled drying oven capable of maintaining a temperature of 105-110°C.
7. 20mm riffle box.

Procedure

1. Obtain a 20 kg representative sample of the material, in accordance with the procedures detailed in AS1141.3..
2. Split the sample down to approximately 2.5 kg using the riffle box.
3. Pass the material over a 4.75mm sieve. Discard all material passing through the sieve, and wash the retained material using a wire basket .
4. After washing, dry the sample at 105°C to 110°C for 24 hours.
5. After removal from the oven allow the material to cool for a minimum of 4 hours, then weigh the sample and record the mass as M_t.

6. Examine the sample using the magnifying glass and inspection light, removing all foreign material. The foreign materials are classified and separated into three categories, as follows:

High density (M_h): Metal, glass, brick, asphalt, stone, ceramics and slag.

Low density (M_l): Plastic, rubber, plaster, clay lumps and other friable materials.

Organic (M_o): Wood and other vegetable matter.

Calculations

The foreign material as a percentage of total mass for each of the three categories is determined using the following equation:

$$\text{Foreign material \%} = \frac{M_{(h/l/o)}}{M_t} \times 100$$

The results should be expressed to the nearest 0.1%.

RTL TESTING PROCEDURES

Preparation of samples.

A 100kg sample of RCA was obtained from the production stockpile of Alex Fraser Pty. Ltd. at Port Melbourne, in accordance with the requirements of AS1141.3 (1986), as discussed in section 4.2.1. This material was sampled on the 1/7/92 and was also used for the first of the six, monthly tests. From the 100kg bulk sample 50kg of material was split down for the triaxial tests. This material was used for all of the stage modulus and permanent strain tests.

Compaction of the samples.

All sub-samples were compacted into a 100mm diameter by 207mm high, steel, split mould, using an automatic dynamic compaction device. As the aim was to obtain a uniformly compacted material, ten layers were used.

The number of blows per layer (N) to give a Modified compactive energy of 2705KkJ/m^3 was computed from:

$$N = \frac{E.V}{M.H.g.L}$$

where M = mass of hammer (4.9kg) E = compactive energy (2705kJ/m^3)

H = height of drop (450mm) V = volume of the split mould (1.626 litres)

g = acceleration due to gravity (9.81m/s^2)

L = number of layers (10)

From the equation it was calculated that 20 blows per layer was required.

All sub-samples were dried to a constant mass over 24 hours at 105°C. After removal from the oven they were allowed to stand for a minimum of 4 hours. The appropriate amount of water was then added to achieve the desired moisture content. The material was then mixed thoroughly, placed in a sealed container and allowed to equilibrate at room temperature for 24 hours, after which the following process was followed:

1. The mass of material required for each layer was determined.
2. The split mould was assembled, and the inside coated with oil to enable easier removal of the compacted sample.
3. The material required for the first layer was placed in the split mould and evenly distributed.
4. The automatic compaction machine was set 10 blows and compaction started. After the first 10 blows, any excess material was scrapped off the bottom of the ram and placed back in the mould. The apparatus was then restarted and the final 10 blows applied.
5. Using a straight edge with the appropriate levels marked, the height of the compacted layer was checked. Each layer was required to be within ± 5mm of the required height.
6. The previously compacted layer was scarified with the end of the straight edge before commencing on the next layer. Processes **2** to **5** were continued until the top of the mold was reached.
7. Once all of the layers were compacted any excess material was trimmed from the top of the mold with the straight edge, ensuring no material protruded above the top of the mold.
8. Material passing a 1.18mm sieve was used to fill any gaps at the top of the mould. A 500g stainless steel cap was placed on top of the mould and a final blow applied to the material with a 4.5kg ram falling through 450mm.

9. The remaining material to determine the moisture content of the compacted sample.

Setting up the sample in test apparatus.

1. Samples were carefully removed from the split mould, but remained on the base plate.

2. Rubber membranes were placed on the sample using the membrane stretcher.

3. The top loading cap was then placed on the sample and a 5mm 'O' ring fitted.

4. The sample was lifted onto the pedestal of the triaxial cell and two 3mm 'O' rings were fitted over the membrane and on the pedestal, completely sealing the sample.

5. The top of the triaxial cell was then placed and sealed, ensuring that the loading ram was seated centrally on the loading cap.

6. The air breather valve was then opened and a pneumatic pump switched on to fill the cell with silicone oil. Once oil discharged through the breather valve it was then closed off and the cell checked for bubbles of air. Any air found in the cell was removed by tilting the triaxial cell until the air was located under the breather valve, which was then opened, removing the air.

7. The external LVDT was then placed in position and adjusted within its range using the visual display from the computer screen.

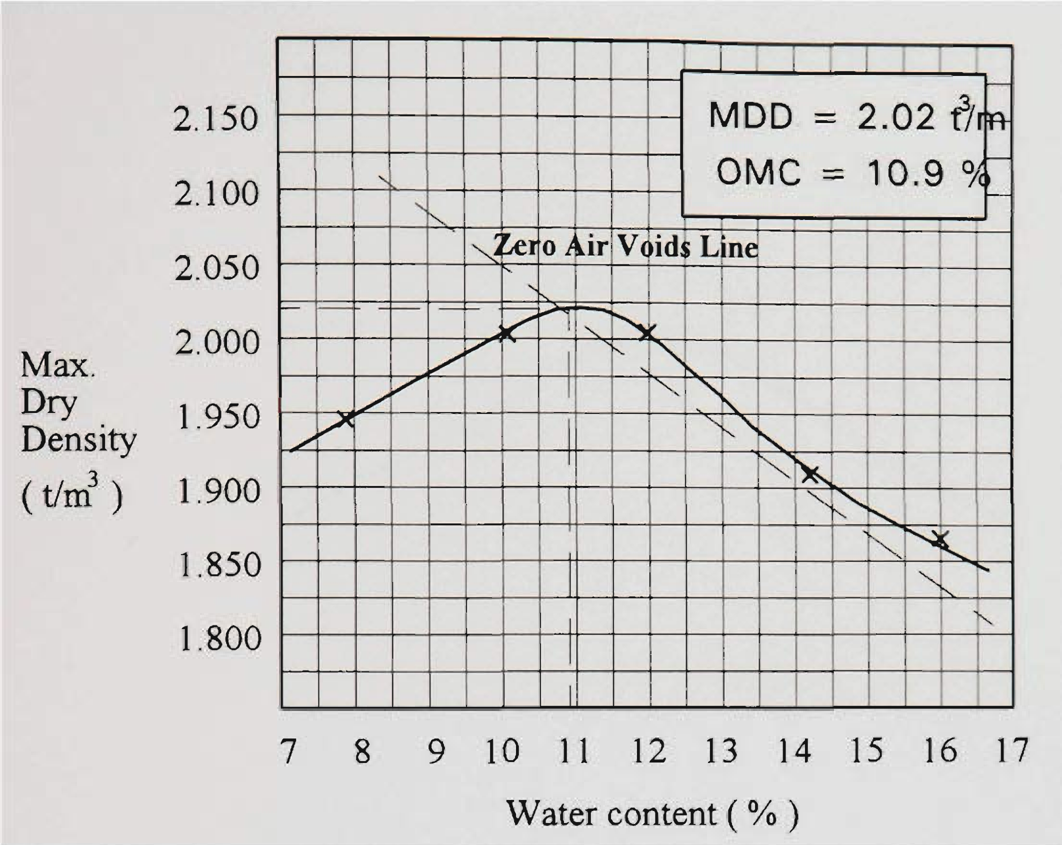
8. The air supply to the apparatus was opened and all taps closed off to ensure the sample is tested in the undrained condition.

9. All of the test conditions are checked on the main menu of the UMAT computer software which controls the test.

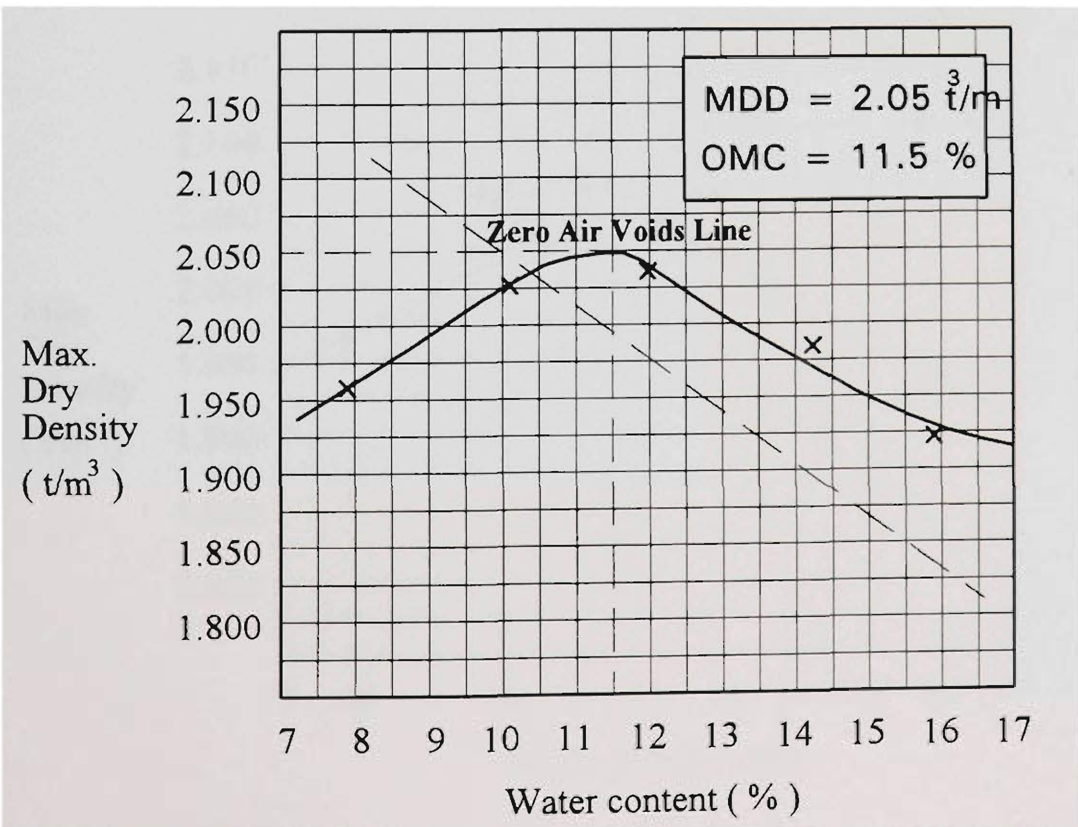
10. Once the test is started the computer software first performs the pre-conditioning stage and then proceeds to the main test. The results of the test are output to a computer file.

APPENDIX C: RTL AND COMPACTION RESULTS

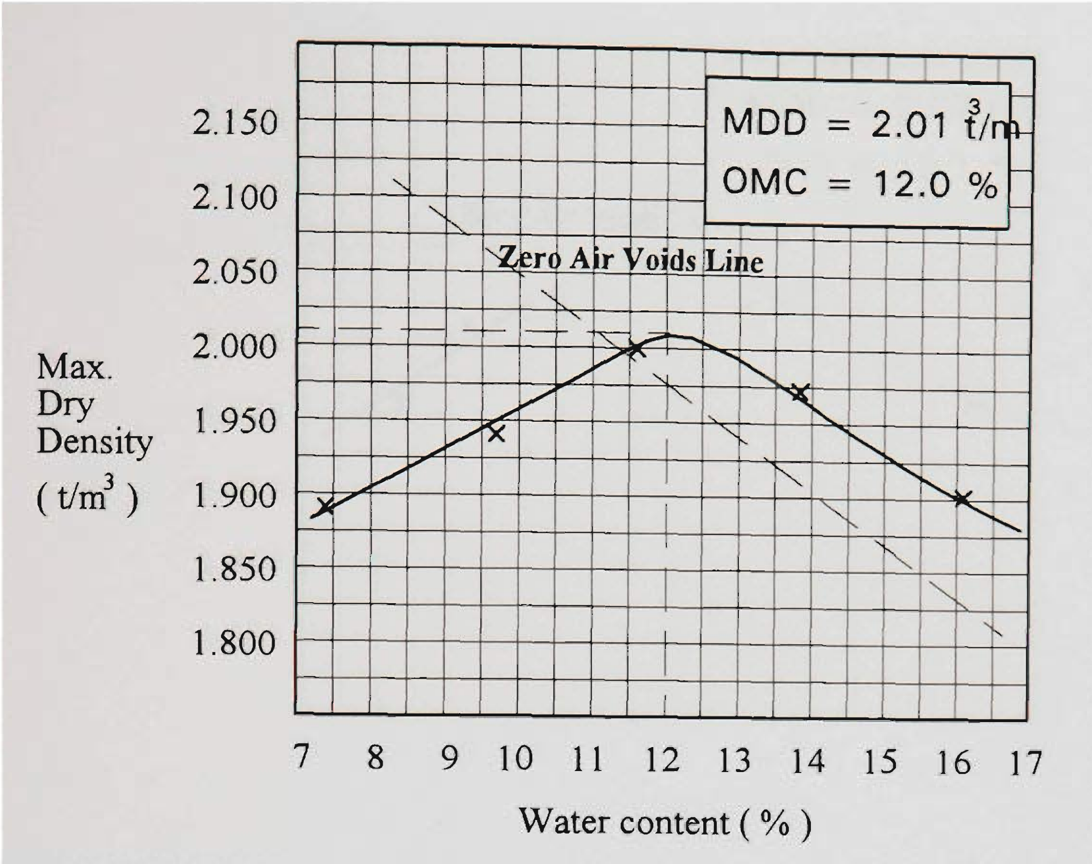
- Compaction curves
- Pre-conditioning graphs
- Stage modulus results
- Bulk modulus graphs
- Contour design charts
- Permanent strain test results



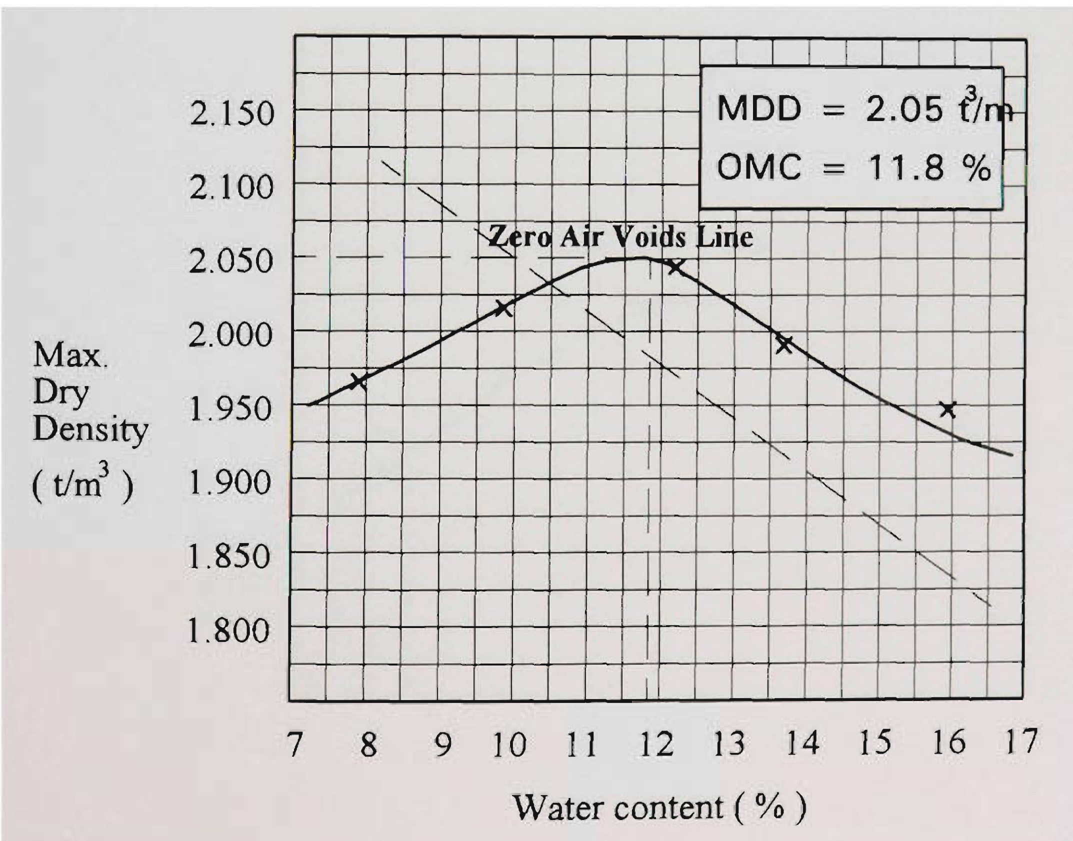
Modified Compaction Curve Monthly Sample One (MS1)



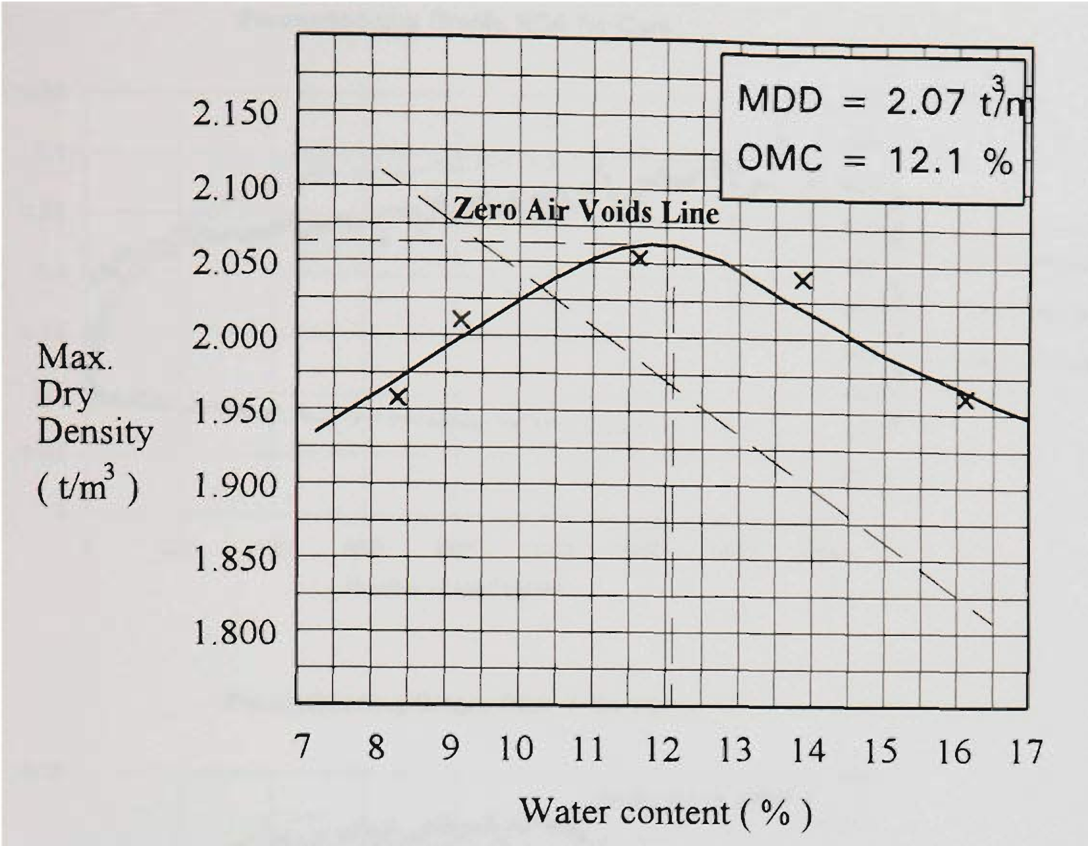
Modified Compaction Curve Monthly Sample Two (MS2)



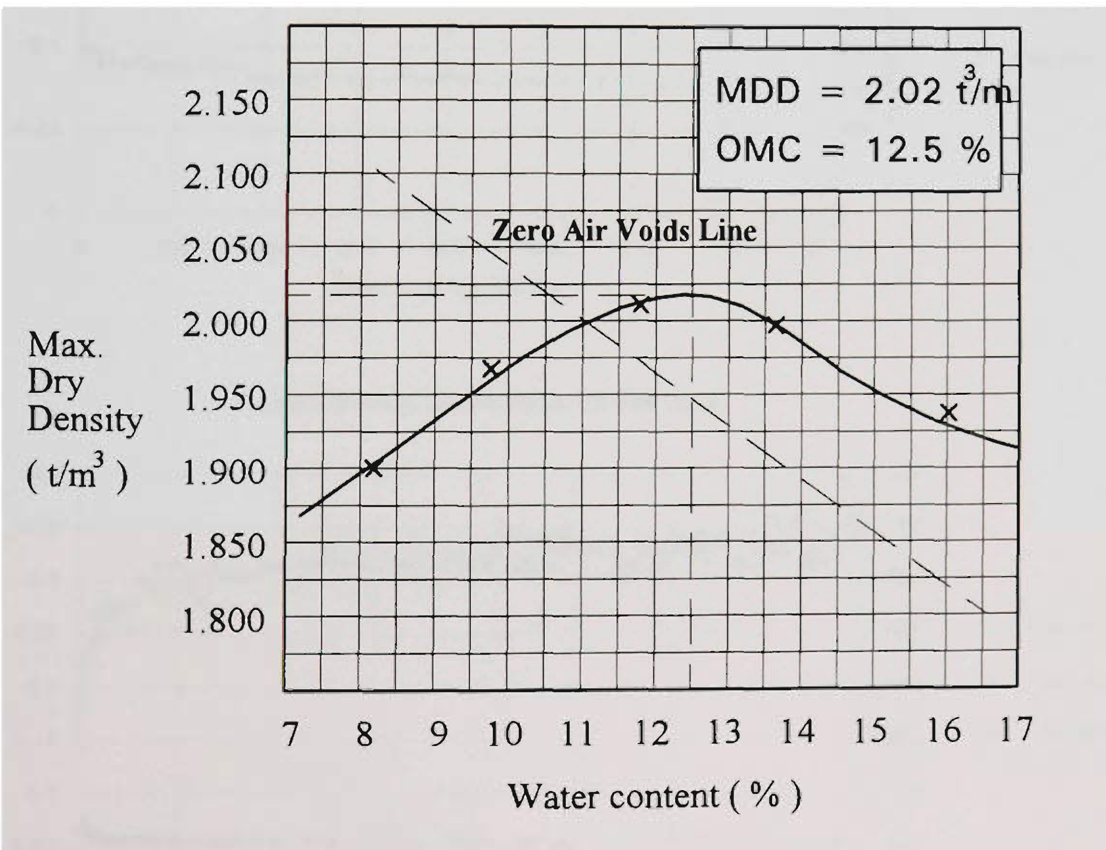
Modified Compaction Curve Monthly Sample Three (MS3)



Modified Compaction Curve Monthly Sample Four (MS4)

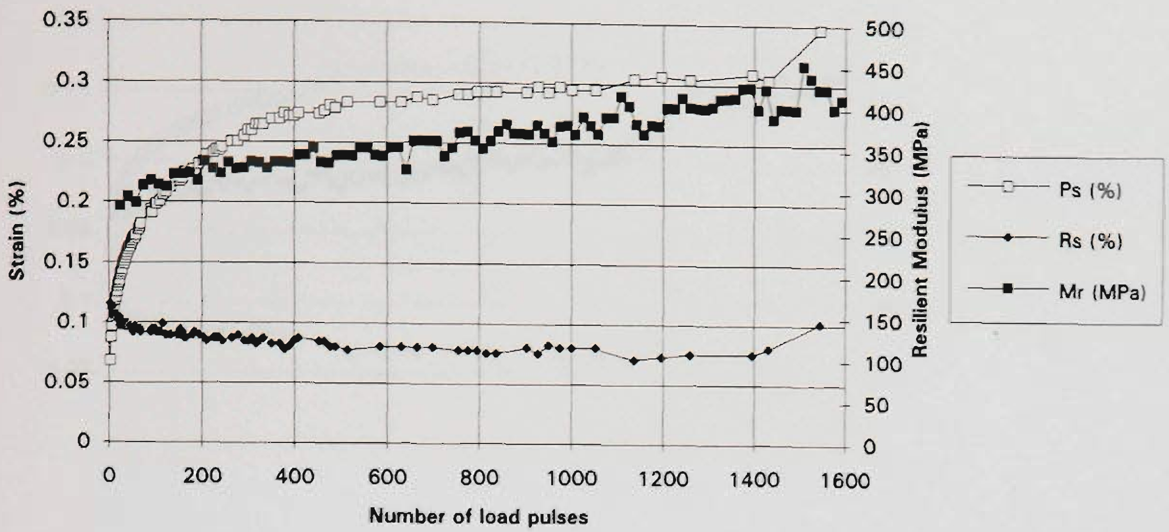


Modified Compaction Curve Monthly Sample Five (MS5)

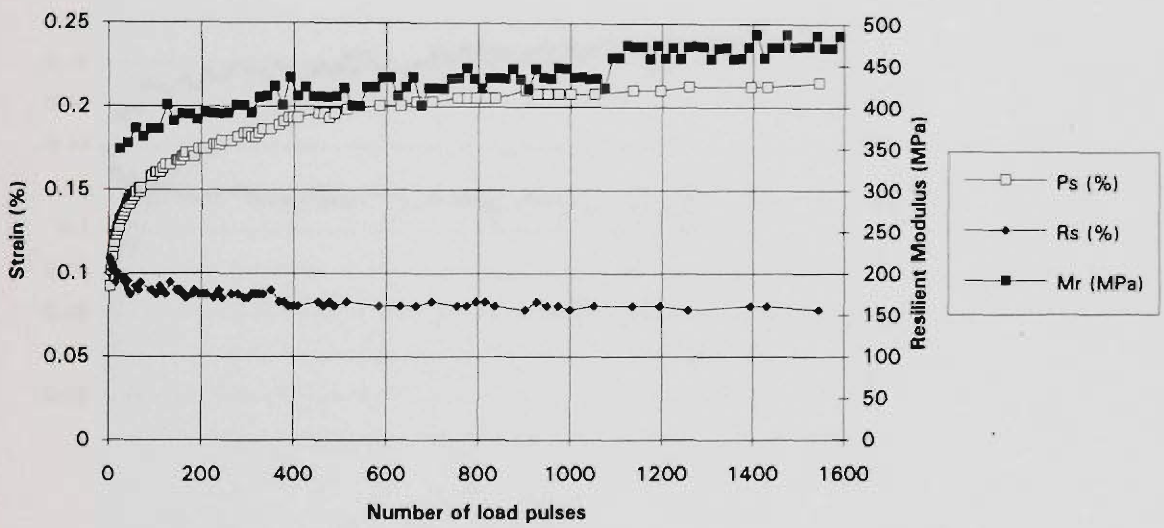


Modified Compaction Curve Monthly Sample Six (MS6)

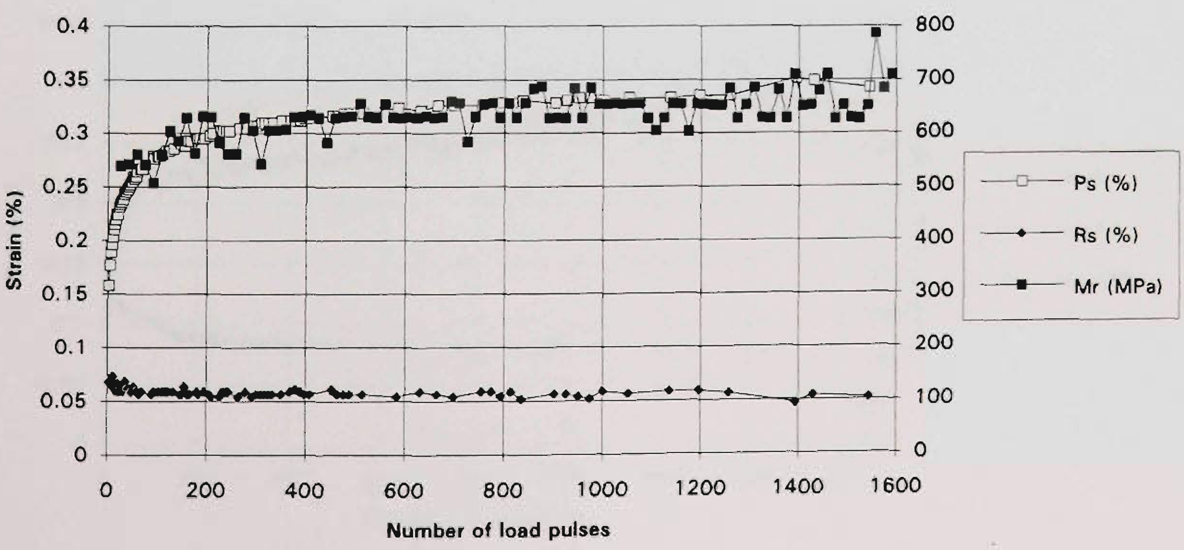
Preconditioning Graph: RCA No-Cure



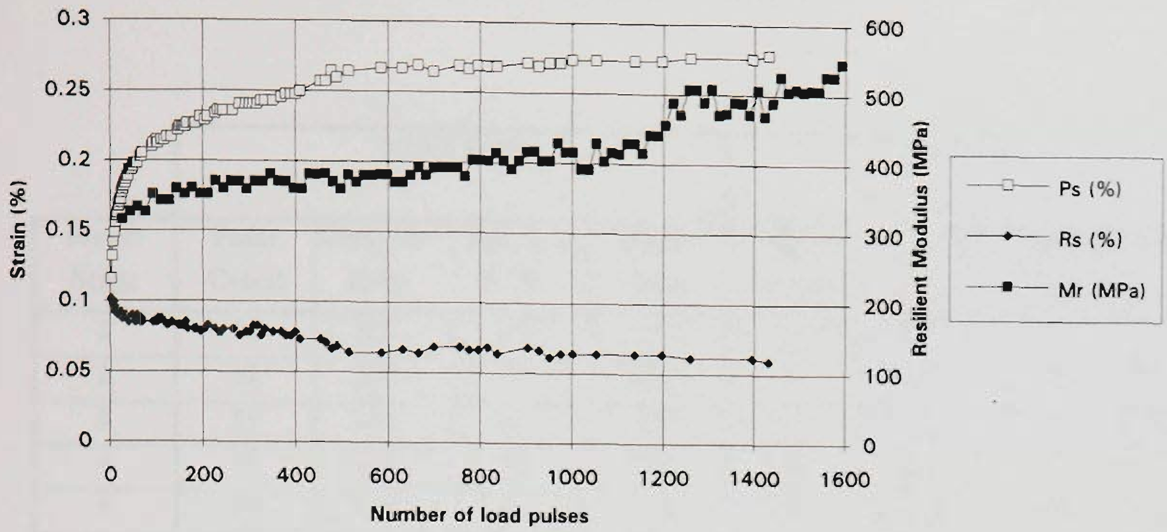
Preconditioning Graph: RCA 7 day cure



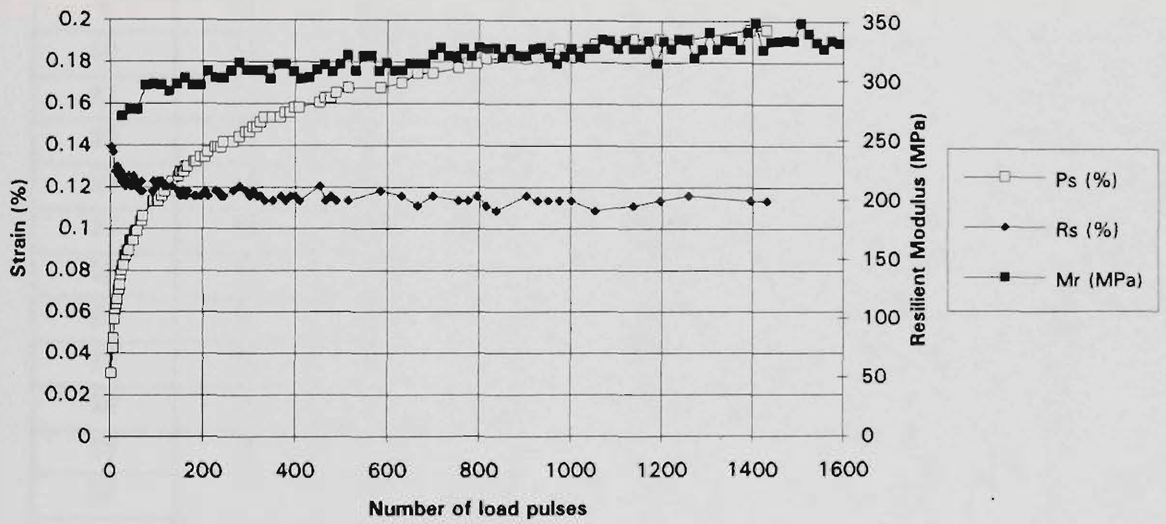
Preconditioning Graph: RCA 28 day cure



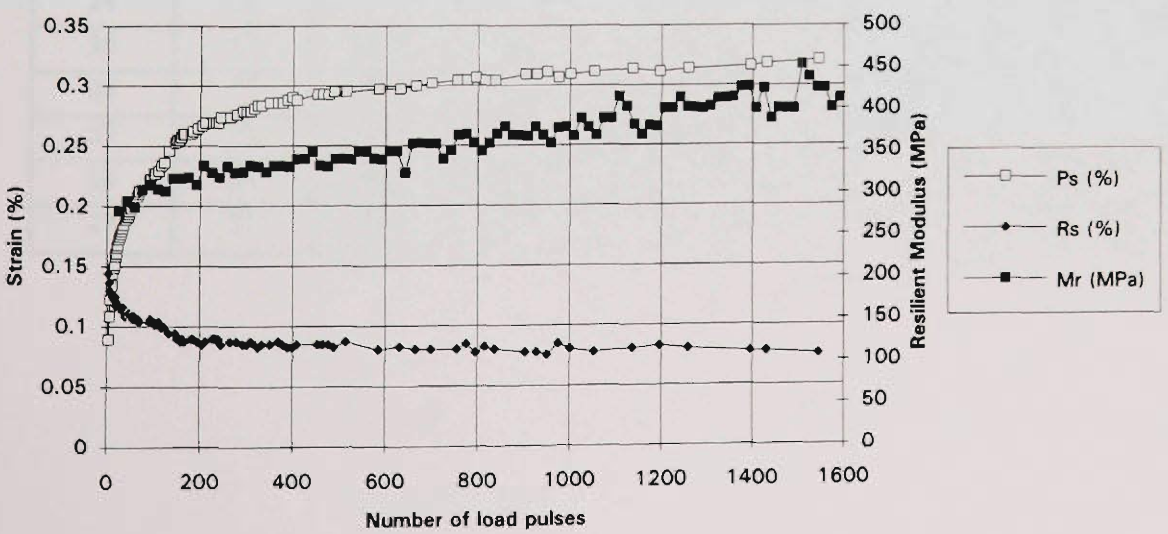
Preconditioning Graph: 75% of OMC



Preconditioning Graph: 30% Added brick



Preconditioning Graph: 80MPa source concrete



NOTE: DUE TO PROBLEMS WITH DATA FILES, PRE-CONDITIONING GRAPHS FOR THE 15%BR AND 32MPa SAMPLES COULD NOT BE INCLUDED.

STAGE MODULUS RESULTS

	0DAY Cure				7DAY Cure			
Stress Stage	**Pulse Count**	**Vert. Str KPa**	**onf. Str. KPa**	**R.Mod MPa**	**Pulse Count**	**Vert. Str KPa**	**onf. Str. KPa**	**R.Mod MPa**
1	51	122	10	117.4	51	121	8	96.7
2	51	247	21	162.1	51	245	20	158.7
3	51	373	36	186.3	51	370	33	191.3
4	51	501	49	198.7	51	498	46	219.4
5	51	618	64	213.3	51	623	60	245.8
6	51	103	16	68.9	51	103	16	80.5
7	51	210	40	115.7	51	209	38	137.6
8	51	318	60	162.2	51	317	59	180.9
9	51	426	83	204.5	51	425	83	219.8
10	51	535	107	239.8	51	535	106	257.1
11	51	640	129	279.1	51	639	127	291.1
12	51	89	22	66.9	51	88	22	82.5
13	51	181	51	134.3	51	182	52	152.7
14	51	278	81	179.3	51	276	80	190.8
15	51	376	112	222.7	51	371	108	231.1
16	51	471	139	260.6	51	470	139	270.5
17	51	566	169	296.9	51	562	165	307.7
18	51	78	27	69.3	51	77	28	92.6
19	51	163	63	158.6	51	160	61	150.9
20	51	248	98	209.8	51	246	96	209.6
21	52	331	132	264.2	51	328	130	243.6
22	51	417	167	283.6	51	413	163	283.7
23	51	500	199	341.3	51	496	197	325.4
24	51	69	32	71	54	69	33	95.8
25	67	147	71	151.6	53	146	71	170.5
26	71	223	111	234.6	69	220	110	233.5
27	71	300	150	269.4	51	297	148	260.4
28	53	375	189	304.9	57	372	186	315.4
29	51	450	226	344.1	51	447	222	344.9

STAGE MODULUS RESULTS

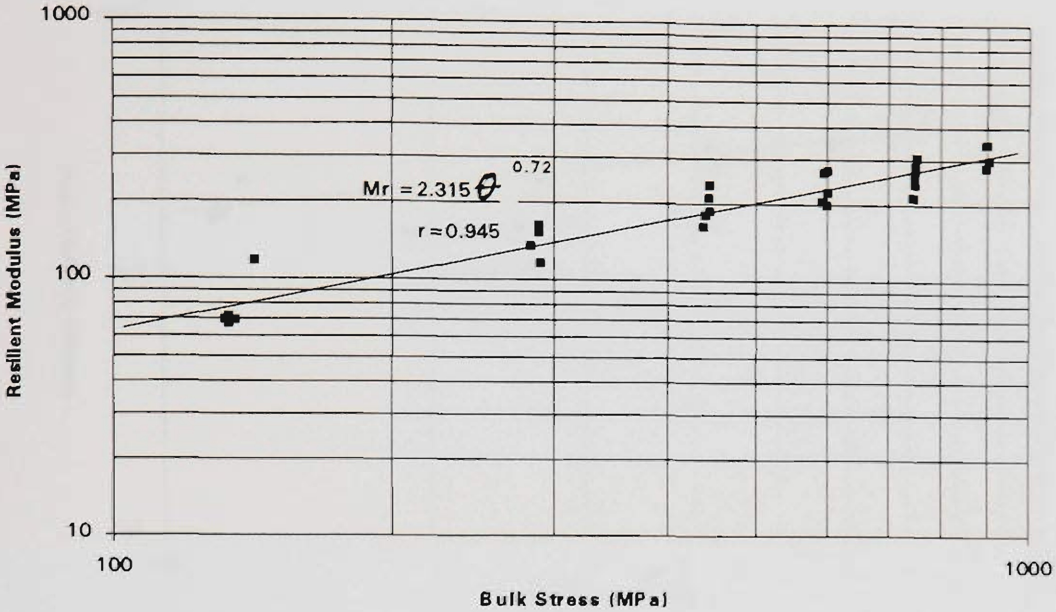
	28DAY Cure				75% of OMC			
Stress Stage	Pulse Count	Vert. Str KPa	Conf. Str. KPa	R.Mod MPa	Pulse Count	Vert. Str KPa	Conf. Str. KPa	R.Mod MPa
1	76	115	4	237.4				
2	51	237	13	299.4	51	246	20	240.1
3	51	362	26	328.6	51	372	33	270.9
4	51	489	39	359.3	51	503	51	324.6
5	51	642	52	385.1	51	626	63	313.8
6	51	96	10	186.3	51	103	15	142.7
7	51	202	32	240.9	51	212	40	182.4
8	51	310	54	275.1	51	323	65	237.4
9	51	417	77	327.2	51	432	90	296.9
10	51	527	101	370.6	51	540	111	343.8
11	51	633	122	397.6	60	646	133	381.6
12	51	83	17	173.9	51	91	24	143.1
13	51	174	45	208.8	51	187	56	199.6
14	53	270	75	262.3	51	285	87	263.2
15	51	366	104	323.3	51	381	118	330.3
16	51	462	133	386.3	51	475	143	381.8
17	51	558	162	431.5	109	569	171	413.5
18	69	72	21	165	55	80	29	137.1
19	61	158	59	203.7	51	171	70	217.6
20	51	241	92	282.6	51	255	104	280.1
21	55	324	126	337.4	51	337	137	343
22	51	410	161	410.3	51	420	169	397
23	51	493	194	446.2	83	503	202	443.1
24	114	62	26	174.6	81	71	34	135.1
25	60	140	65	231.2	53	154	78	220.3
26	51	219	107	297	71	231	118	306.2
27	51	294	145	358.7	61	304	154	358.2
28	51	369	183	447.7	51	379	191	405
29	61	444	220	493	51	453	227	463.9

STAGE MODULUS RESULTS

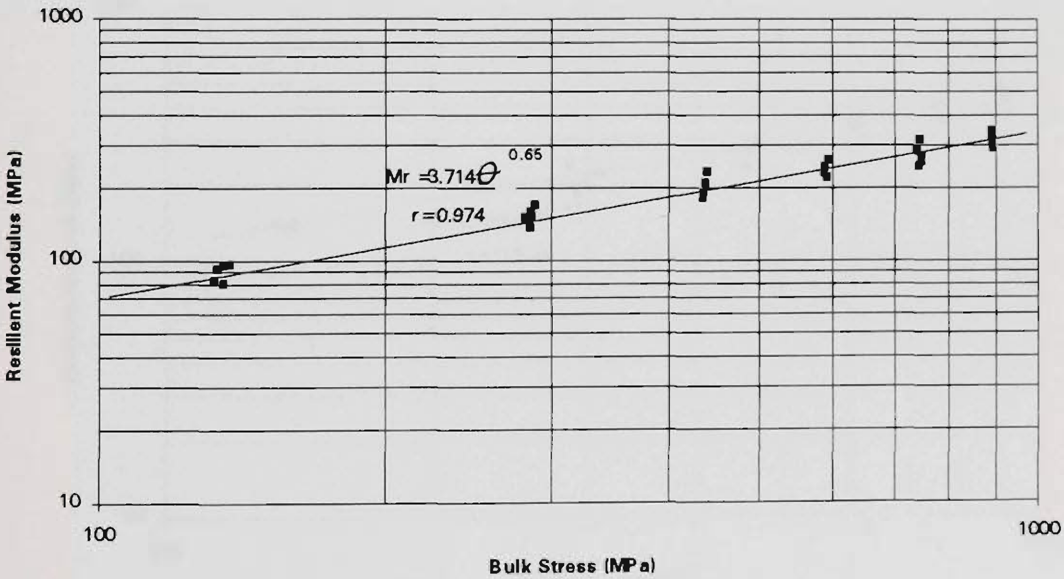
	32MPa Source Concrete				80MPa Source Concrete			
Stress Stage	Pulse Count	Vert. Str KPa	onf. Str. KPa	R.Mod MPa	Pulse Count	Vert. Str KPa	onf. Str. KPa	R.Mod MPa
1	51	129	3	152.7	51	121	8	102.1
2	51	263	7	203.8	51	245	20	136.5
3	51	399	17	212.9	51	370	33	158.3
4	51	537	28	228.5	51	498	46	174.4
5	51	652	41	238.6	51	623	60	210.8
6	51	114	9	102.8	51	103	16	74.7
7	51	236	26	136.1	51	209	38	115
8	51	358	43	174.9	51	317	59	149.5
9	51	480	58	202.5	51	425	83	178.8
10	51	602	75	227.3	51	535	106	200.6
11	51	700	92	240	51	639	127	245.5
12	51	96	15	87.6	51	88	22	76
13	51	204	39	118	51	182	52	137.8
14	51	308	62	155.5	51	276	80	176
15	51	415	84	192.1				
16	51	520	106	227.2				
17	51	622	128	261.5				
18	51	82	21	82.6				
19	51	172	51	119.1				
20	51	261	80	160				
21	51	350	111	203.4				
22	51	442	142	245.5				
23	51	534	172	301.2				
24	51	66	28	73.8				
25	52	142	66	119.2				
26	51	217	105	177.1				
27	51	292	143	228.7				
28	51	370	182	277				
29	51	445	221	332				

STAGE MODULUS RESULTS

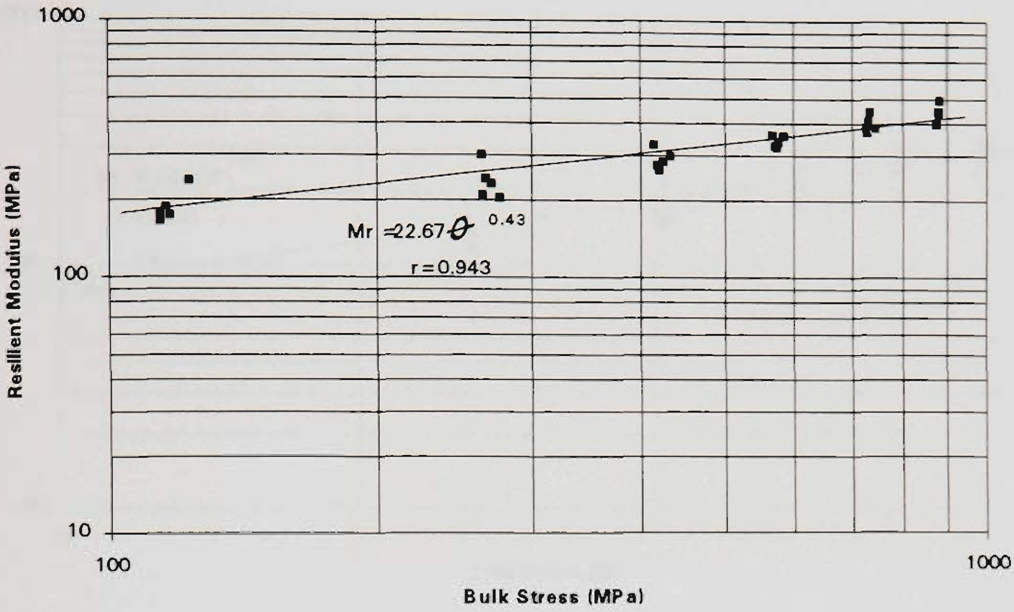
	15% Added Brick				30% Added Brick			
Stress Stage	Pulse Count	Vert. Str KPa	onf. Str. KPa	R.Mod MPa	Pulse Count	Vert. Str KPa	onf. Str. KPa	R.Mod MPa
1	51	122	10	105.8	51	110	0	79.3
2	51	247	21	132.7	51	236	10	107.5
3	51	373	36	158.2	51	365	27	133.3
4	51	501	49	173.1	51	493	41	150.7
5	51	618	64	182	51	612	57	168.1
6	51	103	16	74.6	51	93	6	60.2
7	51	210	40	117.4	51	201	28	88.6
8	51	318	60	148	51	309	52	116.7
9	51	426	83	177.5	51	417	75	149
10	51	535	107	199.8	51	527	99	178.5
11	51	640	129	245.3	51	631	119	203.9
12	51	89	22	78.6	51	79	11	60
13	51	181	51	138.6	51	172	41	91.4
14	51	278	81	176.8	51	269	71	126.1
15	51	376	112	206.9	51	364	101	157.4
16	51	471	139	248.7	51	463	131	188.6
17	51	566	169	269.5	51	555	157	221
18	51	78	27	78.7	51	66	16	58.2
19	51	163	63	142.5	51	152	52	104
20	51	248	98	191.8	51	238	88	136.1
21	52	331	132	248	51	323	124	166
22	51	417	167	264.5	51	406	156	201.5
23	51	500	199	310.9	51	489	189	233.8
24	51	69	32	90.6	52	61	22	65
25	67	147	71	158.4	51	140	63	110.4
26	71	223	111	218.4	51	215	103	139.8
27	71	300	150	249.1	51	290	139	183.8
28	53	375	189	309.5	51	367	179	205
29	51	450	226	337.9	51	439	213	240.5



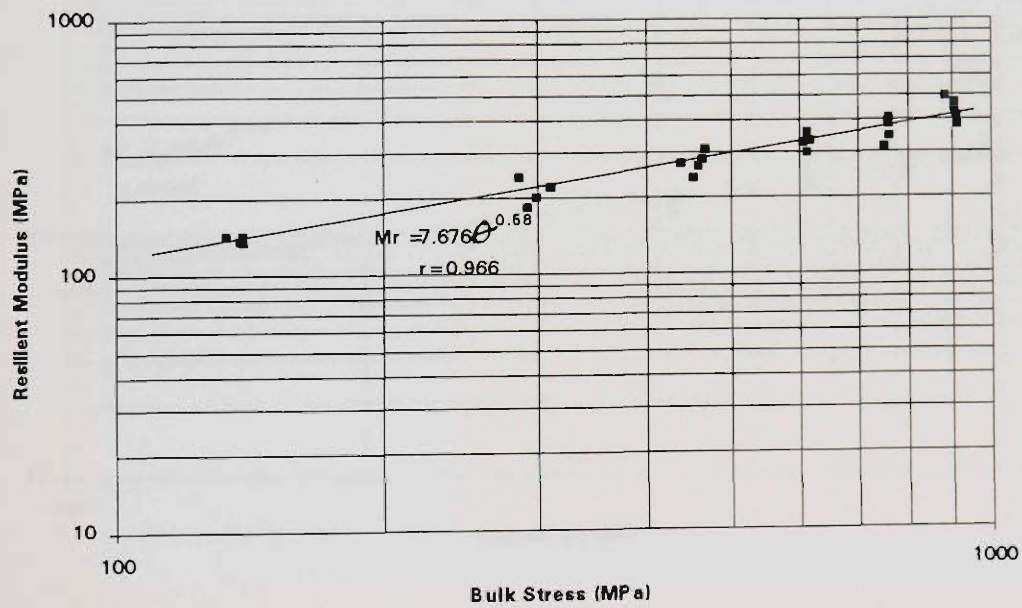
RCA: Bulk stress versus resilient modulus



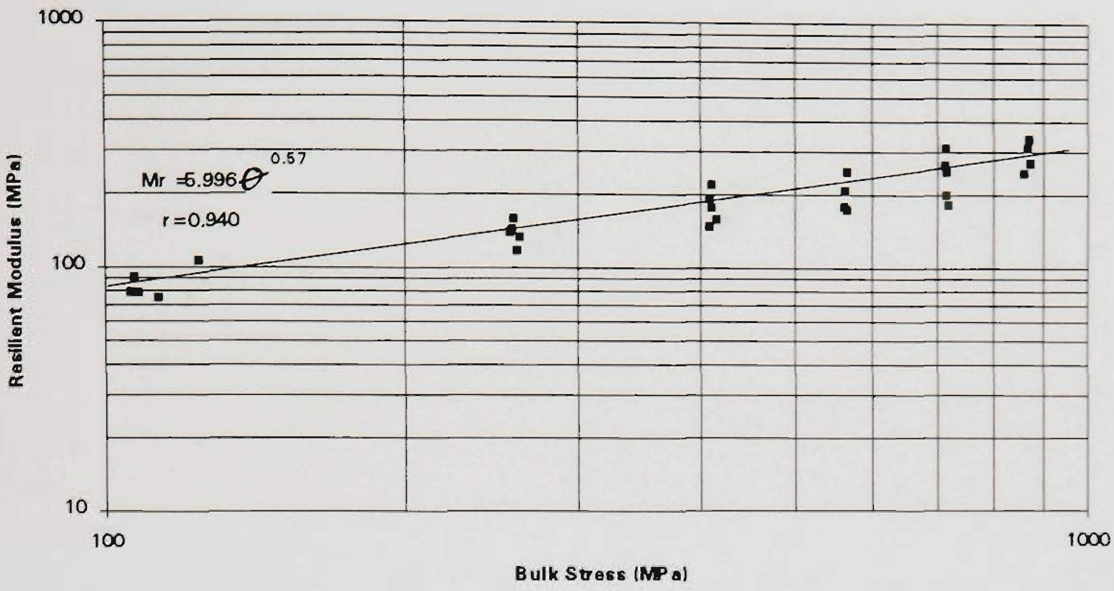
7Day: Bulk stress versus resilient modulus



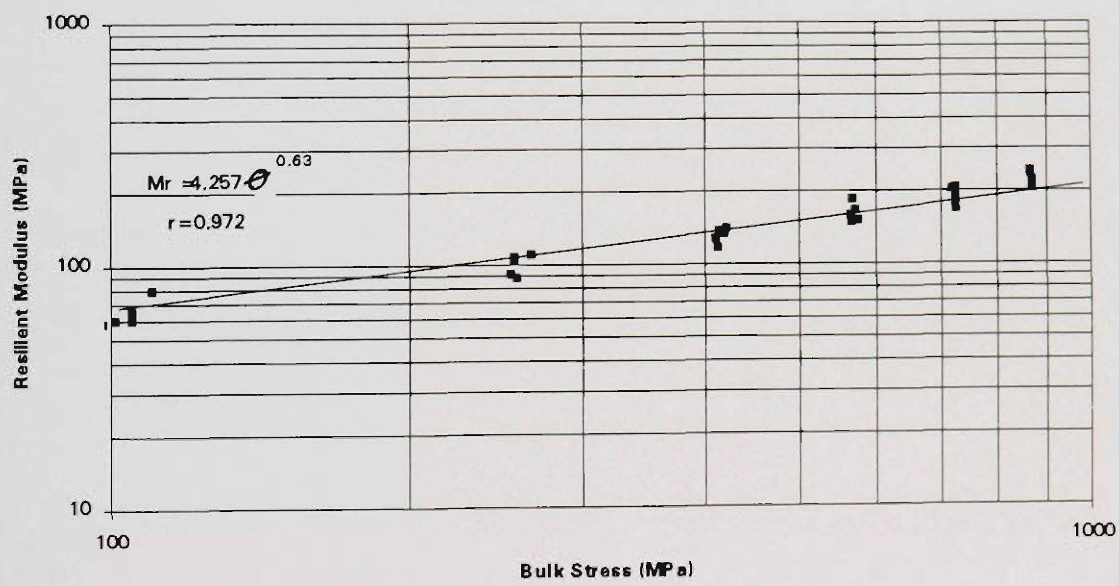
28Day: Bulk stress versus resilient modulus



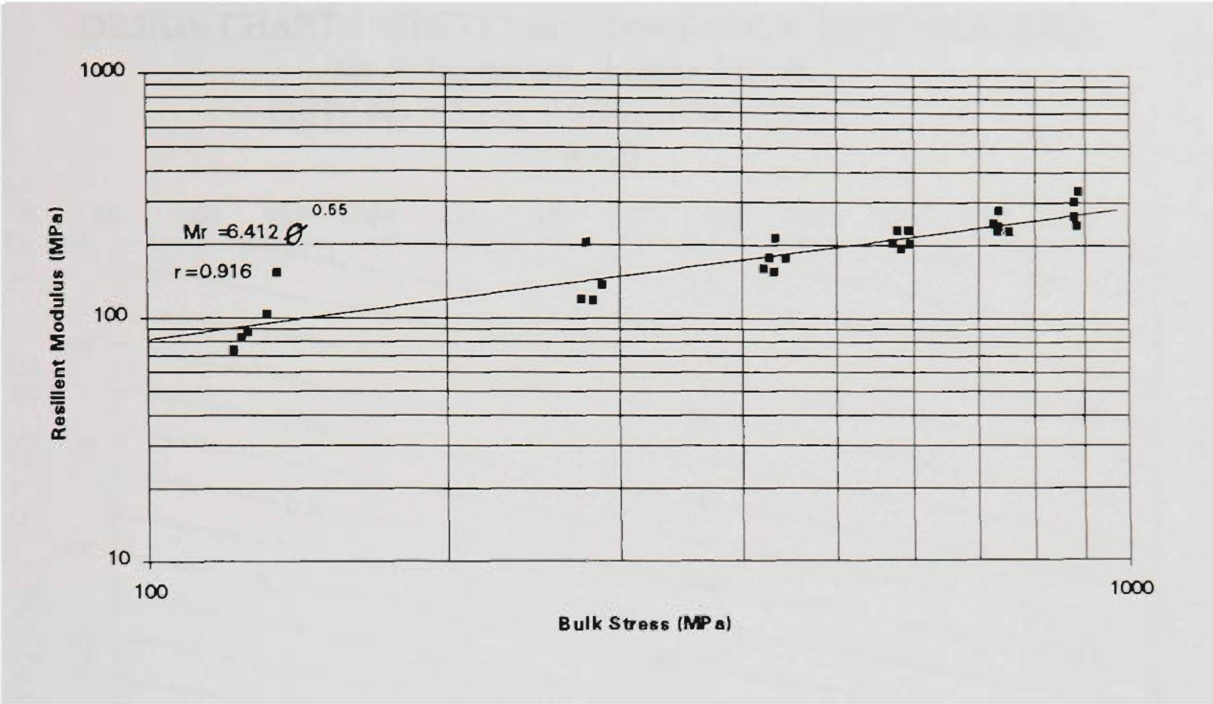
75%OMC: Bulk stress versus resilient modulus



15%BR: Bulk stress versus resilient modulus



30%BR: Bulk stress versus resilient modulus



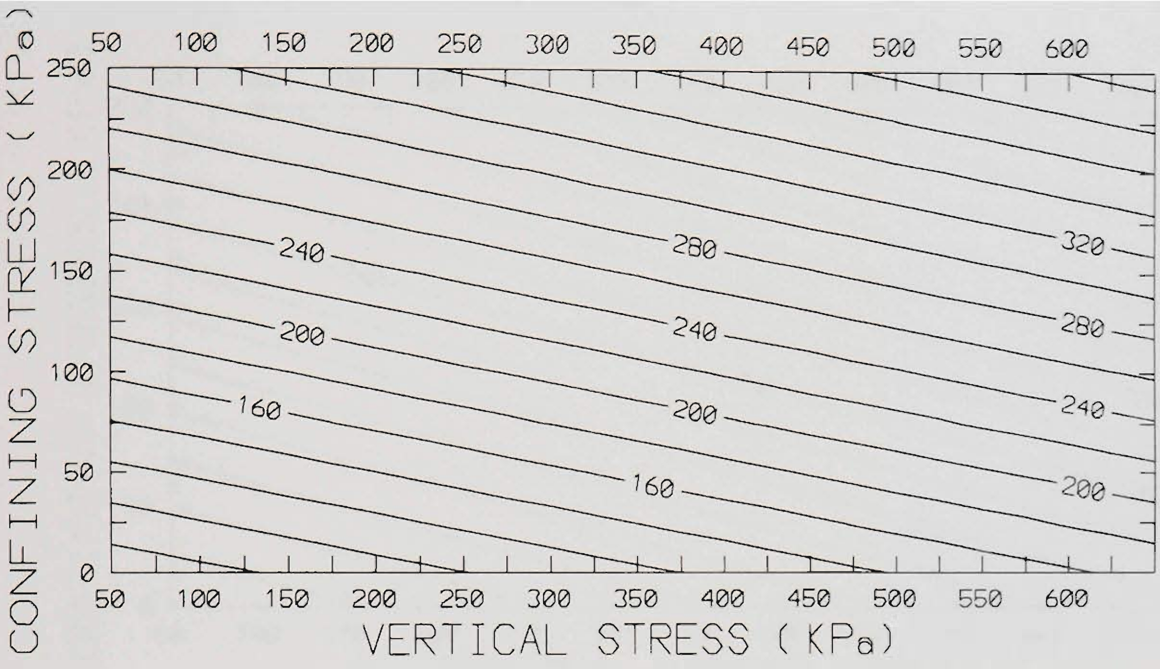
32MPa: Bulk stress versus resilient modulus

DESIGN CHART 1: RECYCLED CONCRETE AGGREGATE (0Day)

No curing period.- **Linear Model.**

Eq(1): $M_r = 58.04 + 0.166x + 0.9703y$

$r = 0.970$

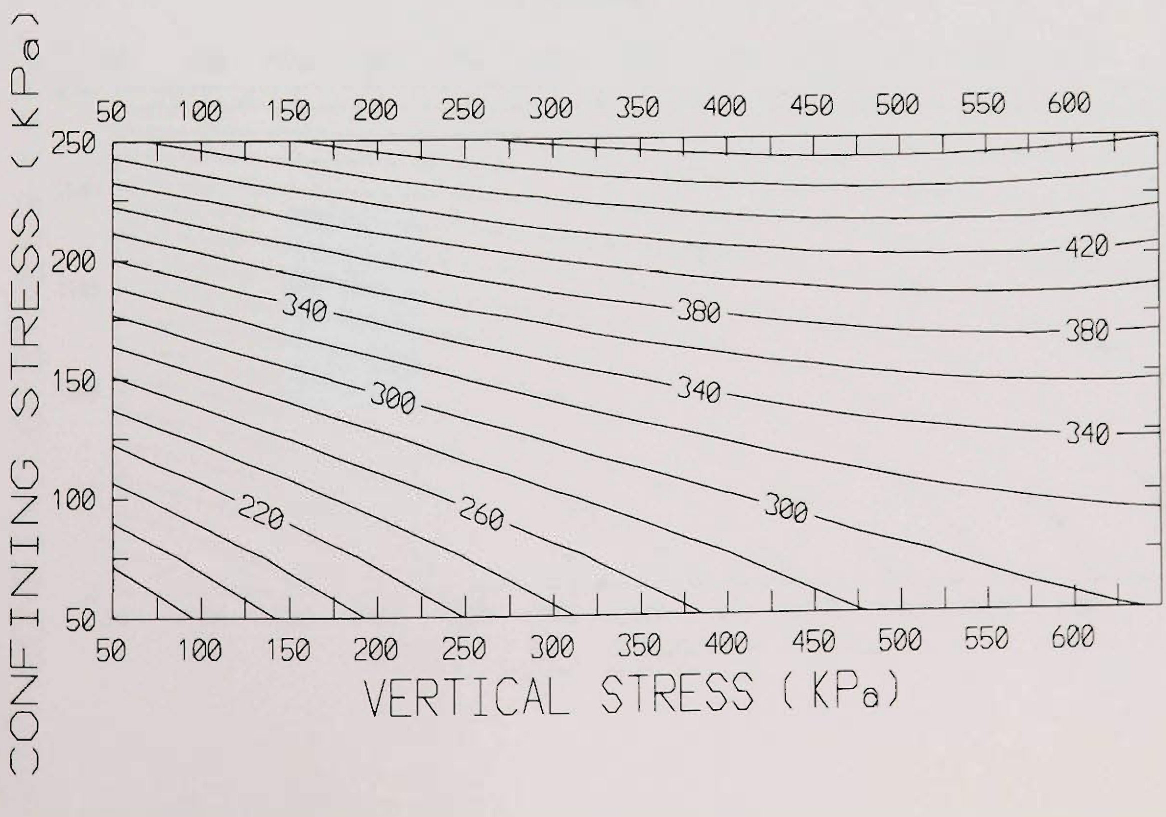


DESIGN CHART 2: RECYCLED CONCRETE AGGREGATE (0Day)

No curing period.- **Quadratic Model.**

Eq.(2): $M_r = 23.5 + 0.449x + 0.9258y - 0.0002899x^2 - 0.0009274xy + 0.001338y^2$

$r = 0.982$

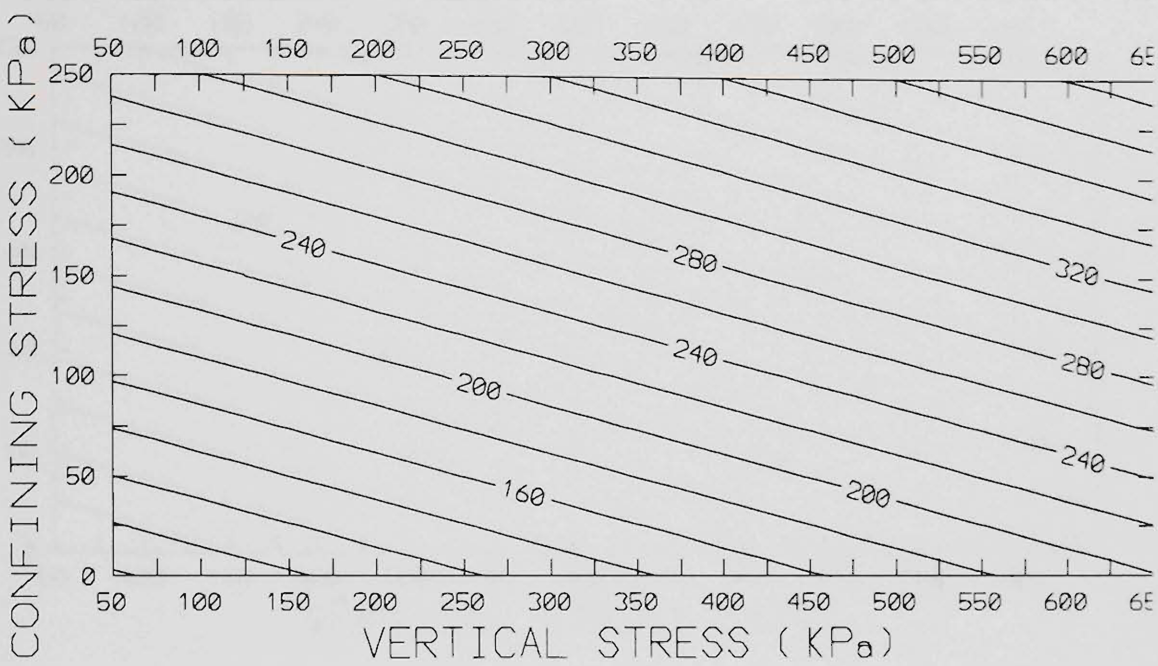


DESIGN CHART 3: RECYCLED CONCRETE AGGREGATE (7Day)

7 Day curing period.- **Linear Model.**

Eq.(3): $M_r = 67.29 + 0.2017x + 0.8485y$

$r = 0.986$

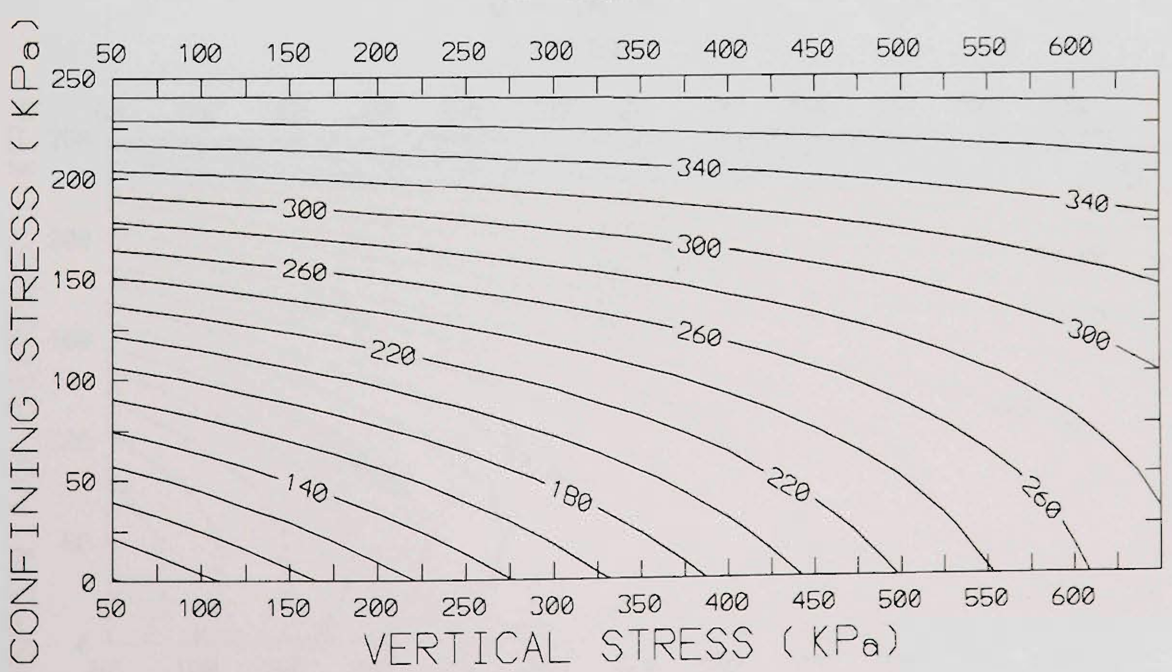


DESIGN CHART 4: RECYCLED CONCRETE AGGREGATE (7Day)

7 Day curing period.- **Quadratic Model.**

Eq.(4): $M_r = 40.13 + 0.3611x + 1.063y - 0.001472xy + 0.001443y^2$

$r = 0.992$

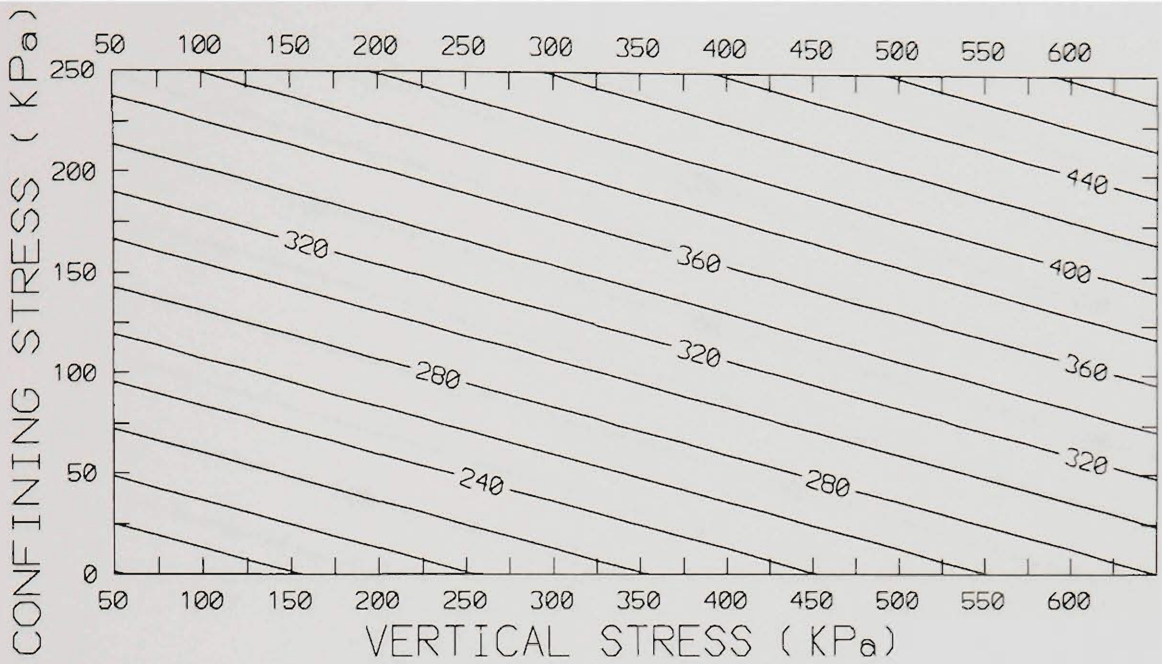


DESIGN CHART 5: RECYCLED CONCRETE AGGREGATE (28Day)

28 Day curing period.- **Linear Model.**

Eq.(5): $M_r = 148.6 + 0.3137x + 0.7527y$

$r = 0.961$

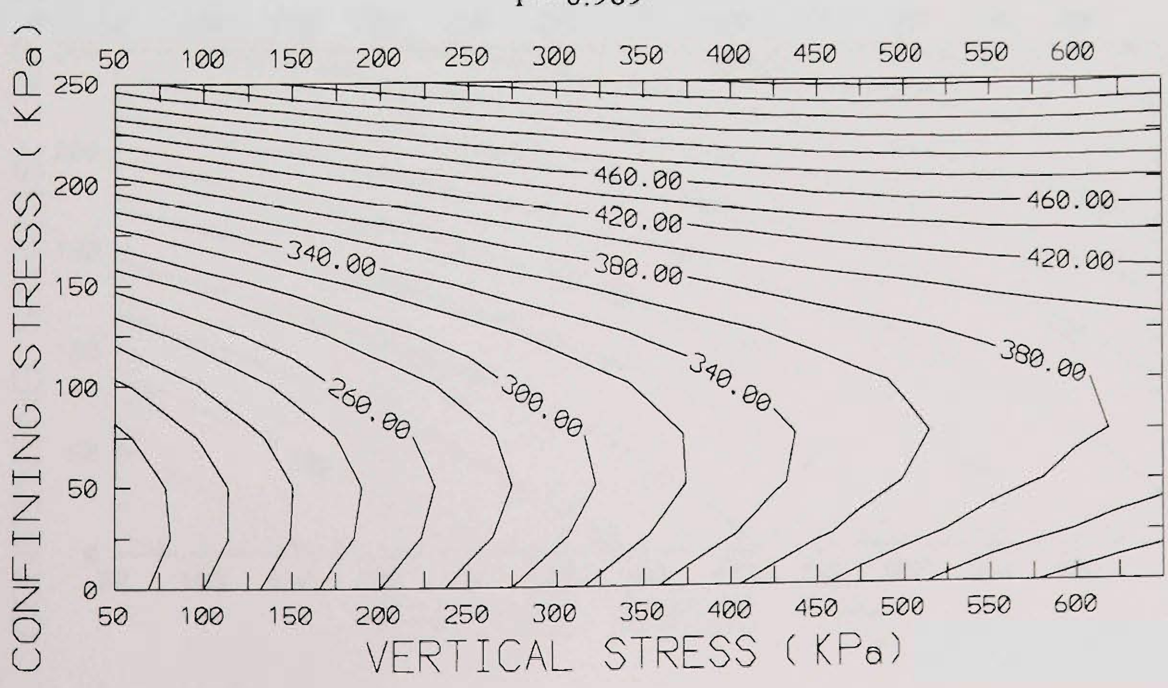


DESIGN CHART 6: RECYCLED CONCRETE AGGREGATE (28Day)

28 Day curing period.- **Quadratic Model.**

Eq.(6): $M_r = 132.8 + 0.707x - 0.3858y - 0.0003634x^2 - 0.001369xy + 0.007352y^2$

$r = 0.989$

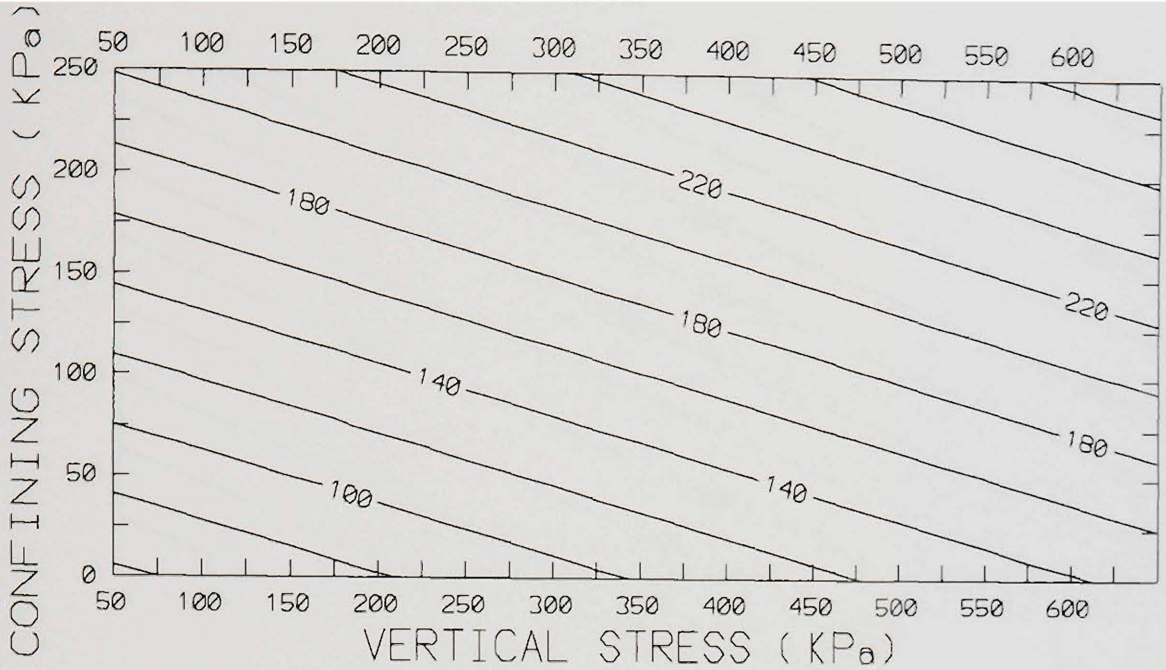


DESIGN CHART 7: RECYCLED CONCRETE AGGREGATE (30BR)

30% of brick added.- **Linear Model.**

Eq.(7): $M_r = 48.86 + 0.1487x + 0.5802y$

$r = 0.990$

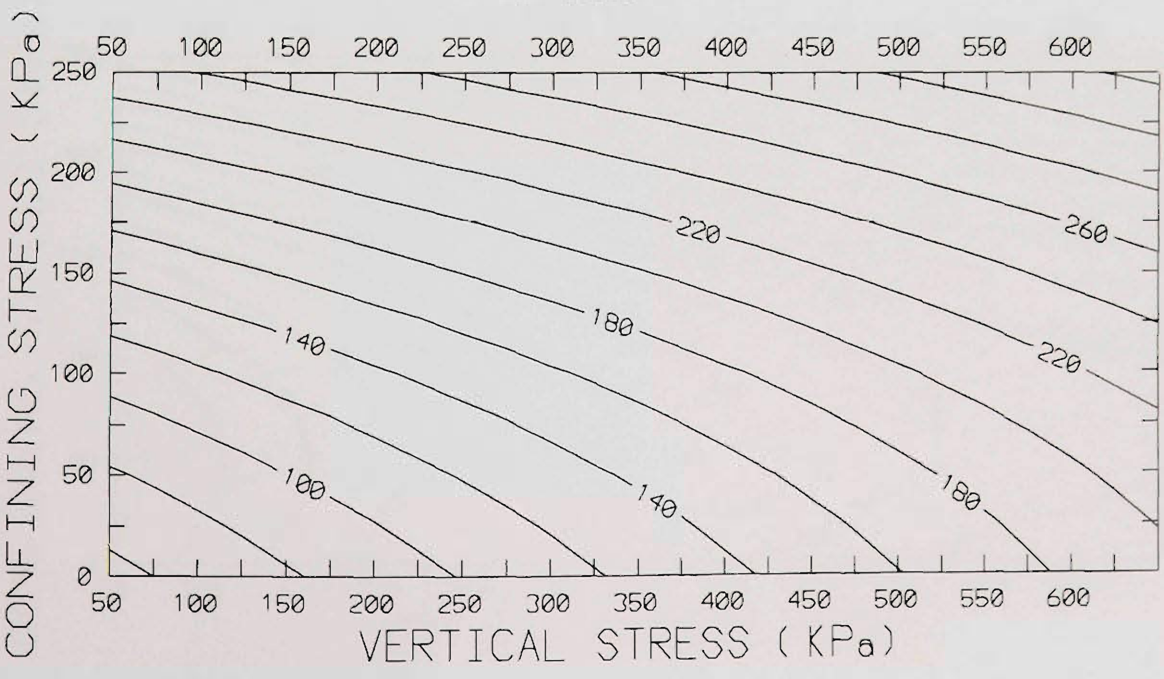


DESIGN CHART 8: RECYCLED CONCRETE AGGREGATE (30BR)

30% of brick added.- **Quadratic Model.**

Eq.(8): $M_r = 42.32 +0.234x + 0.4239y - 0.0003209xy + 0.00123y^2 + 0.00123y^2$

$r = 0.988$

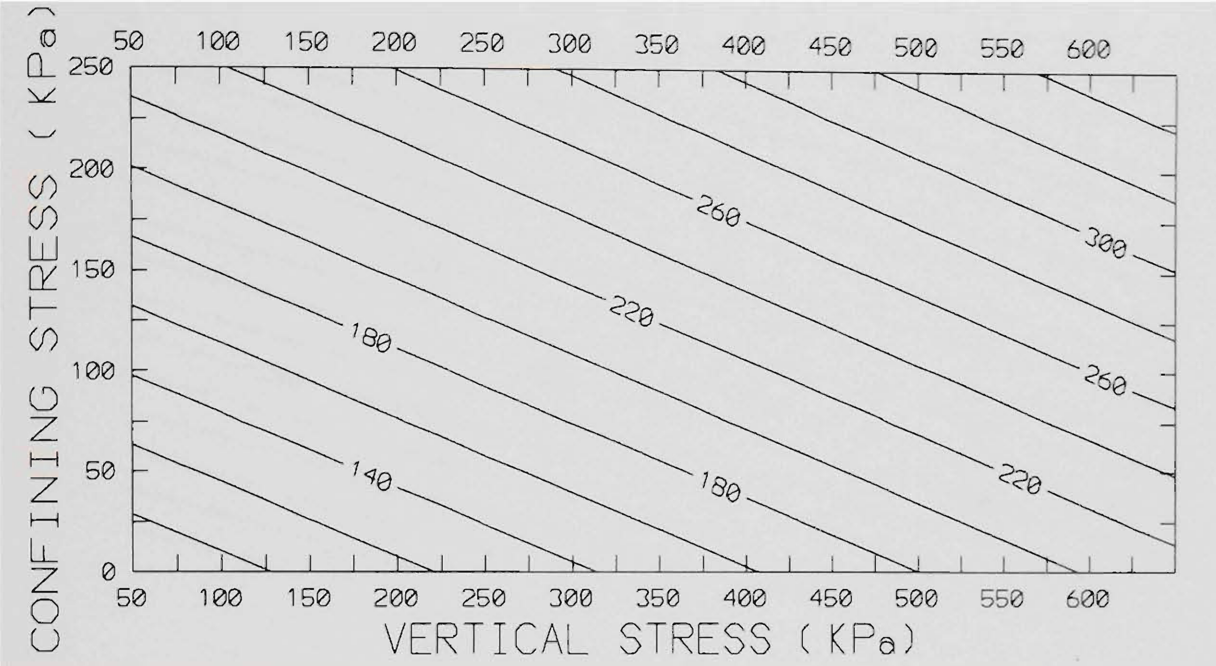


DESIGN CHART 9: RECYCLED CONCRETE AGGREGATE (32MPa)

32MPa source concrete.- **Linear Model.**

Eq.(9): $M_r = 72.48x + 0.2149x + 0.5703y$

$r = 0.922$

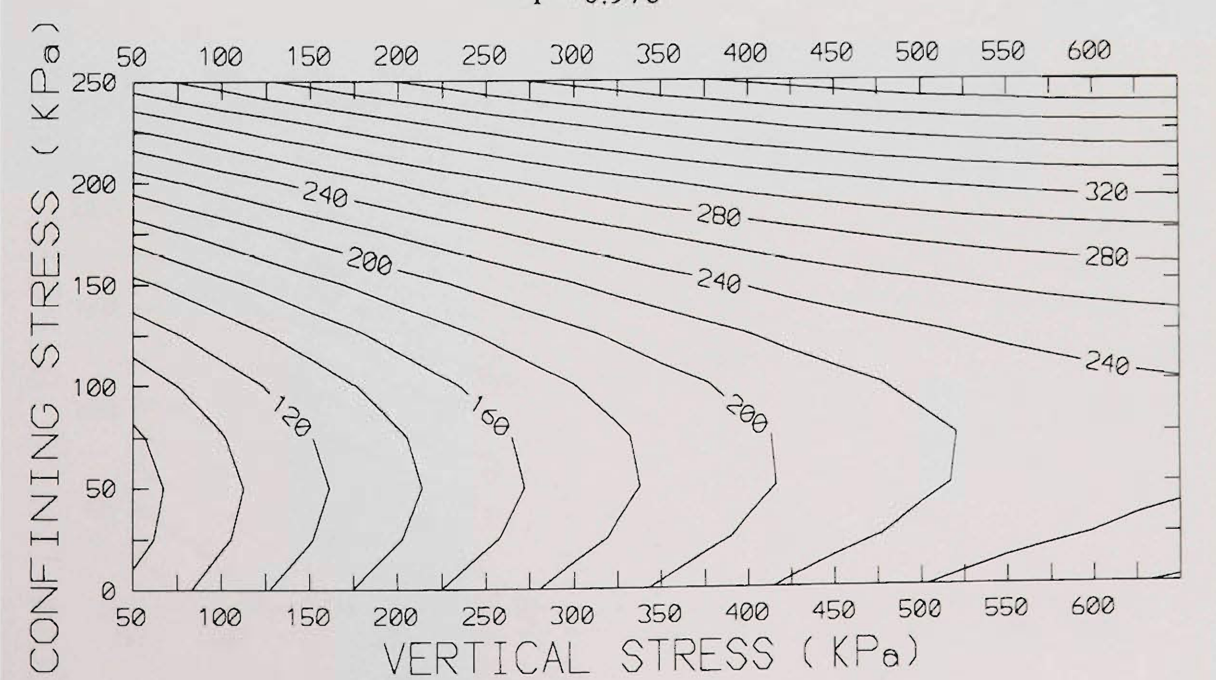


DESIGN CHART 10: RECYCLED CONCRETE AGGREGATE (32MPa)

32MPa source concrete.- **Quadratic Model.**

Eq.(10): $M_r = 58.5 + 0.5238x - 0.5038y - 0.0004553xy - 0.0003245x^2 + 0.00576y^2$

$r = 0.978$

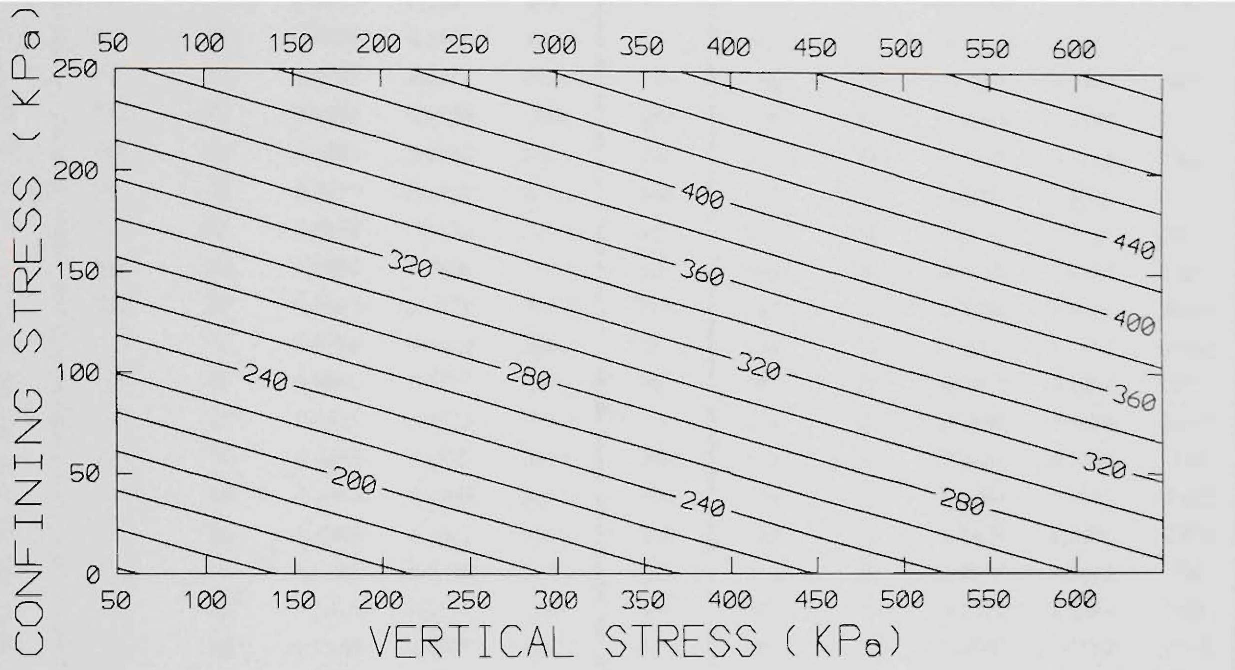


DESIGN CHART 11: RECYCLED CONCRETE AGGREGATE (75OMC)

75% of OMC.- **Linear Model.**

Eq.(11): $M_r = 103.8 + 0.2597x + 1.039y$

$r = 0.983$

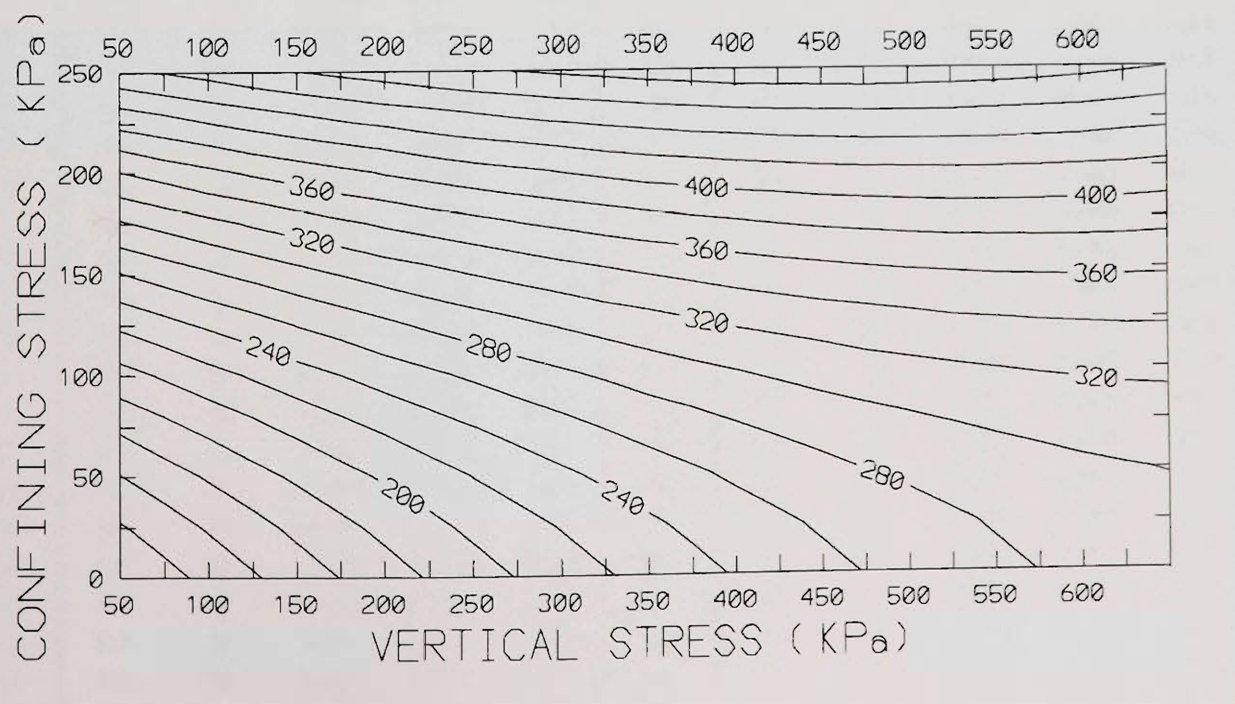


DESIGN CHART 12: RECYCLED CONCRETE AGGREGATE (75OMC)

75% of OMC.- **Quadratic Model.**

E(12): $M_r = 73.03 + 0.5592x + 0.6819y - 0.0003452x^2 - 0.0009549xy + 0.002808y^2$

$r = 0.991$



PERMANENT STRAIN TEST DATA

Pulse Count	Vert. Stress (kPa)	Conf. Stress (kPa)	Perm. Strain (%)	Res. Strain (%)	Res. Mod (MPa)	Pulse Count	Vert. Stress (kPa)	Conf. Stress (kPa)	Perm. Strain (%)	Res. Strain (%)	Res. Mod (MPa)
3	610	76	0.0519	0.17	323.5	233	514	73	0.21	0.1585	287.6
5	522	77	0.0614	0.1629	282.7	239	514	73	0.2124	0.1561	292
7	517	73	0.0684	0.1582	289.5	245	515	73	0.2124	0.1632	279.7
9	513	73	0.0708	0.1606	283.4	265	513	73	0.2171	0.1585	287.2
11	514	72	0.0755	0.1559	292.7	279	514	73	0.2195	0.1608	283.7
13	514	72	0.0802	0.1559	293	293	513	72	0.2266	0.1585	287.5
15	512	72	0.0802	0.1582	287.1	301	515	72	0.2242	0.1608	284.1
17	511	72	0.0873	0.1559	291.2	309	514	73	0.2289	0.1561	291.5
19	513	73	0.0873	0.1583	287.2	317	514	73	0.2313	0.1585	287.3
21	514	73	0.0897	0.1606	283.5	325	514	73	0.2313	0.1585	287.3
23	512	72	0.0968	0.1559	291.4	333	512	72	0.2336	0.1585	287.2
25	513	72	0.0968	0.1583	288.2	351	514	73	0.236	0.1561	291.9
27	513	72	0.0991	0.1583	287.5	369	515	72	0.2407	0.1561	292.5
29	512	72	0.1015	0.1583	287.4	379	513	72	0.2384	0.1609	283.2
31	513	73	0.1038	0.1583	287.5	389	513	72	0.2431	0.1561	292
33	512	72	0.1086	0.1559	291.6	399	515	73	0.2454	0.1561	292.5
35	511	72	0.1086	0.1607	282.2	409	515	73	0.2478	0.1538	296.8
37	513	72	0.1109	0.1583	287.4	453	514	72	0.2525	0.1562	292
39	512	72	0.1156	0.1583	287	465	516	73	0.2572	0.1514	302
41	511	72	0.1156	0.1607	282.3	477	515	73	0.2549	0.1562	292.8
43	513	72	0.118	0.1583	287.8	489	515	73	0.2572	0.1585	287.7
45	512	71	0.1204	0.1583	287.3	515	515	73	0.2596	0.1585	287.9
47	513	72	0.1204	0.1583	287.5	585	514	73	0.269	0.1538	295.9
49	512	72	0.1251	0.1583	287.1	631	514	72	0.2761	0.1515	301.6
51	514	73	0.1251	0.1583	287.7	665	516	73	0.2785	0.1515	301.8
53	512	72	0.1251	0.1607	282.7	699	515	73	0.2808	0.1538	296.7
55	512	71	0.1274	0.163	278.8	755	516	74	0.2856	0.1538	297
57	513	72	0.1298	0.1583	287.8	775	514	72	0.2879	0.1515	301
59	513	72	0.1322	0.1583	287.4	795	516	74	0.2903	0.1491	306.2
65	511	71	0.1369	0.1583	286.6	815	514	72	0.2903	0.1538	296.6
67	514	73	0.1392	0.1583	288.2	837	517	74	0.2926	0.1515	302
69	512	72	0.1369	0.1631	278.8	903	515	73	0.295	0.1515	301.1
91	513	72	0.1534	0.1607	283.1	927	515	73	0.2974	0.1515	301.5
93	513	72	0.1558	0.1584	287.7	951	515	73	0.2997	0.1491	305.8
101	513	72	0.1581	0.1607	283.5	975	514	73	0.3021	0.1491	305.8
103	515	72	0.1605	0.1631	280.5	1001	515	74	0.3044	0.1468	310.6
111	513	72	0.1652	0.1607	283.2	1053	514	73	0.3068	0.1491	305.6
117	515	73	0.1676	0.1584	288.5	1137	516	73	0.3115	0.1468	311.4
123	514	72	0.1723	0.1584	287.9	1197	516	73	0.3139	0.1468	311.6
133	513	72	0.1746	0.1584	287.5	1259	515	73	0.3162	0.1492	306
147	514	72	0.1817	0.1584	287.7	1395	514	73	0.321	0.1492	305.9
151	513	72	0.1841	0.1584	287.2	1431	516	74	0.3233	0.1444	316.6
155	513	72	0.1841	0.1584	287.1	1545	514	73	0.328	0.1444	315.8
159	514	73	0.1864	0.1584	287.7	1585	514	72	0.328	0.1444	315.9
163	514	72	0.1888	0.1561	292.4	1669	513	72	0.3304	0.1444	315
167	515	73	0.1888	0.1608	284	1945	515	73	0.3398	0.1421	321.6
181	514	73	0.1959	0.1561	292	2047	516	74	0.3398	0.1445	316.1
185	513	72	0.1959	0.1561	292.1	2101	515	73	0.3446	0.1421	321.2
195	515	73	0.2006	0.1584	287.9	2155	515	73	0.3446	0.1421	321.2
205	515	73	0.203	0.1561	292.5	2211	516	73	0.3469	0.1397	327.1
211	512	72	0.203	0.1608	282.7	2327	515	72	0.3469	0.1421	321.8
227	514	72	0.2077	0.1584	288.1	2387	516	73	0.3493	0.1397	327.1

PERMANENT STRAIN TEST DATA

Pulse Count	Vert. Stress (kPa)	Conf. Stress (kPa)	Perm. Strain (%)	Res. Strain (%)	Res. Mod (MPa)
2449	516	73	0.3516	0.1397	327.4
2577	515	73	0.354	0.1374	332.2
2713	514	73	0.3564	0.1374	331.3
2783	515	74	0.3564	0.1374	332.1
2855	516	74	0.3564	0.1374	332.9
2929	515	72	0.3587	0.1374	332.9
3005	515	73	0.3587	0.1374	332.3
3083	515	73	0.3611	0.1374	332.2
3163	515	73	0.3611	0.135	337.9
3245	514	72	0.3634	0.1374	331.9
3329	514	73	0.3634	0.1374	331.8
3415	515	73	0.3658	0.135	338.5
3687	514	73	0.3705	0.1303	349.8
3783	515	74	0.3705	0.1327	344.2
3881	514	73	0.3705	0.1327	343.4
4085	514	73	0.3729	0.1303	350
4191	515	73	0.3752	0.1303	350.1
4299	517	74	0.3752	0.1303	351.5
4411	515	74	0.3752	0.1279	356.4
4525	515	73	0.3776	0.1303	350.3
5275	515	72	0.3823	0.1256	363.9
5995	516	74	0.387	0.1208	378.1
6151	516	75	0.387	0.1232	370.7
6641	518	74	0.3918	0.1208	379.7
6813	515	72	0.3941	0.1208	378.4
7171	516	73	0.3965	0.1161	394.4
7357	516	73	0.3988	0.1137	402.1
7743	516	73	0.4012	0.1161	394.1
8361	516	73	0.4106	0.1114	411
8577	517	75	0.413	0.1137	401.8
10001	517	75	0.4201	0.1066	428.3
11365	516	75	0.4224	0.1138	400.5
13251	516	75	0.4295	0.1019	447.8
15059	516	75	0.4295	0.1043	436.8
15449	514	74	0.4295	0.1019	445.8
15849	512	73	0.4319	0.0995	455.7
17557	516	74	0.4319	0.0995	458.1
18479	513	73	0.4319	0.0995	456.3
19449	516	74	0.4342	0.0948	481.6
19953	516	75	0.4342	0.0972	469.3
21001	514	73	0.4319	0.0972	468.4
21545	514	74	0.4319	0.0948	479.2
22103	515	74	0.4342	0.0948	481.2
24485	513	73	0.4342	0.0948	479.5
25119	512	72	0.4342	0.0972	466.9
27123	512	72	0.4342	0.0948	479.5
28547	511	72	0.4366	0.0924	490.7
29287	513	73	0.4342	0.0901	504.3
31623	516	73	0.4366	0.0877	521.5
32443	512	72	0.4342	0.0948	479.3
33283	514	73	0.4366	0.0924	492.4
35031	511	74	0.4413	0.0877	515.2
35939	512	72	0.439	0.0877	518.1
37825	511	73	0.4413	0.0877	516.1
39811	512	73	0.4366	0.0853	531.9
40843	509	72	0.439	0.0901	501.8
41901	511	73	0.439	0.083	545.2
42987	512	73	0.4342	0.0877	516.9
44101	512	74	0.4319	0.0924	490.1
47619	510	73	0.4342	0.0853	528.9
48853	511	74	0.4272	0.0924	489.2
50119	511	75	0.4295	0.0901	501.1
54117	512	73	0.4248	0.0901	504
56959	509	73	0.4224	0.0924	487.6
58435	510	74	0.4201	0.0924	488.1
59949	510	73	0.4224	0.0901	501.1
64731	512	75	0.4248	0.0877	515.4
66409	513	74	0.4224	0.0877	517.5
69895	510	74	0.4295	0.0853	529.1
71707	511	75	0.4272	0.0901	500.5
73565	512	74	0.4248	0.0877	516.2
75471	508	73	0.4248	0.0877	512.5
77427	508	74	0.4248	0.0877	512.3
79433	509	73	0.4248	0.0877	512.9
87993	507	72	0.4177	0.0901	498.6
90273	507	72	0.4201	0.0853	526.3
97475	514	74	0.4248	0.0853	532.6
100001	512	73	0.4224	0.0877	516.9
105251	510	74	0.4319	0.083	544.2
113647	509	72	0.4248	0.0853	529.5
119613	511	72	0.4248	0.0901	502.7
122713	512	73	0.4272	0.0853	530.9