Report

Cement Concrete & Aggregates Australia

Research Report

MANUFACTURED SAND

National test methods and specification values

January 2007

CEMENT CONCRETE
& AGGREGATES AUSTRALIA

Table of Contents

Cement Concrete & Aggregates Australia
Technical Liaison Committee

ACKNOWLEDGEMENT

The contribution made by members of the Manufactured Sand Subcommittee in initiating, planning, designing and steering the research project to achieve its objectives is acknowledged. The subcommittee comprised the following members:

Mr Tony Thomas *(Chairman)*	Boral Construction Materials
Mr Ion Dumitru	Boral Construction materials
Mr Michael van Koeverden	Hanson Construction Materials
Mr Geoff West	Rocla Quarry Products
Mr Gary Basford	Rinker Australia
Mr Gary Lucas	Rinker Australia
Mr Wayne James	Rinker Australia
Mr Tom Kovacs	Barro Group
Mr Peter Clarke	Consultant
Dr Samia Guirguis	Cement Concrete & Aggregates Australia

Executive Summary

BACKGROUND

The reduced availability of natural sands, particularly along the east coast of Australia, and the need to better utilise sand-size material generated in the aggregate crushing process, has combined to encourage the development of 'Manufactured Sand'.

Approaches have been made to Standards Australia to rewrite the Concrete Aggregate specification, AS 2758.1. However, although all major quarrying companies have made significant progress in using manufactured sand, there is little common agreement on which tests might be applied to the product or what limits should be specified for supply of the product. As a consequence Cement Concrete & Aggregates Australia (CCAA) established a sub committee in November 2004 to develop a research project that would recommend national test methods and specification limits for manufactured sand.

TECHNICAL OBJECTIVES

The following objectives for the research project were established.

1. To determine the most appropriate aggregate tests for quality control and specification of manufactured sands
2. To determine the 'repeatability' of the aggregate tests.
3. To determine specification limits for the aggregate tests which would ensure the supply of fit-for-purpose manufactured sand
4. To present a body of research findings to Standards Australia which would be sufficient to support an industry submission for the specification of manufactured sands for use as fine aggregate in concrete.

METHODOLOGY

To achieve the Technical Objectives, twenty-one sources of manufactured sand from across Australia were tested by Hanson's Wallgrove laboratory in 2006. In selecting the sources, preference was given to those that already had some history of product supply for concrete production. The rationale for this was that if the manufactured sand was being used successfully, the test results should define an acceptable product.

Suppliers were asked to supply samples from sources in the condition in which the manufactured sand product is supplied from the quarry to the concrete producer. This research project did not investigate the properties of the final concrete fine aggregate blend. It was targeted at determining the properties of manufactured sands that form one component of acceptable fine aggregate blends.

All samples were tested for a range of physical, chemical and mineralogical properties; the results of this testing are summarised in this report and are presented in detail in the accompanying Laboratory Report.

This project was limited to testing only the quarry product; later projects may extend the work to testing fine aggregate blends (manufactured sand and natural fine sands). For this reason, sufficient sample was collected so that later projects could use the same material. As the research work extends, there will be no question of results from earlier projects not being relevant as a consequence of sampling variation. The testing laboratory took additional precautions to ensure that retained sample was representative of the material tested in this project.

EVALUATION OF TESTS AND SPECIFICATION RECOMMENDATIONS

The tests and results were analysed to determine if:

- a test was useful for specifying manufactured sand or whether it should be limited to a quality control procedure, with limits and application to only some sources;
- a test should be used on its own or should be considered in combination with other tests;
- when a test was to be used for specification, what acceptance criteria should be required.

In summary, the findings were:

Grading (particle size distribution) Members agreed that product grading should not be a specification test. Instead, the product supplier should provide a submitted grading to which the deviation limits current in AS 2758.1 would apply. How these deviation limits might be applied to the broad range of possible product gradings will require careful consideration. The period over which a submitted grading might apply and how submitted gradings could be altered would also bear consideration.

Gradings would obviously become a Quality Control tool with results of interest to individual suppliers and their customers. However, it was considered necessary for the purposes of definition to specify that 'manufactured sands' for use in concrete would have:

between 90% and 100% passing 4.75-mm sieve;

between 15% and 80% passing 0.6-mm sieve;

between 0% and 20% passing 75 micron sieve.

For additional details relating to limits on passing 75 micron sieve refer to **Appendix 4**.

Deleterious fines A range of procedures attempt to control the quantity or quality of fines in the sand grading. Measures of quantity include the Passing 75 micron, material less than 2 micron (both these measures are specified in AS 2758 and numerous other specifications) and the Clay and Fine Silt test. Measures of quality include the Methylene Blue Value (MBV) and X-ray Diffraction.

The project demonstrates that a combination measure that identifies not only the quantity but also the quality of fines appears to offer the best possibilities of control for manufactured sand. For ease of use and greatest 'accuracy' the combination of Passing 75 µm multiplied by MBV shows promise. Manufactured sand would be accepted to a value of 150 with materials up to a value of 200 considered with further supporting evidence of successful performance. Materials with a value over 200 would be considered unacceptable.

The ability to control the effects of deleterious fines by blending with 'clean' natural sands was not addressed. A suitable control value for the fine aggregate component of a concrete mix may be determined in further research.

Shape and surface texture Shape and surface texture are measured indirectly by the Flow Cone procedure and have some influence on the outcome of the packing density test. However, as changes in grading will also influence the Flow Cone it is not practical to design a test specification that could be used over a range of products. The flow cone is best used as a design procedure to help determine suitable workability in fine aggregate blends The test might also be used as a quality control procedure on specific sources where changes in results would indicate possible changes in crushing characteristics.

The Packing Density test was not considered sensitive enough to act as either a specification or a quality control test. The test is intended and should be used only to develop a necessary design parameter for the Laboratoire Central des Ponts et Chaussees (LCPC) mix design method.

Durability Tests For this project, durability tests included Sodium Sulphate Soundness, Sand Equivalent and Degradation Factor (fines). Both the Sodium Sulphate and Degradation Factor are limited in that they test only a portion of the sand grading and may therefore be limited as product control tests unless combined with a measure that evaluates deleterious fines. The Sodium Sulphate test maximum limit in the Standard appears to be high. It is recommended that a lower limit be adopted to identify higher quality material. Both the Degradation Factor and the Sand Equivalent appear to measure clay activity and clay quantity contained either in the product grading or liberated from rock particles by agitation. Only the Sodium Sulphate may also measure rock strength (as resistance to swelling pressure).

Examining various options and tests, showed that the Micro Deval test may eventually prove a useful fine aggregate durability test. Until this can be demonstrated, the committee recommends using a selection from a number of durability tests, with a choice made based on local experience.

Sodium Sulphate Soundness should be combined with a control measure for deleterious fines. The specification limit for Sodium Sulphate should be maximum 6% weighted loss for all exposure classifications.

The Sand Equivalent limit would be 60 minimum. The application of the test in acid igneous and metamorphic rocks (particularly greywackes) that contain significant sericite and mica would need careful consideration. The test is a product measure and should stand alone as a control. However, it may not evaluate particle strength and may need to be combined eventually with a measure such as the Micro Deval.

The Degradation Factor (fines) is considered a source rock test and may need to be combined with a control measure for deleterious fines. Where used, the suggested specification is minimum 60. The application of the test in acid igneous and metamorphic rocks (particularly greywackes) that contain significant sericite and mica would need careful consideration. The test may not evaluate particle strength and may need to be combined eventually with a measure such as the Micro Deval.

CONCLUSIONS AND RECOMMENDATIONS

Grading The research demonstrated that product with wide range of grading could be used successfully as manufactured sand. It is therefore impractical to specify an acceptance envelope without the specification becoming meaningless. However it is necessary to control and specify the variation in product grading and to continue to use grading analysis as a quality control measure.

It is recommended that:

- The grading of individual manufactured sands or components to the fine aggregate for concrete mixes should not be specified in AS 2758.1
- The specification should require that the producer of the manufactured sand provide the concrete producer with a 'submitted grading' of the manufactured sand. Variation of the product will be controlled within the current variation limits of AS 2758.1, with the exception that the variation at 75 micron shall be reduced to ± 3%, and the concrete producer must be advised if any product grading exceeds the AS 2758.1 variation limits at any sieve size.
- The specification should define grading limits for manufactured sand at an upper size, at the mid size range for sand and at the 75 micron.

Deleterious fines Specification to control deleterious fines requires that both the quantity and activity of the fines be considered in combination. Simply specifying a limit on the passing 75 micron or 2 micron will result in the rejection of materials with inert fines that will perform successfully. The Clay and Fine Silt test could not be recommended for specification as there is no history of specification limits and there is some question within the method of the application of the test to crushed fine aggregate.

It is recommended that:

- The current specification limits for the 75 micron should be modified and the limit for 2 micron size should be removed. Instead, deleterious fines shall be controlled by limiting the multiple of the MBV and the passing 75 micron to 150 for product acceptance. Product with a multiple to 200 may be accepted with evidence of successful performance. Product with a multiple beyond 200 shall be rejected.
- Alternatively, product with a sand equivalent equal to or greater than 60 should be accepted with respect to deleterious fines.
- The Clay and Fine Silt test should not be specified. The test may be used for quality control and local limits may be developed based on successful performance.

Particle Density Although testing of particle density was difficult, there was no data to indicate that a change of current specification was required. Manufactured sands will be normal weight materials. The LCPC packing density test was not sufficiently sensitive to be used for specification.

It is recommended that:

- The SSD density of manufactured sand should be specified between 2.1 and 3.2 tonnes per cubic metre.
- The LCPC Packing Density test should not be specified.

Shape and surface texture The research demonstrates that there are difficulties with the use of the Flow Cone apparatus in testing manufactured sands, and unless these issues were resolved, it would not be practical to use the method for specification. However the NZ Flow Cone will prove useful for Quality Control and for determining fine aggregate blends that include manufactured sand. No other suitable procedure was found for specifying the shape and surface texture of manufactured sand that did not require specialised equipment and highly trained staff. Such specialised testing used locally can be useful in setting relevant quality control properties.

Mineralogy X-Ray Diffraction results proved useful for the purposes of investigation. However, the results provide data on the individual clay types present but do not provide a measure of the combined activity of the combination of clays. Clay activity is best defined by the MBV but only when used with a measure of the quantity of fines in the product (see earlier recommendation).

It is recommended that:

- X-ray Diffraction not to be used as a specification procedure.
- MBV should be specified in combination with the passing 75 micron result.

Durability Durability tests include the Sodium Sulphate Soundness and the Degradation Factor (fines) for testing fine aggregate. Both tests will adequately assess materials for durability factors associated with oxidation, erosion, salt exposure, expansion of included clays and chemical attack. Both tests only use part of the product grading for assessment and therefore the specification must always include an assessment of deleterious fines. The Sand Equivalent Test, which is sometimes assumed to be a durability test, is better considered as a means of assessing reactive fines. It is recommended that any new material be assessed initially by both procedures. Unless the Sand Equivalent result indicates a reason to continue to do the test Degradation Factor test should be carried out. Neither of the two methods will assess the resistance to abrasion and breakdown while the manufactured sand is being handled or placed or resistance to abrasion in service. The literature indicated that the Micro Deval test may best evaluate manufactured sands' resistance to abrasion.

It is recommended that:

- The durability of manufactured sand should be specified by the Degradation Factor (fines) and acceptable product should have a value of 60 or greater. Alternatively the durability of a product should be defined by a weighted total sodium sulphate loss of 6% maximum.

This project did not investigate manufactured sands for alkali reactivity or for the effects of soluble salts. It is recommended that, until other data is available, the specification limits for these properties specified in AS 2758.1, be applied to manufactured sands.

FURTHER RESEARCH

It is recommended that further research work be conducted:

1 To investigate the application of the Micro Deval test to manufactured sands. Overseas research suggests that the test has a great deal of promise, is reliable and relatively inexpensive. The test is reported widely in asphalt applications and may offer a useful mean of resolving one of the RTA's concerns, namely the evaluation of abrasion resistance of fine aggregate used in concrete road pavements.

2 To investigate the effects of the physical properties reported in this project on the properties of concrete mortars.

1 INTRODUCTION

The reduced availability of natural sands, particularly along the east coast of Australia, and the need to better utilise sand-size material generated in the aggregate-crushing process, have combined to encourage the development of 'Manufactured Sand'. This quarry product has been defined by the quarrying industry as:

> *"A purpose-made crushed fine aggregate produced from a suitable source material and designed for use in concrete or other specific products. Only source materials with suitable strength, durability and shape characteristics should be considered. Production generally involves crushing, screening and possibly washing. Separation into discrete fractions, recombining and blending may be necessary."*

The industry in Brisbane and parts of south east Queensland has been using manufactured sands as part of the fine aggregate blend for concrete for about ten years. Acceptance of the product in the industry was hastened because environmental legislation had closed coarse natural sand resources. Even with this experience, very few sources of manufactured sand are used as a total replacement for natural fine aggregate in concrete. Most are used in combination with natural fine sand to produce a fine aggregate blend.

In NSW, SA and Victoria, manufactured sand has been used over as long a period, but its acceptance in the construction industry is not as widespread. For much of the NSW and Victorian market areas, natural sands are still available and are probably favoured. The RTA claims to have experienced difficulty with manufactured sand in northern NSW concrete road works. The RTA continues to specify special requirements for the fine aggregate fractions of base-course concrete which they believe contribute to successful abrasion resistance and polishing resistance at the surface.

Approaches have been made to Standards Australia to revise AS 2758.1 *Concrete Aggregates*. The current standard is restrictive in dealing with fine crushed aggregate. However, although all major quarrying companies have made significant progress in using manufactured sand, there is little common agreement on which tests might be applied to the product or what limits should be specified for supply of the product.

As a consequence, Cement Concrete & Aggregates Australia (CCAA) funded a research project to investigate and to develop and recommend test methods and specification limits for manufactured sand. This report summarises the work undertaken between November 2004 and July 2006 and covers the following:

- a description of the test and a discussion of its relevance to manufactured sands;
- an analysis of the specific test results from this programme and the relationship of the results to current standard specifications limits (if known) for the method;
- a discussion as to whether the test method should stand alone or be reported and reviewed in conjunction with the results from other test methods;
- a discussion and recommendation as to whether the test method should be a Quality Control measure only (ie mainly useful for monitoring the variability of a single source) or whether it should be used for setting specification limits;
- recommendations regarding specification and/or variability limits.

2 OBJECTIVES

The following objectives for this research project were established:

1 To determine the most appropriate aggregate tests for quality control and specification of manufactured sands

2 To determine the 'repeatability' of the aggregate tests.

3 To determine specification limits for the aggregate tests which would ensure the supply of a fit-for-purpose manufactured sand.

4 To present a body of research findings to Standards Australia which would be sufficient to support an industry submission for the specification of manufactured sands for use as fine aggregate in concrete.

3 METHODOLOGY

To achieve the Technical Objectives, the research project tested twenty-one sources of manufactured sand from across Australia although eighteen samples were from the east coast. Most of these sources tested already had some history of product supply for concrete production. The rationale for this was that if the manufactured sand was being used successfully, the test results should define an acceptable product.

It was intended to test five sources that the RTA in particular found to be unacceptable in performance. It was hoped that testing these sources might define a range of test properties indicative of non acceptable product. However, it was not possible to identify sources of material known to have performed poorly. Nevertheless, the quarry masters included at least two sources expected to be of marginal performance.

The samples were supplied from the process used to supply product to market. If the quarry fines are sourced from select quarry material, shaped, washed, blended or otherwise processed, the samples were supplied in that state. Only quarry products were tested, not product blended with natural sand at a concrete plant.

For the interpretation of the results and preparation of the submission to Standards Australia, the producers were asked to supply details on successful blends with natural sands. The project interpretation would be concerned with the dilution effects of the natural sand on reactive mineralogy and adverse shape properties in the manufactured sand.

This project was limited to testing only aggregate properties. Later projects should examine the properties of mortar and concrete produced with the manufactured sands.

The project was controlled by a single laboratory, Hanson's Materials laboratory at Wallgrove. Some testing was sub contracted but a significant proportion of the work was completed at Wallgrove. Regardless of where the testing was conducted, with the exception of the XRD tests, all tests were completed in duplicate. Each duplicate test on the same sample was completed by the same laboratory operator, using the same equipment and was completed within a short time of the first test.

This process was followed in order to develop data on the repeatability of the tests. Later projects should examine the reproducibility of the recommended test procedures but this work will be conducted on a limited subset of these samples.

Samples were sourced from quarries producing manufactured sand across Australia, ensuring that a representative range of rock types was included.

Samples were taken at source in accordance with the procedures set out in AS 1141.3.1. using power operated equipment from a single location in the product stockpile. After forming a sample stockpile, the material was blended to provide a homogenised sample. The sample dispatched to the testing laboratory comprised a full 200-litre metal or stabilised plastic drum. The size of the sample was excessive, but was intended to provide sufficient material for this programme and for later programmes of reproducibility testing or for mortar trials. The contracted laboratory was required to retain the samples for a period of at least two years from completion of this first project.

The testing laboratory was instructed to remove each sample from the drum and blend it prior to obtaining four sub samples for conducting the tests as outlined below. The remainder of each sample was to be returned to the drums for storage.

1 Sufficient material split to complete the following tests in duplicate:

Particle size distribution to AS 1141.11

Material passing 75 micron to AS 1141.12

Material finer than 2 micron to AS 1141.13

Particle density and water absorption to AS 1141.5

Clay and fine silt to AS 1141.33

Sodium sulphate loss to AS 1141.24

Degradation factor – fine aggregate to AS 1141.25.3

Sand equivalent value to AS 1289 3.7.1

2 1.5-kg test samples prepared using a second laboratory sample, as follows:

— Dry the sample and remove any +4.75-mm material. Reduce the sample mass to 1.0 kg

— Dry the sample and remove any +4.75 mm and all passing 75 micron material. Reduce the sample mass to 1.0 kg

— Dry the sample and remove any +2.36 mm material. Reduce the sample mass to 1.0 kg

— Dry the sample and remove any +2.36 mm and all passing 75 micron material. Reduce the sample mass to 1.0 kg.

Test each of the prepared samples in duplicate to determine Voids content, Flow time to method NZS 3111:1986 except that in clause 19.3.1(b) do not determine oversize, and in clause 19.3.1 (c), use a constant mass of 1.0 kg for all samples.

3 Sufficient sample for the following:

Test a sub sample using XRD for a semi –quantitative mineralogical analysis of the whole sample.

Remove the passing 75 micron fraction from a second sub sample and, using XRD analysis, obtain a semi-quantitative mineralogical analysis of the minus 75 micron fraction of the sample

Using two further sub-samples, determine the MBA value of the sample in duplicate using the ISSA Bull 145 procedure.

4 A sample for use in testing the Packing Density to the procedure of Laboratoire Central des Ponts et Chaussees (LCPC).

During the testing programme, the following variations to the published methods were discussed and adopted:

— Rather than using the French standard for the determination of the particle density of the sand tested for Packing Density, the Australian Standard method AS 1141.5 was adopted.

— In conducting the particle density procedure, the laboratory experienced a common issue with the method, namely determining the point of 'saturated, surface dry moisture'. The test relies on distinguishing the point at which a conical sample of the sand will just slump to determine this moisture content. However, manufactured sands with a large proportion of the grading coarser than 1.18 mm often do not retain the coned shape even with moisture contents beyond SSD. Visual assessment (an allowed procedure in the method) was therefore adopted.

— Several samples are coarse enough or contain poorly shaped particles that prevent the flow of the manufactured sand through the orifice of the Flow Cone. In these cases, the testing laboratory adopted the procedure of tapping the side of the cone with a metal rod to initiate flow. Usually, once flow commenced, the sample ran through the orifice. Where the laboratory has used this procedure, the number of taps to achieve flow has been recorded. In these results it was noted that 'Sample did not flow' For the sake of completeness, both sets of data are included in the Laboratory reports.

4 PROJECT SAMPLE SOURCES

Samples of manufactured sand were supplied from twenty-one sources from around Australia; in most instances the sources were supplying the product to concrete manufacture (see Table 2). Of the sources used, eight were from Queensland, seven from New South Wales, three from Victoria, two from South Australia and one from Western Australia. Nine sources are operated by Boral Ltd, four by Hanson plc, six by Readymix Ltd and two by Wagner's Pty Ltd.

Sources were selected to represent the widest possible range of rock types, and **Table 1** identifies the number of sources of each rock type tested in the project.

TABLE 1 – Rock types included in research

Rock type	Number of sources
Basalt	3
Granite	3
Latite	2
Limestone/dolomite	2
Meta argillite	1
Meta greywacke	2
Picrite	1
Quartizite	2
Rhyodacitic tuff	1
Rhyolitic tuff/ignimbrite	2
Trachyte	1

TABLE 2 – Information on samples

Sample ID	Material used singularly as sand	Material used as a proportion of sand		Comment
		Typical proportion	Maximum limit (if any)	
A75	No	20%	20%	Unwashed
B41	No	30%	35%	Max % market driven-dependent on customer, workability and finishing requirements In winter months higher amounts of man sand may be able to be used
B58	No	50%	no max limit set, variation to improve performance	The ratio may vary depending on strength
BM58	No	46%	No limit set	
B90	No	20–35% of fine fraction	40%	
C77	No	25%	50%	Unwashed
D69	No	40%	100%*	Max % market driven-dependent on customer, workability and finishing requirements. In winter months the use of higher amounts of manufactured sand may be possible. **In special applications*
G13	No	55%	90%	Max % market driven-dependent on customer, workability and finishing requirements In winter months higher amounts of man sand may be able to be used
G80	Yes	100%	N/A	
H73	No	20%	35%	Sometimes marginal source – requires care
H85	No	20–30% of fine fraction	50%	Limit based on unwashed manufactured sand
L16	No	30%	40%	Max % market driven-dependent on customer, workability and finishing requirements In winter months higher amounts of man sand may be able to be used
L24	No	70%	N/A	Washed
N33	No	20%	N/A	
N53	No	20%	50%	Washed??
N76	No	40%	50%	Washed
P99	No	None		
S51	No	20%	50%??	Utilised surplus stocks – not purpose-made as manufactured sand
S68	No	100–200 kg	25%	12.5 to 25%
T68	No	100–200 kg for kerbmix 400–600 kg for shotcrete 100–150 kg for "N" Class	25% 75% 18.75%	12.5 to 25% 50 to 75% 12.5 to 18.75%
T88	No	77% manufactured sand 8% other dust 15% natural sand	N/A	

All samples were assigned a random identification code prior to the commencement of testing. To assist in the interpretation of the results and in establishing appropriate performance levels, details of fine-aggregate blends (blends of the manufactured sand with local natural fine sands) were obtained. This information and the coding is given in **Table 2**.

5 TEST METHODS AND RELEVENCE TO MANUFACTURED SAND

5.1 Product Sizing

Grading

The particle size distribution or grading of manufactured sands is most often determined by sieve analysis. A sample of dry aggregate of known mass is separated through a series of sieves, usually made of woven wire, with progressively smaller openings. For samples tested to the Australian Standard, the sieves conform to AS 1152 and form part of the metric 'half series', where each successive sieve opening is half the size of the next largest sieve in the series.

Once separated, the mass of particles retained on each sieve is measured and compared with the mass of the total sample. Particle size distribution is then usually expressed as the cumulative mass percentage passing each sieve. Results are usually presented in tabular form or as graphs in a semi logarithmic format.

Particle size distributions developed from sieving analysis through square mesh will provide a sizing close to the intermediate dimension of the individual particles. The size distribution will be different if sieves with round mesh are used or if the distribution is developed from visual analysis techniques (eg the proposed 'vision sizing technique') although correlations can be developed between different methods.

The test method for grading used in this research is described in AS 1411.11. In accordance with this method (washed grading method was adopted), and if the material passing the 75 micron was to be reported or specified, the sample charge to the sieves had to be a dried, washed sample. Manufactured sands generally have a significant percent passing the 75 micron fraction; in this research the samples submitted had percentages passing the 75 micron fraction ranging from 5.7% to 22.2%. A dry grading of unwashed samples of manufactured sand will not accurately represent the fines content within the sand.

Particle size distribution, or grading, is one of the most influential and commonly reported characteristics of an aggregate. Numerous research papers and design methods demonstrate how grading influences concrete durability, porosity, workability, cement and water requirements, strength and shrinkage. However, it is the total aggregate grading in the mix that is critical to the mix performance. The grading of an individual component (ie where manufactured sand forms a part of a fine aggregate blend) is not critical to the mix performance if an unsuitable grading can be improved by blending with other components. In this case the individual grading is not critical, but, once the blend is established, the consistency of individual components is critical to the production of a consistent blend. Therefore, gradings of individual components are used to control and report product consistency.

Passing 75 micron in aggregates (by washing)

In this method, a dried aggregate sample of known mass is washed in clean water and the wash water and fines from the washing is decanted over a 75-micron sieve. The sieve will often be protected with a stronger but coarser mesh, but this coarser mesh is not critical to the method. The process of washing and decanting is continued until the wash water is clear.

In AS 1141.11 the washed aggregate sample is weighed, dried, and then used as the charge for a sieving analysis. In this procedure the percentage passing the 75 micron is calculated from the loss resulting from washing plus any material that passes the 75-micron sieve in the dry grading. In AS 1141.12 the aggregate sample after washing is dried and weighed. The percentage passing 75 micron is calculated as the loss on washing expressed as a percentage of the original sample mass.

The passing 75 micron test is highly relevant to the specification of manufactured sand; the material contained in this fraction of the aggregate grading is significant in determining the performance of a concrete mix but current specification limits set for natural aggregates may be misleading when applied to manufactured sands. The 75-micron fraction size is used in Australia as a near approximation to a 60-micron size limit that, in geological terms, marks the boundary between fine sand and silt. In natural aggregates the total passing 75 micron will include the silt and clay sizes and will be composed of silt and clay minerals. In many specifications, including AS 2758.1, the percentage passing 75 micron has been restricted as a control over clay and silt fines that may cause water and cement demand, shrinkage and cracking

With manufactured sands, produced from sound durable rock, it is possible that the passing 75 micron material will be composed of finely ground rock flour with little deleterious mineralogy. It is possible that high quantities of inert fines with a high specific surface could still cause an increase in water demand. However, some research has indicated that inert, passing 75 micron fines in manufactured sand can act as filler and as part of the binder, increasing the workability of the mix in the plastic state and reducing porosity in the hardened state. Clearly the action and specification of the passing 75 micron material in manufactured sand will be highly relevant both for the producer of manufactured sand and for the concrete producer.

Material finer than 2 micron

This test uses all the wash water from the passing 75 micron method as sample. The procedure may form part of a total sizing analysis or may be conducted as a separate test. The procedure used in this research is described in AS 1141.13.

The sample is reduced to a thick slurry by evaporation of water; the slurry is then dried and the mass of minus 75 micron material is measured. A sub-sample is taken up in distilled water with a deflocculating agent and the suspension is allowed to settle for a controlled period. At a time calculated by Stokes' Law, a measured volume of liquid and suspended solids is removed by pipette from the sedimentation column from a depth where the liquid would suspend 2-micron or finer sized particles. The liquid and suspended solids are dried and by calculation, the mass of 2-micron and finer material can related to the sample of minus 75-micron material, and may be related to the original sample mass from which the minus 75-micron sample was recovered.

There are other techniques for determination of clay-sized (– 2 μm) material including instruments such as the 'Sedigraph' and laser size discriminators. Care must be exercised in using results from these and other techniques as they will certainly give different results to that obtained from the method used in this research and referenced in AS 2758.1 for supply of concrete aggregate.

The method is limited to testing sand with at least 4% passing 75 micron. This limit was included in the procedure simply because it was expected that if less than 4% passed 75 micron there was little possibility that there would be greater than 1% less than 2 micron. 1% less than 2 micron is the present specification limit for supply of aggregate; the test limitation simply reduces the need to test sample in a difficult procedure unnecessarily.

The test result is affected by the density of the solids in suspension. Most laboratories will adopt the standard suggested particle density of 2.30 g/cm^3; this means that the quantity of clay will be overestimated if the sample is high in Montmorillonite and will be underestimated if the sample is high in Kaolinite.

The test has relevance to the supply of manufactured sand. It provides a reasonably accurate measure of the quantity of clay-sized material in the product although it provides no information on the mineralogy of the clay. The test has been nominated in Australian Standards to curtail any excessive use of crusher fines in concrete aggregate, particularly those containing any significant quantity of clay-sized material. By limiting the less than 2 micron material in any component of the aggregate blend to less than 1%, the Standard has ensured that the concrete mix is unlikely to be affected by deleterious fines. However, the limitation has meant that it has not been possible to use many manufactured sands in high volumes. It was always the intention of Standards Australia to review this limitation once sufficient data on the properties of manufactured sands and their use was available for consideration.

Clay and Fine Silt test (settling method)

The Clay and Fine Silt test (settling method), also known as the volumetric silt test, is a rapid field procedure for testing for deleterious components in concrete sands. The method was originally developed to allow identification at the concrete plant of natural sands containing quantities of silt and clay that might cause water demand, shrinkage or dusting problems in concrete. The test was designed to use simple equipment, to return rapid results and to be easy to interpret. The method followed in this research is given in AS 1141.33. Similar methods are detailed in NSW Roads & Traffic Authority (RTA) method T268.

The test measures the volumetric ratio (reported as a percentage) of silt and clay compared with the proportion of sand-sized particles in the test portion. The test requires that approximately 100 ml of sample is agitated in a similar volume of 1% NaCl solution and the slurry formed then allowed to settle for 3 hours. Sand particles settle rapidly in the liquid column while the silts and clays settle slowly, forming a distinct sediment layer above the sand. It is thought that the Na^+ ions in the liquid assist in keeping the clay in suspension by ion exchange on the clay layers. After 3 hours, the heights of the silt-and-clay column (F) and of the sand column (S) are read from the graduations on the cylinder. The Clay and Fine Silt result (C) is given as – C = F/S*100.

The relevance of the test to manufactured sands is debatable. At the present time in Australia, the test is rarely used in concrete plants but may be used by the aggregate supplier as a Quality Control procedure for fine aggregate. As the method is described as a field procedure in the scope of AS1141.33 it has never been included in Australian Standards as a specification requirement for the supply of concrete aggregate. The scope of the method states that "…It [the test] is not generally applicable to sands manufactured by crushing rock when there is little silt and clay present". However, the samples tested in this project all returned significant results and it is possible to put a logical interpretation on the results. Of the 21 samples tested in this project, none have less than 5% passing 75 micron and only 6 of the 21 have less than 10% passing 75 micron. Regardless of the comment in the scope of the method all of these samples have sufficient clay- and fine-silt-sized material present to make the results relevant.

For the producer of manufactured sand, this test has the same relevance as it has to the producer of natural sand. The result is indicative of clay activity in addition to providing a rapid measure of clay and silt quantity. The test uses simple equipment and it requires little interpretation. It could be used as a Quality Control procedure to track changes from a single source relatively inexpensively. However, because the procedure has not been used as a specification, little is known about its correlation with concrete performance in either the plastic or hardened state. It would be necessary for the producer to establish local process criteria to make the test relevant to production control.

5.2 Shape, Texture and Density

New Zealand Flow Cone

The New Zealand Flow Cone is a modification and improvement on ASTM Method C1252 Standard test method for Uncompacted Void Content of Fine Aggregate (as influenced by Particle Shape, Surface Texture and Grading). A sample of 1 kg of fine aggregate is passed through a 12-mm orifice mounted at the base of a sample hopper. The material free falls into a collecting container of known volume while the time taken for the sample to pass through the orifice is measured. At the end of sample flow the mass of material held in the collection container is determined; from this determination, the uncompacted unit mass of the fine aggregate can be calculated. The particle density of the fine aggregate is determined, and the relationship between the unit mass and particle density of the aggregate allows for the evaluation of the uncompacted voids content of the aggregate. The results are reported graphically on a plot of voids versus flow time.

There are few simple procedures that allow for the evaluation of particle shape or surface texture in fine aggregate. But these properties will have a significant effect on the water demand and workability of concrete mixes. In addition, these properties will impact the flow characteristics of fine aggregate and will impact on the current and future design of plant aggregate hoppers, chutes and gates. The introduction of manufactured sands focussed interest on the shape and surface texture properties of fine aggregate. Most natural sands in use were both rounded and smoothed as a result of natural erosion and sorting processes. Thus there was little need to develop testing procedures to measure or specify these properties.

Some attempt has been made to measure these properties visually but the processes are complicated, require expensive and specialised equipment and professional staff to perform and interpret the test. By contrast, the Flow Cone Test uses relatively simple equipment and can be performed rapidly by competent laboratory technicians. The New Zealand method has improved on the ASTM procedure by using a larger and fixed sample size and by measuring the flow time in addition to measuring voids. The test result is affected by the grading of the sample, by the particle shape and by the surface texture of the particles. The flow of the material is most affected by the shape and surface texture of the particles while the voids result is more determined by grading and shape.

The test has been standardised in New Zealand as NZS 3111; the New Zealand authorities have developed interpretive diagrams for plotting the results, based on experience gained from the testing and performance of natural sands. The test has not been standardised in Australia although several laboratories conduct the procedure. Unfortunately there is evidence that over a period of time, several designs have evolved for the equipment and it is likely that results using different equipment would not be reproducible.

Particle Density and Water Absorption

The Particle Density and Water Absorption Test, AS1141.5, is universally accepted within the Australian Construction industry as the definitive measure of fine aggregate density and water absorption; it is used to determine these properties in both natural and manufactured sands

The Particle Density test produces results similar to Specific Gravity, (Apparent Particle Density) but also takes into account the voids that may be present in the material being tested. At the same time, the amount of water that is held within those voids is calculated and reported as the Water Absorption of the material. The AS 1141.5 Particle Density Test can be used to determine these properties in natural and manufactured fine materials.

For fine aggregates, the particle density test is carried out on material of size less than 4.75 mm and a test portion of about 500 g. This portion is immersed in water at room temperature for at least 24 hours and agitated in a manner that removes all the entrapped air. This is to ensure the pores are filled with water. The sample is then dried back to a point where the SSD condition can be determined. This point is normally determined by using a cone apparatus and tamping rod. When the material is sufficiently dry (SSD), it should collapse on removal of the supporting cone. If it fails to collapse, it is deemed to still be too wet and further drying is required. This procedure of determining SSD works well for rounded natural sands with low quantities of passing 75 micron fines. However, in this research, the cones of manufactured sand collapsed before the point of SSD due to the higher proportions of material coarser than 1.18 mm in the samples The testing laboratory in many cases had to use visual assessment of the sample to determine when particles appeared damp but had no surface films of water

Once the sample has reached SSD, the volume of the particles is determined by water displacement while the mass is determined at the SSD condition and again when the sample has been oven dried.

By calculation, the following determinations can be made:

Apparent density
The dry mass of particles divided by their volume with the volume including only the impermeable voids.

Particle density dry
The dry mass of particles divided by their volume with the volume including both permeable and impermeable voids.

Particle density saturated surface dry (SSD)
The SSD mass of particles divided by their volume, with the volume including both permeable and impermeable voids.

Water absorption
The ratio, expressed as a percentage, of the mass of water held in the permeable voids of the particles brought to SSD condition following soaking under water for 24 hours, to the oven dried mass of the material.

The test property provides key design parameters for concrete mixes and is therefore a highly relevant property of manufactured sand. The property is not a specification value, as all natural aggregates fall within a fairly narrow density range, all of which are acceptable for concrete. Some attempt has been made in a range of specifications to limit the water absorption of aggregates, usually to avoid the practical difficulties that arise when dealing with highly absorptive aggregates. SSD density, which accounts for water contained within permeable voids allows for the calculation of mix yield and concrete voids in the design process. Because the density determination has accounted for the water in voids, which does not enter into the cement hydration process, a more accurate determination of mix water demand and therefore the water-cement ratio design parameter is possible.

LCPC Packing Density

This test result is a critical design input for a new concrete design procedure developed by the Laboratoire Central des Ponts et Chaussees (LCPC). The theory of the design method is best described in *Mixture-proportioning of high performance concrete* by Francois de Larrard and Thierry Sedran, Cement and Concrete Research, May 2002. In very simple terms, the design method models the plastic concrete mix as a framework of coarse and fine particles through which the binder (which includes the cement, admixtures, SCMs, water and aggregate microfines) penetrate as a rheological fluid. Aggregate microfines are defined as all material in the aggregate grading finer than 75 micron. Modelling of the interaction of the framework and the binder can be used to design for strength, shrinkage, porosity and workability of the mix.

The packing density test for all aggregate sizes provides the design criteria that allows for the calculation of the aggregate framework and determination of the void space in the framework that will be filled with the binder. The design method is available in Australia as 'Betonlab'.

The packing density test, described as LCPC Test No. 61, is applied to both coarse and fine aggregates. A sample of aggregate is compacted into a cylinder using a specified placement and compaction procedure. Following compaction, the height of the compacted mass of aggregate is determined, allowing for the calculation of the compacted volume. The mass of aggregate is determined at the same time; this allows for calculation of the compacted unit mass. By comparing this result with the particle density of the aggregate a relative density figure is obtained, the unit mass as a proportion of the particle density. This ratio is known as the 'Packing Density' and is clearly an inverse of a voids calculation for the material at the specified compaction.

There is no specification for the test because the test is not intended as a means of certifying or selecting aggregate of any particular quality. The test is designed to provide an input to a design and, in theory, any aggregate could be accommodated by the procedure.

5.3 Mineralogy

X-Ray Diffraction

The test method used in this research was as per AMDEL test method provided in **Appendix 1**. The samples were tested each way as both a 'full sample' (as submitted), the passing 75-micron fraction sample (obtained by wash sieving and drying at 105°C); in both cases the 2 micron material was removed and assessed.

The principle purpose of this break-up relates to the view that the type and proportion of clay minerals associated with manufactured sand may affect the use of that sand in concrete. This test method looks for the presence of minerals (clay and other) and reports these as either Dominant, Co-Dominant, Sub-Dominant, Accessory, Trace or not measurable. These categories reflect the relative size of peaks of the XRD graph.

In general, the expectation is that the more expansive clays that are deleterious to concrete are likely to be degradation products and as such are more likely to concentrate in the –75 micron and –2 micron fractions of the sand. If this is the case there should be an increasing trend in such materials as successively finer fractions are investigated.

The key clay minerals (–2 micron fraction) in this research were selected as the following general types:

— Mica (also recognised as illite and sericite)
  A clay mineral and an alteration product of muscovite mica and potassium feldspar (fine mica and illite can be detrimental to concrete in quantity, although illite is significantly more so).

— Chlorite
  A mineral that may not be similar in structure to the other ones listed here but has been known to cause problems in concrete when present in sufficient quantity.

— Kaolinite
  A relatively volumetrically stable clay mineral that is not detrimental to concrete in lower quantities.

— Smectite
  A family of clay minerals that are generally very detrimental to concrete when present in quantity.

Methylene Blue Absorption Value

Methylene Blue dye absorption has been used for a considerable period as a means of determining and specifying the presence of clay minerals in aggregates. A number of methods are defined in the literature, most varying in the concentration of dye solution used and in the method of measuring the end point, or amount of dye absorbed.

This research used the procedure defined in the International Spray Seal Association's Technical Bulletin 145. This method is specified by the New South Wales RTA for crusher dusts used in hot-mix asphalt. The test is completed on the passing 75-micron fraction recovered from a sample of fine aggregate of known mass. A Methylene Blue solution of 1mg/ml is titrated against a slurry of the passing 75-micron material. As each aliquot of MB is added, the sample is tested for end point by removing a small drop of the slurry on a stirring rod and placing the dyed dust and liquid drop onto a filter paper. The filter paper draws off a 'halo' of water from around the dust particles. At the end point, when the dust cannot absorb any further MB, this 'halo' is permanently stained a light blue colour. The MB value of the aggregate is reported as the number of milligrams of dye absorbed per gram of material passing 75 micron

The MBV expresses the quantity of MB required to cover the total surface of the clay fraction with a mono-molecular layer of the MB. It is therefore proportional to the product of the clay content times the specific surface of the clay. However, the result can be affected by the presence of organics, zeolites and iron hydroxides. Some literature also suggests minor absorption by carbonates and unbalanced charged particles on freshly crushed surfaces, but these effects are considered minor.

5.4 Durability Tests

Sand Equivalent Test

The Sand Equivalent Test was originally developed by Francis Hveem in 1952 as a rapid field test. Hveem's original work suggested that low sand equivalent could indicate either clay or dust contents in aggregates. The latest publication of this test in Australian Standards is AS 1289.3.7.1—2002; this method was used for the testing conducted for this research project. Other versions of the test are given in Queensland Main Roads method Q 124.

Fine aggregate (passing the 4.75 mm) is placed in a transparent, graduated cylinder and is agitated in a power-operated machine in an aqueous solution containing a flocculant and a preservative. When testing fine aggregates the sample is made up of both the passing 4.75 mm material and the fines brushed from any aggregate coarser than 4.75 mm.

Following agitation and procedures to assist in taking clay- and silt-sized material into suspension, the sediment column is allowed to stand for 20 minutes. At this time the height of the sand and flocculated column is measured. A plunger is inserted into the cylinder that slightly compresses the sand column and allows its height to be measured.

The Sand Equivalent is the ratio of the height of the sand column to the height of the sand and flocculated clay x 100. The higher the percentage, the greater the proportion of sand-sized material or the lower the proportion of clay-sized materials. Higher SEs are taken to indicate better material.

The test has long been specified in Victoria (VicRoads) for the control of road base as a quick quality control test to alert potential changes in the grading in terms of quantity and quality of the fine fraction, ie the presence of plastic fines. As such, it has been adopted and accepted in the true sense of being a 'Product Test'.

Although the test has not been used extensively in Australia, it is used widely in the United States where it is specified for manufactured sands used for asphalt production. (In addition to their use in concrete, manufactured sands in Australia will be used widely in asphalt production.) The Sand Equivalent test and research associated with the use of manufactured sand in asphalt will be relevant to the Australian industry and the local development of manufactured sand.

However, local experience in Victoria has shown that the test may cause 'false' specification failures in acid and metamorphic rock types with high proportions of sericite. The fine mica is held in suspension in the flocculant column resulting in low Sand Equivalent values, when in fact the quarried material may perform adequately.

Degradation Factor – Fine Aggregate Test

The Degradation Factor test for Fine Aggregate is a modification of the Degradation Factor test for coarse aggregate which in turn is modelled on the Washington Degradation test, (Washington State Highways Department Method 1134). The test followed in this research is detailed as AS 1141.25.3. Similar methods are given in VicRoads 370.05 and Northern Territory Methods 302.2 and 302.3.

The test determines the clay and fine silts generated by vigorously agitating clean aggregate in the presence of water. In the Fine Aggregate method, washed fine aggregate is sized to form a combined test sample of 50 g each of four size fractions between 4.75 mm and 425 µm. The combined sample is agitated in water in a Sand Equivalent Test cylinder using the power-operated shaking device for the Sand Equivalent test. The agitation is continued for 20 minutes.

Following the attrition by agitation of the aggregate particles, the water, carrying the attrition products, is recovered and the aggregate is cleaned with further water. The water sample is transferred to a Sand Equivalent test cylinder and the clay and silt is flocculated with the same flocculant used in the Sand Equivalent test. The sample is allowed to settle for 20 minutes, the height of the flocculant column is then read.

The Degradation Factor is given by:

$$D_f = \frac{380 - H}{380 + 1.75 \times H} \times 100$$

Unlike the Sand Equivalent test which measures the clay and fine silt adhering to aggregate particles or existing as contaminant within the void space of the aggregate, the Degradation Factor Test commences with clean aggregate. It is reported to measure the fines generated by attrition between particles during the agitation. Expansive clays in aggregate close to the particle surface may be released into the water at this time. In cases of weaker rock with highly expansive clays, or in cases where soft rocks were tested, complete breakdown of particles may occur, but this would be a rare occurrence.

The Degradation Factor (Fines) is a 'Source Rock' test and has found wide and successful usage in assessing drill-chip samples. Background research indicated that the test was developed for basic igneous rocks (basalt, gabbro, dolerite, etc) and possibly intermediate igneous rocks (andesite, latite, etc). However, advice from Victorian industry representatives suggests that the test is now widely applied to all quarry materials without difficulty with test interpretation or specification limits.

The test is thought to evaluate those reactive clays (and perhaps other reactive mineralogy) that can be released from the rock fabric with moderate autogenous grinding and agitation. As a source rock test it is important; when used in association with other appropriate proposed tests it may be ideal as a manufactured sand quality indicator. There is some history of its application in Victoria while its application for coarse aggregate is extensive in the US.

The test might be useful for the identification of reactive mineralogy but, unlike the Sodium Sulphate test, it is not an indicator of rock weakened by cleavage, bedding, or micro fracturing. To be successful as a measure of rock 'durability', it would need to be combined with a measure of rock fabric strength. In fine aggregates, the most suitable test is the Micro Deval procedure which was not evaluated in this programme.

Sodium Sulphate Soundness

The Sodium Sulphate Soundness test is one of the earliest recorded tests for aggregate durability with records of the test's development dating back to the early 1800s. The test was published as ASTM C88 in the 1930s. It is used extensively in the US where it was published as AASHTO T 104 and still as ASTM C88–99. It has been used extensively in Australia since at least the 1950s and is published as AS 1141.24 (the method used for this research). Similar methods are published as NSW RTA T266 and Queensland DOT Q209. The test is specified in AS 2758 *Aggregates and Rock for Engineering Purposes*, in Parts 1, 2, 5 and in the proposed Part 6.

The test exposes the aggregate sample to a saturated solution of sodium sulphate at 23°C. The aggregate is separated into size fractions that, for manufactured sand, are: passing 4.7 mm retained 2.36 mm; passing 2.36 mm retained 1.18 mm; passing 1.18 mm retained 0.6 mm; and passing 0.6 mm retained 0.3 mm. The aggregate fractions are exposed to five cycles of immersion in the salt solution, each cycle comprising 8 hours total immersion. Each immersion cycle is followed by a 16-hour drying cycle at 105°C. Recent overseas research has demonstrated swelling pressures of 0.6 MPa caused by the formation of mirabilite ($Na_2SO_410H_2O$) during the immersion cycle. But formation of thenardite (Na_2SO_4) during the drying cycle is reported to create pressures of up to 2 MPa. At the end of cycling, the aggregate fractions are washed over a finishing sieve (about half the aperture of the fraction mid size) to remove the salt and to remove the detritus of broken aggregate particles.

The individual fraction loss is given by:

Loss % = (original mass – final mass) x 100 / original mass

The weighted loss (the loss expected for a sample of the original grading) is given by:

$$\text{Weighted loss \%} = \sum_{1}^{n} \frac{C_n \times P_n}{100}$$

where C is the individual fraction percentage loss, and
P is the percent by mass of each tested fraction in the original sample.

The test was first developed to model the effects of freeze/thaw conditions in the northern states of the US; most US transport departments still retain the test for this purpose. In a recent survey, 35 of 48 responding states reported using sodium or magnesium sulphate testing to assess freeze/thew durability with over half the states specifying a weighted loss of 12% or less as the acceptance criterion.

A significant amount of recent US research questions the validity of the sodium sulphate test as an acceptable measure of freeze/thaw durability. The test is criticised as lacking reproducibility, of failing to accurately model freeze/thaw behaviour and of failing to accurately model the field performance of tested aggregates. Some reports suggest that there are now more-accurate tests which measure freeze/thaw directly, that particle density and water absorption are more consistent predictors of soundness and that Micro Deval correlates well with magnesium sulphate tests but is more reproducible. Several states are replacing the Soundness test with the Micro Deval, particularly when the Micro Deval is used to test wet aggregates.

In Australia the test was never used to any great extent to measure freeze/thaw durability. The test was adopted by a number of State Road Authorities, by the then Commonwealth Department of Works, by the then NSW Public Works Department and by the NSW Water Board among others, as a general measure of durability. As a measure of general durability, common theory was that the salt penetrated voids and fractures in aggregate particles and then caused a disintegration of the rock fabric as the salt expanded, if the aggregate lacked fabric strength. The suggested mechanism is why the test is so often correlated with water absorption if this latter test is considered a measure of permeable voids. It was postulated that the salt preferentially attacked clay within the rock fabric, but whether this was the case, or whether it simply appeared this way because clays lack particle strength was never demonstrated.

The test was first specified in Australian Standards for supply of concrete aggregate in AS-A77, the precursor to the current AS 2758. The test has been specified in all editions of AS 2758 and remains current for both coarse and fine aggregate.

The test remains relevant to manufactured sand at the present time because it is the only test currently specified in National Standards capable in part of testing fine aggregate. The common specification limit for the Sodium Sulphate Soundness test for coarse aggregate is 12% maximum weighted loss. The Australian Standard accepts this maximum for aggregates in Exposure Classifications A1 and A2 but imposes harder limits of 9% maximum for Exposure B1 and B2 and 6% maximum for Exposure C. By contrast, the specification for fine aggregate is 12% maximum for the Exposure B and C and 15% for crushed fine aggregate for Exposure A, while natural fine aggregate is not specified. It should be noted that these limits apply to the crushed fine aggregate regardless of the quantity of crushed fine aggregate used in the sand blend in the finished concrete. AS 2758.5, the specification for asphalt aggregate, allows fine aggregate to have a weighted loss of 16% for all applications.

For the foreseeable future in Australia, the Sodium Sulphate test will probably continue as a durability test for crushed fine aggregate, although the relevance of the specification limits may need to be reassessed. Industry should be evaluating the relevance of other durability tests for fine aggregate as possible replacements for the Sodium Sulphate method.

6 TEST RESULTS

Testing was conducted between January and July 2006 with Hanson's laboratory at Wallgrove being responsible for sample preparation, supervision of the testing programme, conducting a significant part of the testing, and reporting of results.

With the exception of the X-Ray Diffraction results, all testing was completed in duplicate so that data on test repeatability could be generated. A copy of the spreadsheet reporting duplicate test results is included as **Appendix 2**, while data on test repeatability is included as **Appendix 3**.

Analysis and discussion on the test results and the use of the tests in the specification of manufactured sands are provided in the following section. For these purposes, average results of tests were used; these averages and the X-Ray Diffraction results are reported in **Tables 3, 4 and 5**.

TABLE 3 – Particle size distribution data for manufactured sand samples

	CUMULATIVE PERCENTAGE PASSING									
AS 1141.11	**Sample ID**									
Washed grading	**A75**	**B41**	**B58**	**BM58**	**B90**	**C77**	**D69**	**G13**	**G80**	**H73**
9.5 mm										
6.7 mm	100		100		100	100			100	100
4.75 mm	99	100	95	100	96	91	100	100	99	95
2.36 mm	69	82	70	93	74	56	78	72	69	62
1.18 mm	39	54	46	57	49	36	45	49	44	37
600 um	23	35	33	37	33	26	29	33	27	22
425 um	19	29	28	30	27	23	23	28	24	18
300 um	15	23	25	25	22	20	19	23	21	15
150 um	13	17	19	19	14	17	13	17	16	11
75 um	10	13	15	14	9	14	9	12	12	8

	Sample ID										
	H85	**L16**	**L24**	**N33**	**N53**	**N76**	**P99**	**S51**	**S68**	**T68**	**T88**
9.5 mm					100			100			
6.7 mm	100	100	100		100		100	100		100	100
4.75 mm	96	99	97	100	95	100	96	99	100	98	99
2.36 mm	68	91	74	93	74	88	78	78	96	85	79
1.18 mm	40	55	49	66	53	61	53	38	65	73	49
600 um	25	35	34	46	37	38	39	21	47	60	31
425 um	21	28	29	38	31	29	33	16	40	49	24
300 um	18	23	26	32	25	22	28	13	35	37	20
150 um	13	15	21	20	16	11	18	10	28	25	13
75 um	10	10	17	14	11	6	12	8	23	19	9

TABLE 4 – Physical test data for manufactured sand samples

Sample ID	Mass % passing 75 micron	Mass finer than 2 micron	Clay and silt (%)	2.36 mm sample voids (%)	2.36 mm sample flow (secs)	Minus 4.75 mm density (SSD) (t/m^3)	Water absorption (%)	LCPC packing density	MBV	Sand equivalent	Degradation factor (fines)	Sodium sulphate loss (%)
A75	10	1.10	11	45.1	28.8	2.64	0.8	0.63	5.40	79.00	94.00	0.90
B41	13	0.90	20	40.0	22.7	2.84	1.5	0.653	16.80	65.00	86.00	1.20
B58	15	1.00	21	41.1	23.4	2.88	2.2	0.653	11.10	61.00	80.00	1.40
B90	9	1.30	16	42.9	26.0	2.56	2	0.663	8.40	68.00	87.00	0.60
BM58	14	0.20	32	42.0	21.7	2.89	2.2	0.644	8.20	69.00	84.00	0.80
C77	14	0.50	18	41.0	33.4	2.63	1.1	0.668	1.80	73.00	94.00	0.10
D69	9	1.40	13	44.0	27.9	2.67	0.9	0.653	3.40	74.00	85.00	0.40
G13	12	1.50	14	46.3	30.6	2.65	1.6	0.652	3.70	60.00	88.00	0.30
G80	12	2.30	31	43.2	26.5	2.63	2.1	0.641	11.80	66.00	86.00	0.70
H73	8	1.70	19	42.3	25.8	2.6	1.7	0.66	14.10	69.00	86.00	1.60
H85	10	0.40	16	42.3	22.3	2.92	1.6	0.635	13.50	66.00	90.00	0.80
L16	10	2.80	22	41.8	23.6	2.67	2.3	0.646	10.80	76.00	88.00	1.40
L24	17	0.70	33	38.8	24.4	2.64	3.3	0.647	11.40	60.00	84.00	1.10
N33	14	1.30	16	44.9	33.7	2.63	0.3	0.669	3.00	72.00	96.00	0.40
N53	11	1.70	22	45.4	25.7	2.61	0.9	0.655	12.00	70.00	90.00	0.70
N76	6	0.20	15	44.5	22.5	2.66	0.9	0.655	9.30	78.00	87.00	1.00
P99	12	1.20	35	44.9	23.1	2.75	3.2	0.666	19.00	51.00	58.00	12.40
S51	8	0.50	13	42.2	26.6	2.67	0.8	0.654	1.20	81.00	89.00	0.20
S68	23	4.40	48	44.7	37.2	2.64	1.7	0.626	14.30	40.00	74.00	1.30
T68	19	4.80	Indeterminate	42.2	22.8	2.48	3.6	0.655	24.20	25.00	53.00	6.00
T88	9	1.50	18	42.5	27.6	2.62	1.2	0.661	9.30	71.00	94.00	0.40

TABLE 5 – XRD results for SAMPLES A75 to H73

MINERAL	SAMPLE ID A75 Head sample analysis	A75 <75 µm sample analysis	B41 Head sample analysis	B41 <75 µm sample analysis	B58 Head sample analysis	B58 <75 µm sample analysis	BM58 Head sample analysis	BM58 <75 µm sample analysis	B90 Head sample analysis	B90 <75 µm sample analysis	C77 Head sample analysis	C77 <75 µm sample analysis	D69 Head sample analysis	D69 <75 µm sample analysis	G13 Head sample analysis	G13 <75 µm sample analysis	G80 Head sample analysis	G80 <75 µm sample analysis	H73 Head sample analysis	H73 <75 µm sample analysis
Quartz	D	D							A-SD	A			CD	CD	CD	CD	SD	SD	SD	A-SD
Plagioclase	SD	SD	D	D	CD	CD	CD	CD	D	D			CD	CD	CD	CD	D	D	D	D
K-feldspar	A	A	SD	SD	CD	CD	CD	CD	A	SD	D	D	A	A	A	A	A	A	A	A
Clinopyroxene			SD	SD	CD	CD	CD	CD			SD	SD								
Olivine					A	A	A	A												
Amphibole																				
Analcime			Tr-A	Tr-A																
Laumontite		Tr																	Tr	Tr
Stilpnomelane															Tr	Tr				
Muscovite	A	Tr				Tr				Tr			A	A	A	A	A	Tr		A
Biotite																				
Chlorite	Tr	Tr											Tr-A	A	A	A	A	A		Tr-A
Kaolinite																				
Smectite			Tr-A	Tr-A	Tr-A															
Calcite										Tr				Tr-A	Tr	Tr-A	Tr	Tr-A		A
Clay Minerals in the clay fraction (<2 µm)																				
Mica (illite)	D	D			A-SD	D	Tr	SD	D	D			D	D	D	D	CD	SD	D	SD
Chlorite	Tr-A	SD											A	A	A	A	D	D	SD	D
Kaolinite			A-SD	SD	A	A	SD	A-SD	SD	SD		A-SD								
Smectite	Tr	Tr-A	D	D	D	SD	D	D	SD	A		D					SD	A	A-SD	A-SD
Clay Minerals in the clay fraction (<2 µm) – Percentages																				
Mica (illite)	85	65			20	50	5	40	50	60			90	80	80	80	40	30	50	30
Chlorite	10	30											10	20	20	20	40	60	25	50
Kaolinite			30	40	20	10	30	20	25	30		20								
Smectite	5	5	70	60	60	40	65	40	25	10		80					20	10	25	20

Semiquantitative abbreviations:

D = Dominant. Used for the component apparently most abundant, regardless of its probable percentage level.

CD = Co-dominant. Used for two (or more) predominating components, both or all of which are judged to be present, in roughly equal amounts.

SD = Sub-dominant. The next most abundant component(s) providing its percentage level is judged above 20%.

A = Accessory. Components judged to be present between the levels of roughly 5 and 20%.

Tr = Trace. Components judged to be below about 5%.

TABLE 5 – XRD results for SAMPLES H85 to T88

	SAMPLE ID H85		L16		L24		N33		N53		N76		P99		S51		S68		T68		T88	
MINERAL	Head sample analysis	<75 µm sample analysis	Head sample analysis	<75 µm sample analysis	Head sample analysis	<75 µm sample analysis	Head sample analysis	<75 µm sample analysis	Head sample analysis	<75 µm sample analysis	Head sample analysis	<75 µm sample analysis	Head sample analysis	<75 µm sample analysis	Head sample analysis	<75 µm sample analysis	Head sample analysis	<75 µm sample analysis	Head sample analysis	<75 µm sample analysis	Head sample analysis	<75 µm sample analysis
Quartz			Tr		Tr		D	D	D	D	D	D			Tr		CD	SD	D	D	D	D
Plagioclase	D	D	D	D	D	CD	A	A	SD	SD	SD	SD	A	D			A	A	Tr-A	A	Tr-A	A
K-feldspar			SD	SD	A	CD	A-SD	A	A	A	A	Tr-A	D	A			A	Tr-A	A	A		
Clinopyroxene	SD	SD	A	SD		CD																
Olivine	A																					
Amphibole									Tr	Tr												
Analcime													A	A								
Laumontite																						
Stilpnomelane																						Tr
Muscovite							Tr	Tr										Tr	Tr-A	A	Tr	Tr
Biotite							A	A	A	A	SD	SD	Tr	A								
Chlorite							Tr	Tr-A	Tr			Tr	Tr				A	A				
Kaolinite																			Tr	A	Tr	Tr
Smectite			A	A	A	A				Tr-A		A	A									
Calcite															D	D	CD	D				
Clay Minerals in the clay fraction (<2 µm)																						
Mica (illite)		A-SD					D	D	D	D	D	D		CD		CD	D	D	D	D	D	D
Chlorite	SD	SD					A	Tr-A	A	A-Tr	Tr	Tr	D	CD			SD	SD			A-SD	A
Kaolinite			SD	SD	A-SD	SD					Tr	Tr			D	CD			SD	SD		
Smectite	D	D	D	D	D	D	A	Tr	SD	A	Tr	Tr	SD	CD			A-SD	A	Tr	Tr		Tr
Clay Minerals in the clay fraction (<2 µm) – Percentages																						
Mica (illite)		20					80	90	50	80	90	90		35		50	50	50	55	55	80	75
Chlorite	40	30					10	5	10	5	4	4	50	30			30	30			20	20
Kaolinite			30	40	20	30					1	1			100	50			40	40		
Smectite	60	50	70	60	80	70	10	5	40	15	5	5	50	35			20	20	5	5		5

Semiquantitative abbreviations:

D = **Dominant.** Used for the component apparently most abundant, regardless of its probable percentage level.

CD = **Co-dominant.** Used for two (or more) predominating components, both or all of which are judged to be present, in roughly equal amounts.

SD = **Sub-dominant.** The next most abundant component(s) providing its percentage level is judged above 20%.

A = **Accessory.** Components judged to be present between the levels of roughly 5 and 20%.

Tr = **Trace.** Components judged to be below about 5%.

7 DISCUSSION OF RESULTS AND SPECIFICATION CONFORMANCE

7.1 Product Sizing

Grading

The results of grading tests in this research programme are given in **Table 3** and presented graphically in **Figure 1**.

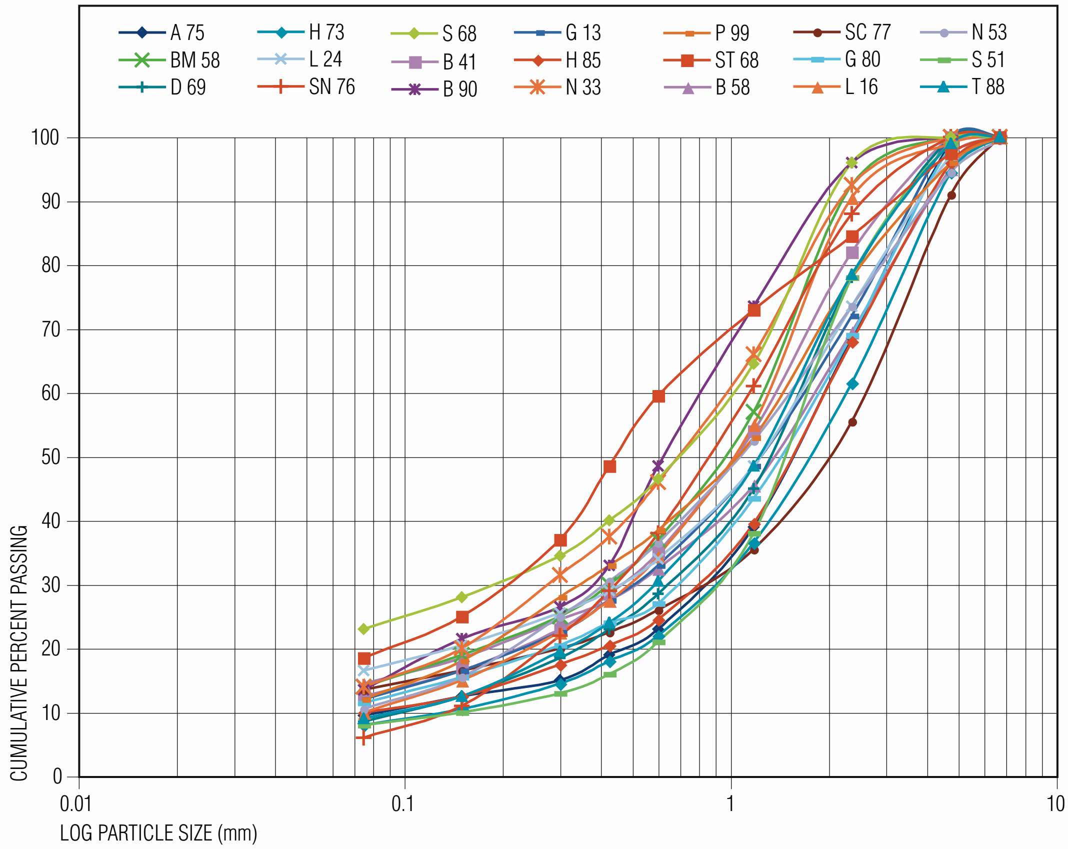

FIGURE 1 – Particle size distribution (average)

The samples tested included materials that could be described as 'graded' by extension of the definition given in the AS 2758 series where graded aggregates are described as those having 15% or more material retained on each of three successive sieves. By this definition, 12 of the 21 samples can be described as graded. None of the samples approach the definition of single sized (60% retained between two successive screens) but clearly the distribution pattern of these samples, nineteen of which are being used as manufactured sands, varies considerably. Similarly, the particle size of these samples is variable. Sample C77 has a particle mean size of 2.6 mm, while the finest four samples have mean sizes between 1.1 mm and 1.3 mm. Yet nearly all samples comply with the current AS 2758.1 grading specification for crushed fine aggregate.

The sample gradings are summarised and compared to current specifications in the following table:

TABLE 6 – Grading summary in comparison with Australian and American specifications

	Range of results		**AS 2758.1 Specs**		**ASTM C33 Natural sand**		**ASTM C 33 Manufactured sand and blends**	
Sieve size	Min	Max	Min	Max	Min	Max	Min	Max
9.5 mm	100	100	100	100	100	100	100	100
6.7 mm	100	100						
4.75 mm	91	100	90	100	80	100	80	100
2.36 mm	56	96	60	100	80	100	60	100
1.18 mm	36	73	30	100	50	85	40	85
600 um	21	60	15	80	25	60	20	60
425 um	16	49						
300 um	13	37	5	40	5	30	10	45
150 um	10	28	0	25	0	10	0	30
75 um	6	23	0	20			0	18
<75 um	5.7	22.2	0	20				

Table 3 identifies sample C77 as non conforming against the Australian Standard at the 2.36-mm sieve, and sample S68 as non conforming at the 150 µm and 75 µm sieves. By contrast, all samples fail the current ASTM C33 specification for natural sands. Compared to the specification for manufactured sands, sample C77 is coarse at 2.36 mm, samples A75, C77, H73, and S51 are coarse at 1.18 mm, and samples S68 and T68 are fine at 75 micron. It appears that the ASTM specification is attempting to define an 'ideal' fine aggregate grading for the production of concrete. In contrast, the Australian standard grading has attempted to encompass all those materials that may be used, either alone or as components of fine aggregate blends. As a consequence, the Australian Standard does not define or control anything. The committee believes that it would be preferable that the 'submitted' grading become a part of a supply specification with the Australian Standard setting the variation limits that would control product and blend variation.

The ASTM specification for manufactured sands is wider than that for natural sands, perhaps reflecting the wider range of products in use; these limits are also specified for blends of manufactured sand and natural sand.

Passing 75 micron in aggregates (by washing)
Material finer than 2 micron
Deleterious fines

The limitation on the passing 75 µm in specifications for natural sands for concrete is a response to the presence of deleterious clay minerals within this fraction size. Clay minerals are prone to cause cracking, dusting and shrinkage in hardened concrete, and increase water demand in the mix design. When designing with natural sands, the typical response of the specifier has been to restrict the passing 75 µm to a level that prevented the possibility of clay minerals being present in quantities that would result in the potential issues described.

With the introduction of manufactured sands there has been gradual recognition that much of the passing 75 µm material will be ground primary minerals and not clay minerals. This material will act as a rock flour or filler and may have advantages in the concrete mix. The effect of this material on water demand will still require careful monitoring and will need to be considered in mix design. It is probable that a large proportion of manufactured sands will be used as blends with natural sands and it will be necessary to determine methods that distinguish between deleterious fines, introduced from either the manufactured sand or in the natural sand, and the rock flour that may be either innocuous or require modification to the mix design to compensate for increased water demand

The existing passing 75 micron limit in AS 2758.1 of 0–20% for crushed fine aggregate was put in place to allow manufactured sand to be used, and to allow the development of a history of usage that would lead to realistic specification limits. However, because there were few records of successful use of manufactured sand at the time, the passing 2 micron limit was deliberately set at 1% to ensure that mixes did not become overloaded with clays to the detriment of concrete performance before sufficient data was available to allow for better specification limits. This did have the effect of restricting most manufactured sands to lower percentage blends with natural sands.

In the eight years since AS 2758.1 was last revised a great deal of experience has been gained in using manufactured sands. As already noted, the ASTM C33 specification has allowed for up to 18% passing 75 micron in manufactured sands or in manufactured sand blends. As **Figure 2** clearly shows, most manufactured sands carry a much higher proportion of fines compared with processed natural sands. A realistic specification limit for the passing 75 micron is required both to limit adverse clay mineralogy and to control the water demand of the mix

The specification limit of 1% maximum less than 2 micron restricts the presence of clay-sized materials in the manufactured sand and this has restricted the presence of adverse clay minerals. It should be noted at this point that AS 2758.1 is unclear on how these limits are to be applied. The specification could be seen to apply to the individual components of a blend or could be applied to the total blend (ie the total of the fine aggregate fraction in the mix). Most often, the specification is interpreted as applying to each individual component, the logic being that if each component complies, then the total blend will comply!

As most of the samples tested in this programme are used in blends, it is useful to consider the dilution effect of the blend on the levels of 75 micron and 2 micron material in the fine aggregate used in concrete. Assuming a typical natural fine aggregate dune sand as the blend material, with passing 75 micron of 3% and with less than 2 micron at 0.5%, then the samples tested in this research, used at their current typical blend levels will deliver fine aggregate blends with the size properties given in **Table 7**.

Clearly, revision of AS 2758.1 needs to address whether the limitations on product sizing are significant as a property of the individual components of a blend, or whether they refer to the blend as a whole. If the sizing properties are to be applied to both the components and the blend as a whole, then it can be assumed that the limits would vary. What then becomes critical, is what limits should be applied.

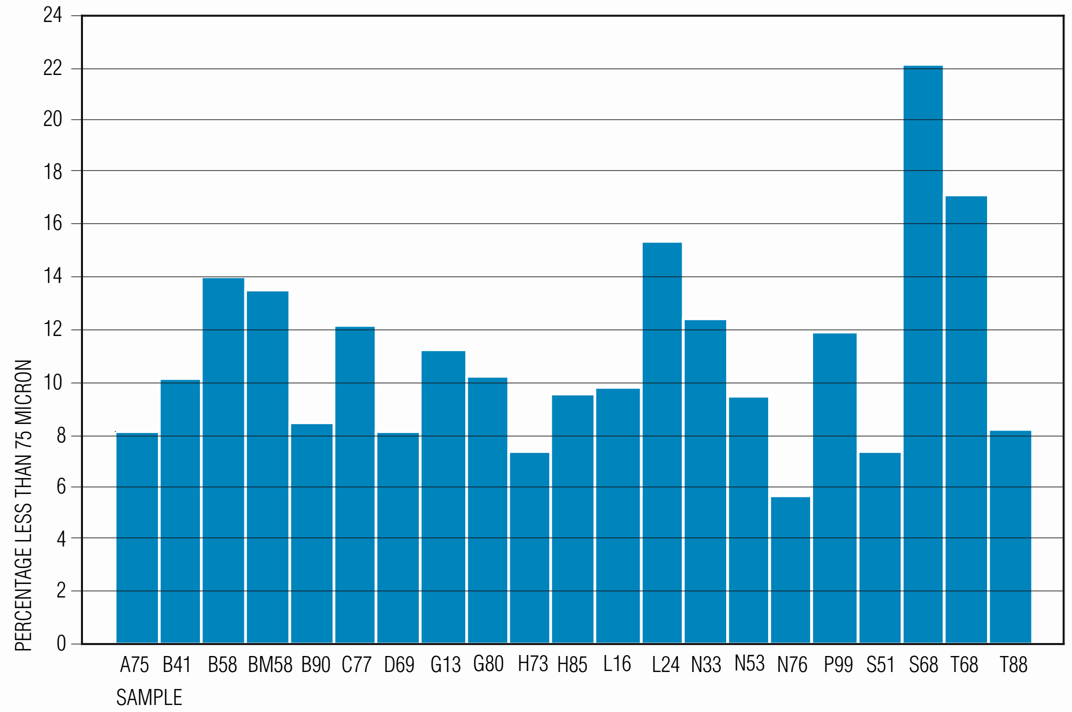

FIGURE 2 – Material less than 75 micron (average)

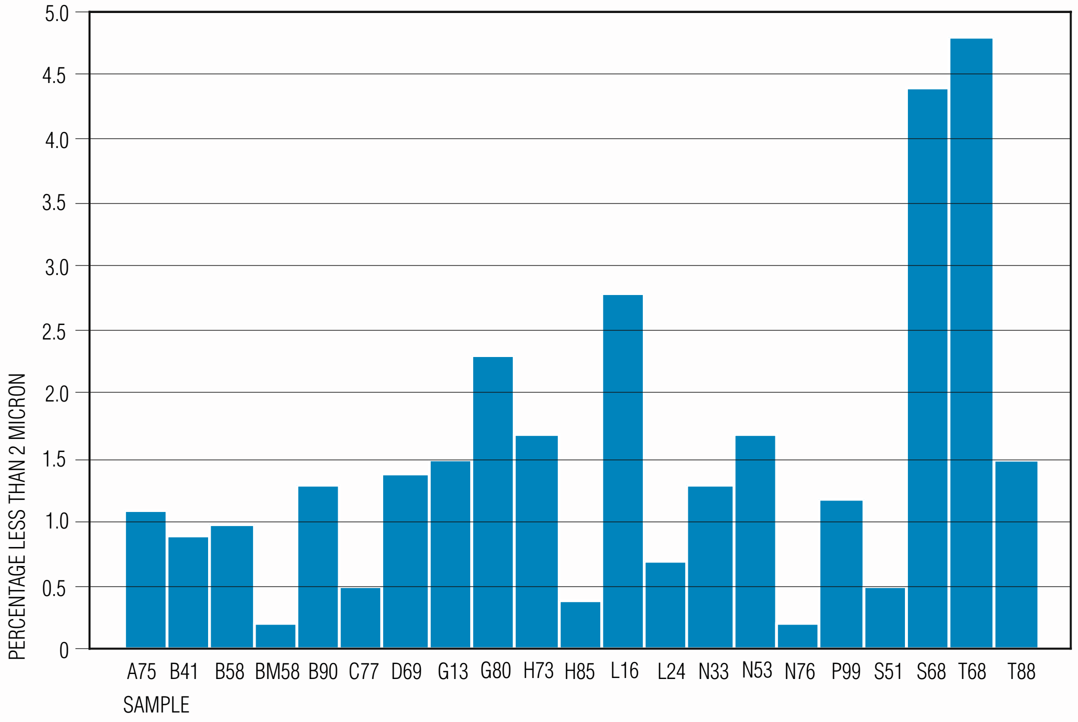

FIGURE 3 – Material less than 2 micron (average)

European and British research associated with the introduction of new specifications for concrete aggregates in 2002 recognised that it was not only the quantity of fines that was significant in the performance of concrete but that the mineralogy of the fines was critical. A proposal was introduced in early drafts of the European Standard that the activity of the passing 75 µm fraction be measured using the Methylene Blue Absorption test. This proposal was eventually rejected by the British who were not convinced that the test was sufficiently reproducible; the committee has not been able to determine if French or German standards adopted the proposal The NSW RTA has specified the Methylene Blue test for control of crusher dusts in asphalt, while the American Transportation Research Board reported the use of MBV in Aggregate Properties and the performance of Superpave Designed Hot Mix Asphalt' NCHRP Report 539.

Thirteen of the twenty-one samples tested in this programme would fail the 1% maximum limit on passing 2 μm as shown in **Figure 3** if the specification is interpreted as applying to each component of the fine aggregate blend.

TABLE 7 – Estimation of fines in fine aggregate blends

Sample ID	Typical mix %	Mass % passing 75 micron	2 micron	Estimated % passing 75 μm in fine aggregate blend	Estimated % passing 2 μm in fine aggregate blend
A75	20	10	1.10	4.4	0.62
B41	30	13	0.90	6.0	0.62
B58	50	15	1.00	9.0	0.75
B90	25	9	1.30	4.5	0.70
BM58	Not in production	14	0.20		
C77	25	14	0.50	5.8	0.50
D69	40	9	1.40	5.4	0.86
G13	55	12	1.50	8.0	1.05
G80	100	12	2.30	12.0	2.30
H73	20	8	1.70	4.0	0.74
H85	25	10	0.40	4.8	0.48
L16	30	10	2.80	5.1	1.19
L24	70	17	0.70	12.8	0.64
N33	20	14	1.30	5.2	0.66
N53	20	11	1.70	4.6	0.74
N76	40	6	0.20	4.2	0.38
P99	Not in production	12	1.20		
S51	20	8	0.50	4.0	0.50
S68	18	23	4.40	6.6	1.20
T68	15	19	4.80	5.4	1.15
T88	77	9	1.50	7.6	1.27

Table 7 demonstrates that blends currently in production are operating with clay-sized material in excess of the current specification, including one manufactured sand used as the total fine aggregate, where the 2 μm fraction is 2.3%. This research makes clear that the quantity of clay-sized material in a manufactured sand is influenced by the amount of microfines (passing 75 micron) but the correlation is not strong **Figure 4**. What is of greater importance is that the clay activity is independent of the quantity of clay or microfines, therefore suggesting that the European intention of evaluating the performance of the fine aggregate on the basis of both quantity of fines and their activity is a correct approach **Figure 5** and **Figure 6**.

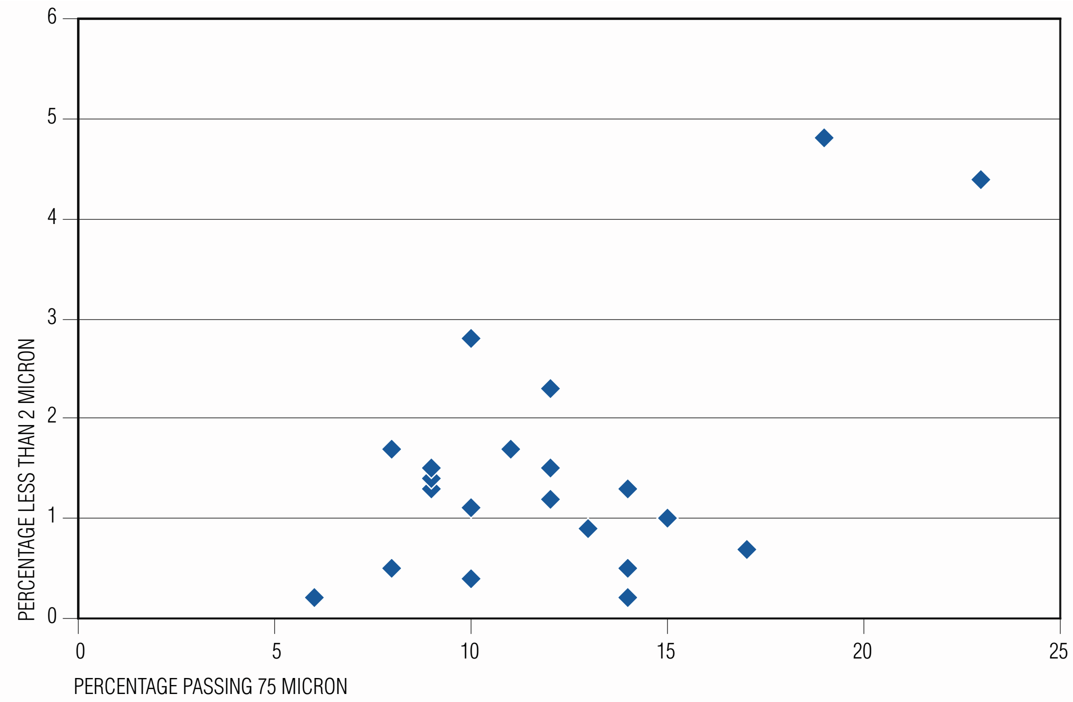

FIGURE 4 – Lack of correlation between passing 75 micron and 2 micron results

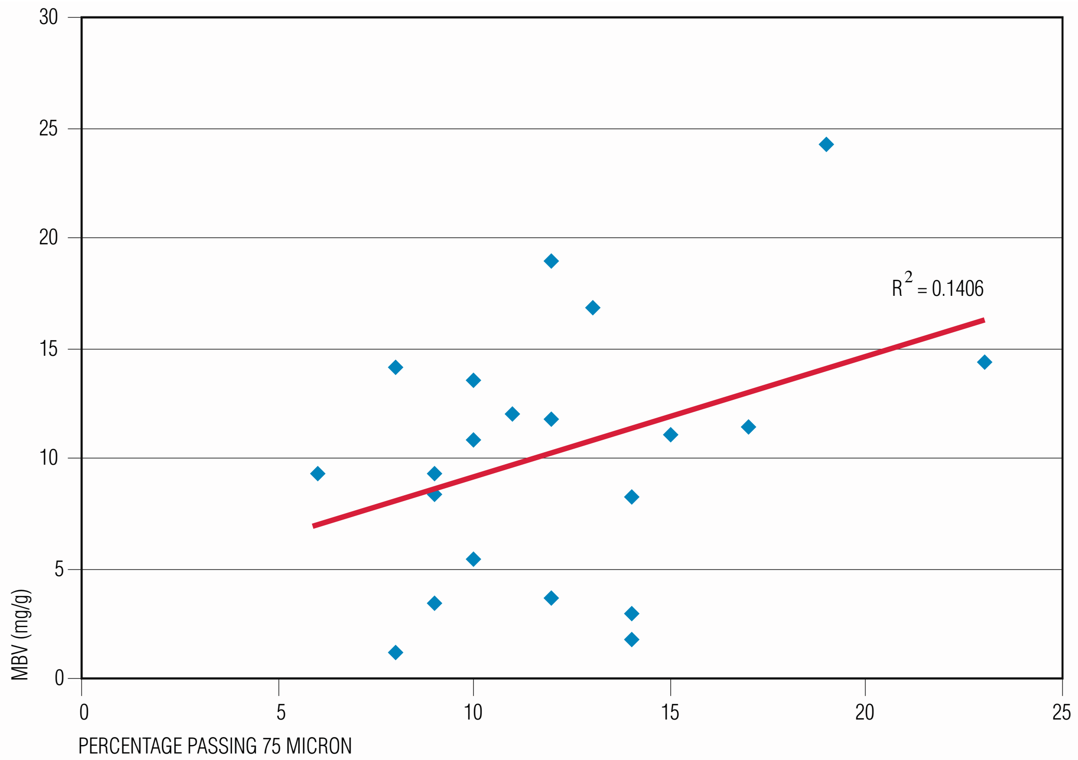

FIGURE 5

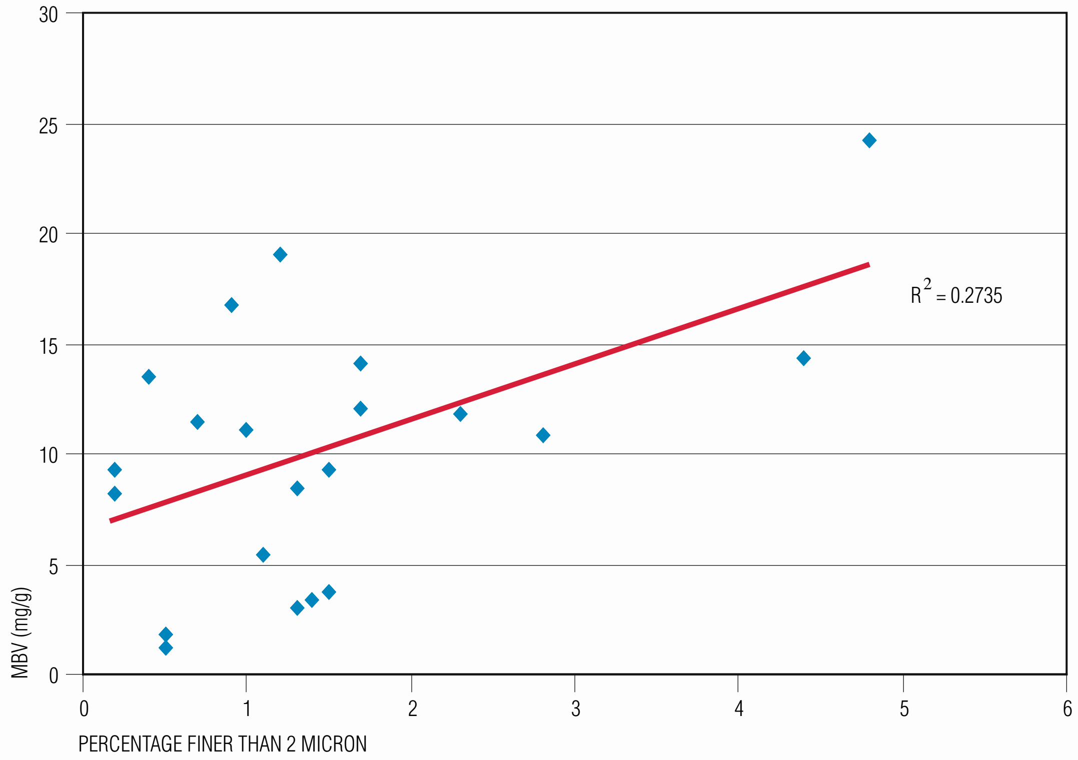

FIGURE 6 – Lack of correlation between quantity of fines and activity of fines

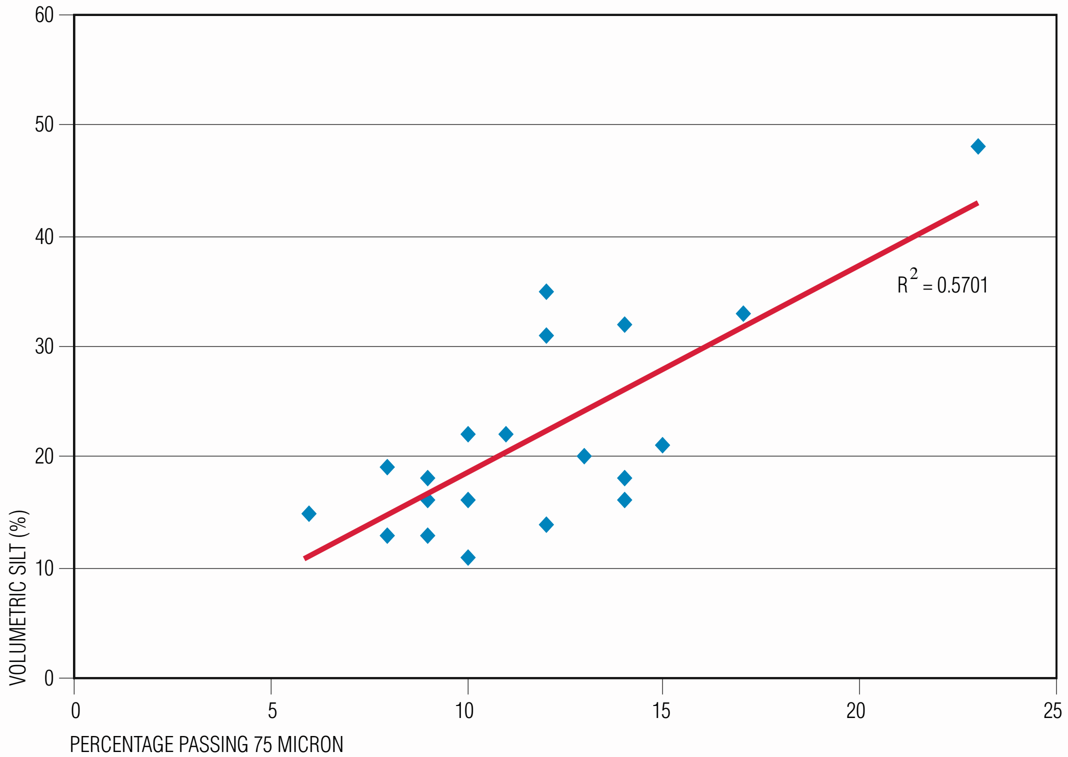

FIGURE 7

TABLE 8 – Clay and fine silt and supporting data

	TEST RESULTS			CALCULATIONS		XRD DATA Approximate percentages			
Sample ID	Clay and silt AS 1141.33	Mass % passing 75 micron	MBV	Ratio clay and fine silt to passing 75 µm	MBV x % passing 75 µm	Mica and illite in head sample	Chlorite in head sample	Kaolinite in head sample	Smectite in head sample
A75	11	10	5.40	1.10	54	85	10		5
B41	20	13	16.80	1.54	218.4			30	70
B58	21	15	11.10	1.40	166.5	20		20	60
B90	16	9	8.40	1.78	75.6	50		25	25
BM58	32	14	8.20	2.29	114.8	5		30	65
C77	18	14	1.80	1.29	25.2				
D69	13	9	3.40	1.44	30.6	90	10		
G13	14	12	3.70	1.17	44.4	80	20		
G80	31	12	11.80	2.58	141.6	40	40		20
H73	19	8	14.10	2.38	112.8	50	25		25
H85	16	10	13.50	1.60	135		40		60
L16	22	10	10.80	2.20	108			30	70
L24	33	17	11.40	1.94	193.8	20	80		
N33	16	14	3.00	1.14	42	80	10		10
N53	22	11	12.00	2.00	132	50	10		40
N76	15	6	9.30	2.50	55.8	90	4	1	5
P99	35	12	19.00	2.92	228		50		50
S51	13	8	1.20	1.63	9.6			100	
S68	48	23	14.30	2.09	328.9	50	30		20
T68	Indeterminate	19	24.20		459.8	55		40	5
T88	18	9	9.30	2.00	83.7	80	20		

Clay and Fine Silt

The average results of the Clay and Fine Silt tests, some calculated values and XRD data relating to the samples are given in **Table 8**. The XRD data relates to analyses taken on the total sample because the Clay and Fine Silt test is conducted on the full sample. XRD data reported elsewhere records data from the –75 micron fraction of the sample. In both cases, the XRD testing is conducted on the 2-micron material extracted from the sized sample.

All samples in the test programme have clay and fine silt levels above 8 to 12% that, based on local experience, may cause increase in water demand and may lead to dusting of concrete, particularly in summer placing conditions. Where the ratio of clay and fine silt to passing 75 micron exceeds 2, experience has suggested the presence of active clay components that may affect the properties of plastic and hardened concrete.

It is reasonable to assume that if the Clay and Fine Silt test is measuring particle size (clay and silt being geological size terms) then there should be reasonable correlation between the measurement of the percentage passing 75 micron and the clay and fine silt result. This correlation is given in **Figure 7**.

Although the data returns the expected relationship, the correlation is not very strong. The research investigated the influence of clay activity on the clay and fine silt result by including the MBV data. From the data collected, the value of MBV x passing 75 µm was calculated (see **Table 8**) and the clay and fine silt result was plotted against this value (See **Figure 8**). The improvement in correlation is taken to indicate that the test is not only measuring a size range, but is also influenced by the clay activity as measured by the MBV.

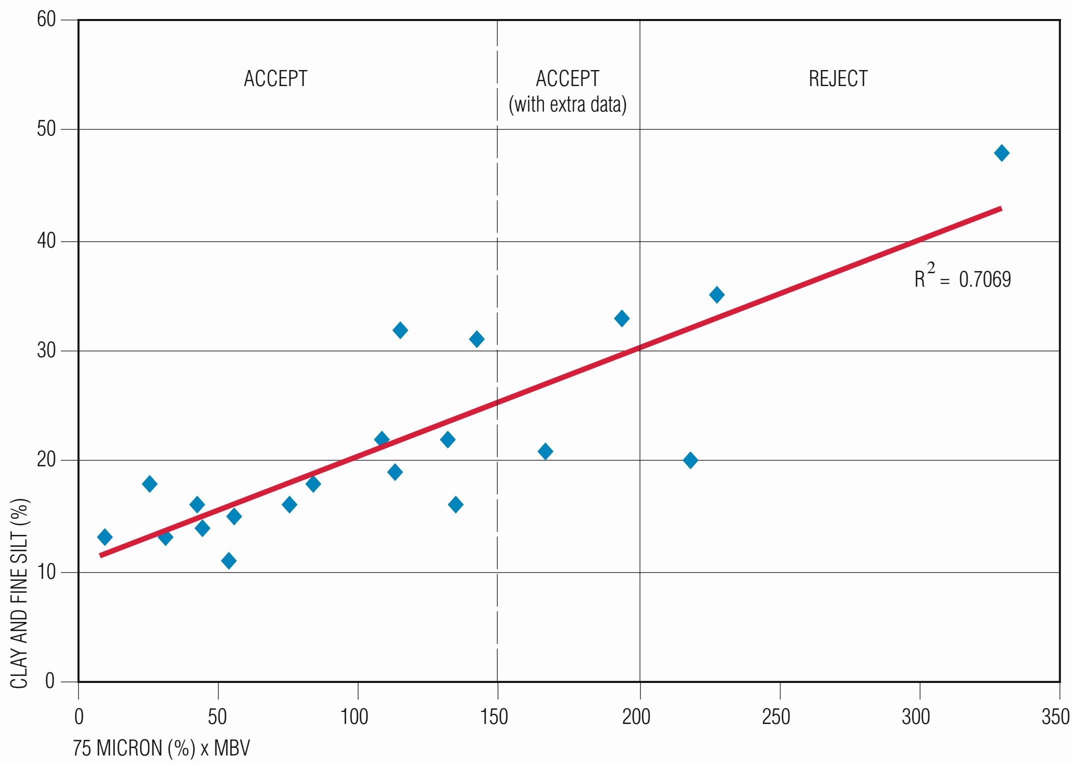

FIGURE 8

The result for sample T68 is reported as 'Indeterminate'. The testing laboratory has used this description where it was impossible to achieve a clear separation between the 'sand' and the 'clay silt' layer in the test cylinder. It is expected that this situation will occur with greater frequency when the test is used for manufactured sands, than is presently the case when testing natural sands. This is believed to be the result of higher proportions of passing 75 μm (ie greater silt and clay fractions) in manufactured sand and/or clay fractions in manufactured sand with higher clay activity. It may be possible to solve this issue on a source-by-source basis by halving the sample mass used in the test (which should have the effect of reducing the clay content and allow a clearer separation of the sediment layers). However, this solution will result in a non-standard test and will prevent reporting of the result on endorsed test certificates and limit use of these results in specifications.

7.2 Shape and Density Properties

Flow Cone

The New Zealand flow cone or very similar methods have been used by all major quarrying companies in Australia to research and evaluate manufactured sands and manufactured sand blends. Typically, the evaluation determines the flow and voids characteristics of the manufactured sand and then examines a series of blends with available natural sands. Usually, concrete or mortar trials are designed around those blends that plot within the region identified on the New Zealand design charts as producing workable mixes in natural sands. The test method may be used to experiment with different natural sands as blending material and again the selection criteria is the blend resulting in the lowest flow time and voids content that is rated as 'workable' on the design chart.

Twelve of the twenty-one samples tested in this programme, and as is true for many manufactured sands, failed to flow through the orifice. This may happen because elongate particles bridge the orifice opening or because the surface texture of the particles creates enough friction that the coarser particles in the sample will not flow past one another. In addition to the potential problems in the method arising from the top size, Boral's laboratory had suggested that excess passing 75-micron material might act as a 'lubricant' in the manufactured sand. To examine these effects, the programme was designed to test material with and without the top size (ie material coarser than 2.36 mm was removed for some tests) and some tests were conducted where the passing 75 micron material had been removed. Where samples failed to flow, the test laboratory adopted a procedure of tapping the exterior of the test apparatus to initiate flow. Since this represents a significant change in method, these results were considered invalid. Nevertheless, the data is recorded in **Appendix 2** with a record of the number of taps required to commence flow.

A typical set of results for the method is shown in **Figure 9** – for the samples tested with the coarse top size removed but with the passing 75 micron material retained in the sample.

The logic of the field descriptions is obvious in the diagram. However, the fields were established based on the performance of natural sands in concrete mixes, and how these natural sands performed in the test equipment. Half the manufactured sands tested in this programme cannot be tested in the equipment. The sand will not flow and a result cannot be obtained. The sample can be 'changed' to obtain a result (remove the top size or, if necessary remove the microfines) or the orifice could be made larger. 'Changing the sample' was investigated in this programme and full results are included in **Appendix 2**.

The average results of the four sets of samples are shown in **Figure 10**.

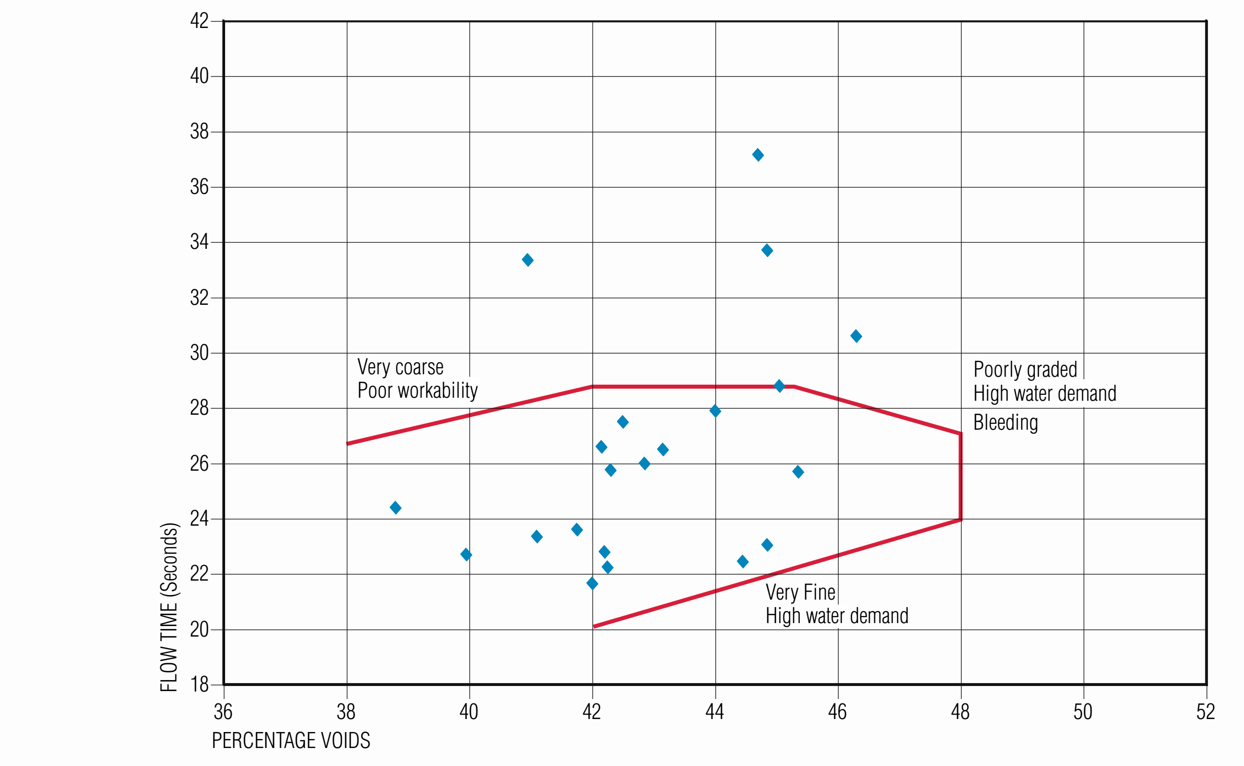

FIGURE 9 – Flow time v voids (average –2.36 mm fraction)

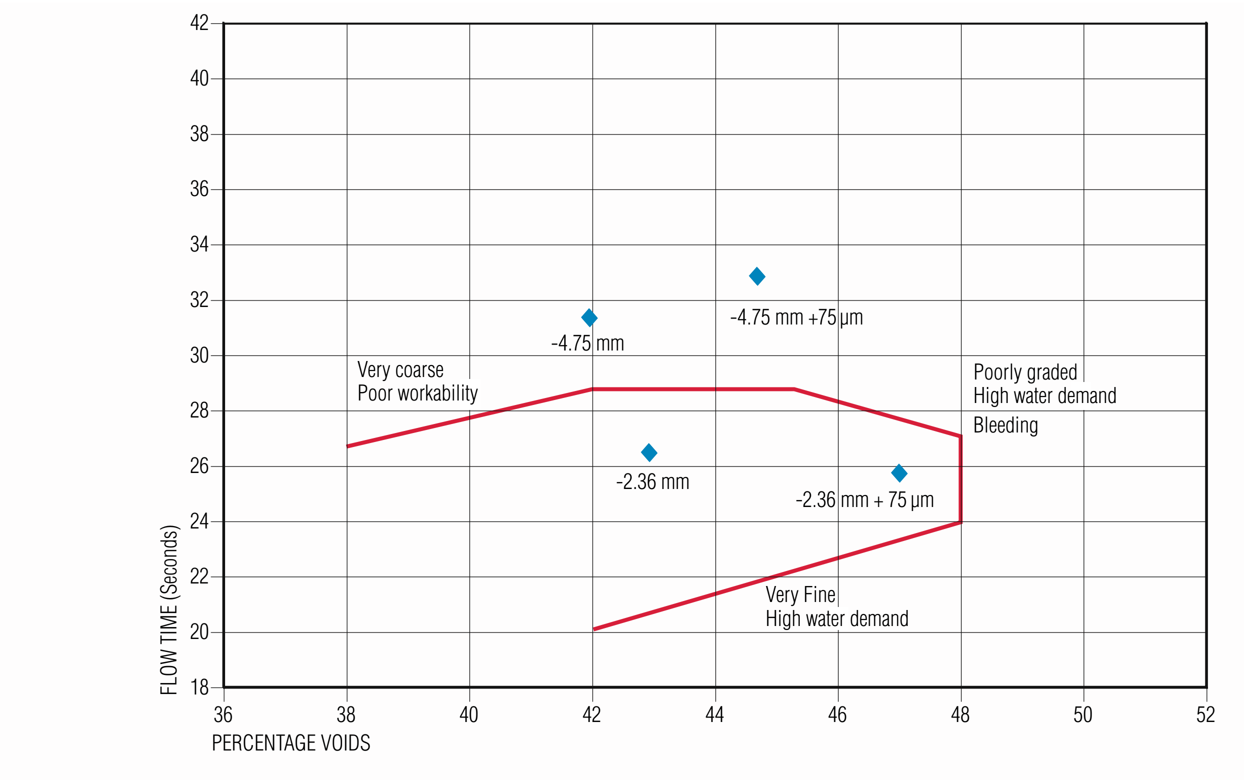

FIGURE 10 – Flow time v voids (average of each fraction)

Changing the sample clearly changes the result plot. Removal of the top size will reduce the flow time significantly and, for these samples, reduces the sample packing. Removal of the passing 75 micron significantly increases voids but does not appear to have much effect on flow time. As the field descriptions are fixed to previous performance measurements and cannot be altered on the basis of that experience, clearly changing the sample will result in an incorrect assessment of the test material in relation to this previous experience. It is to be expected that changing the orifice size would lead to a similar outcome.

Nine samples were tested in accordance with the method (ie using a passing 4.75 mm sample and without tapping the equipment to cause flow). Of these nine samples, seven would be assessed as capable of producing workable concrete see **Figure 11**. It is worth noting that none of these seven samples is used as the whole fine aggregate component in concrete; all are used as blends with natural sands. The two samples in the programme that are used as the total fine aggregate in concrete (a 100% blend) did not flow in this test procedure without tapping. A recommendation has been made for further research into mortars prepared from eight of the samples tested in this programme. If this additional research proceeds, five of the eight samples recommended for inclusion are drawn from the nine samples in **Figure 11**, three of the five from the region considered to produce acceptable concrete. The remaining three samples recommended for further research are drawn from samples that did not flow, including the sample presently used as a 100% blend. One of the outcomes of further research work will be to better define the region of acceptable manufactured sands on the Flow v Voids plot.

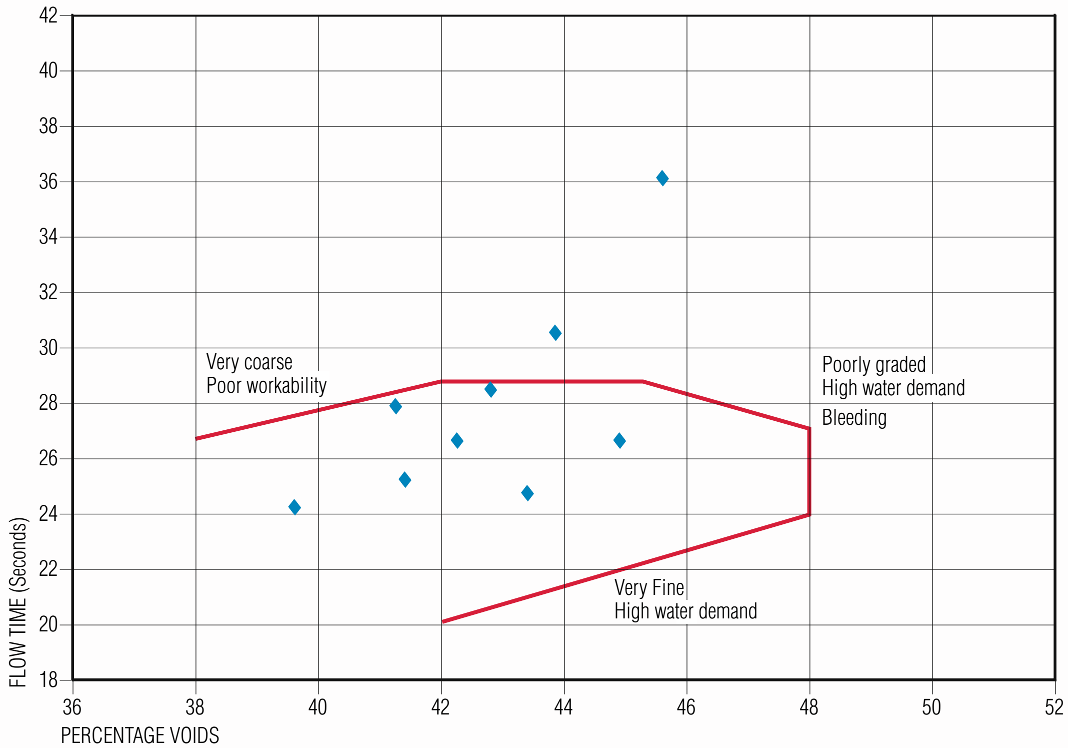

FIGURE 11 – Flow time v voids excluding tapped samples (average –4.75 mm fraction)

The fact that the procedure cannot be used for a large number of manufactured sands at 100% does not prevent it being used to develop blends that will flow and plot within the acceptance region. Also, if a supplier wishes to use the procedure for quality control of a manufactured sand source, but finds it necessary to remove the +2.36-mm fraction to obtain a result, this will pose no difficulty provided the modified procedure remains consistent.

However, it would not be possible to use this procedure as a specification test for manufactured sands until a considerable amount of additional work had been completed to better define the field of acceptable product and to allow for flow in 100% blends, probably by increasing the orifice size. American research has reported using this procedure on seal aggregates up to 20 mm and this work was accomplished by increasing the orifice size in the flow cone.

Particle Density Water Absorption

The particle density of concrete aggregates is measured as part of the design requirements in traditional mix design methods. Particle density in the SSD condition allows for the design of a unit volume of concrete by converting mass of the mix components to a portion of the unit design volume. Using density in the SSD state ensures that the mix is designed as if all permeable voids in the aggregate are filled with water without that water entering into the design of the water/cement ratio as part of the mix strength design.

The Australian Standard also uses the density as a classification. Thus, aggregate with a density greater than 3.2 t/m^3 is classified 'heavyweight'. 'Normal weight' is less than 3.2 t/m^3 but greater than 2.1 t/m^3. 'Lightweight' aggregate is less than 2.1 t/m^3 but greater than 0.5 t/m^3, while ultra-lightweight aggregate is less than 0.5 t/m^3. By definition all aggregates tested in this programme were of normal weight. (**Figure 12**).

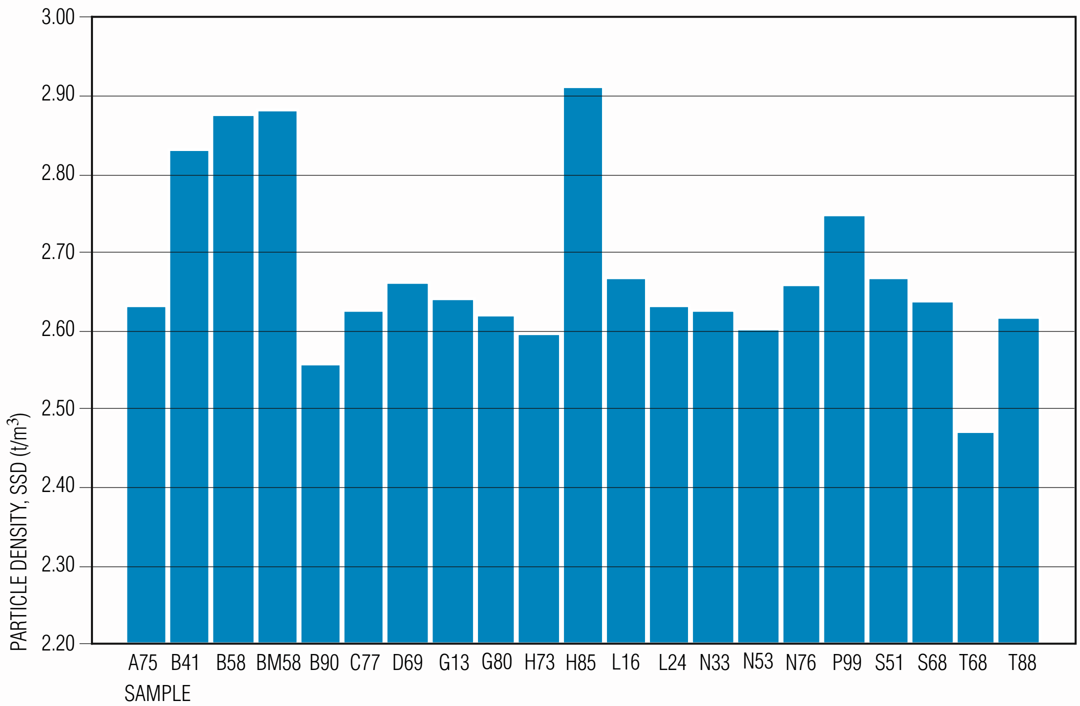

FIGURE 12 – Particle density of test samples

Water absorption is outlined in the majority of specifications within Australia, reference to the Australian Standard methods is common. Many specifications nominate maximum allowable water absorption, as an indirect measure of aggregate quality to give the specifier some overall confidence in the material. This may not be the best approach, but the test has been used in this way for some time. In AS 2758.1, note 2 of Clause 7.3 states that the average water absorption of concrete aggregate is about 2% and in some of the road authority specifications, across a range of concretes, the limit for fine aggregate water absorption is also 2% for natural materials.

One of the main difficulties with the test method would appear to be assessing and obtaining the SSD condition in fine aggregate since determinations, by either method, provide variable results. Whilst two techniques are available in the test method AS 1141.5, it also indicates the difficulty there is in obtaining a SSD condition for fine aggregate with high contents of 1.18 mm sized material present. This situation has mostly been the case with manufactured sands as they often contain high proportions of this material and as such collapse more easily during coning. This seems to results in artificially higher moisture contents reported as SSD, and therefore unrealistic density determinations. In most cases, therefore, SSD condition is reported by a visual assessment.

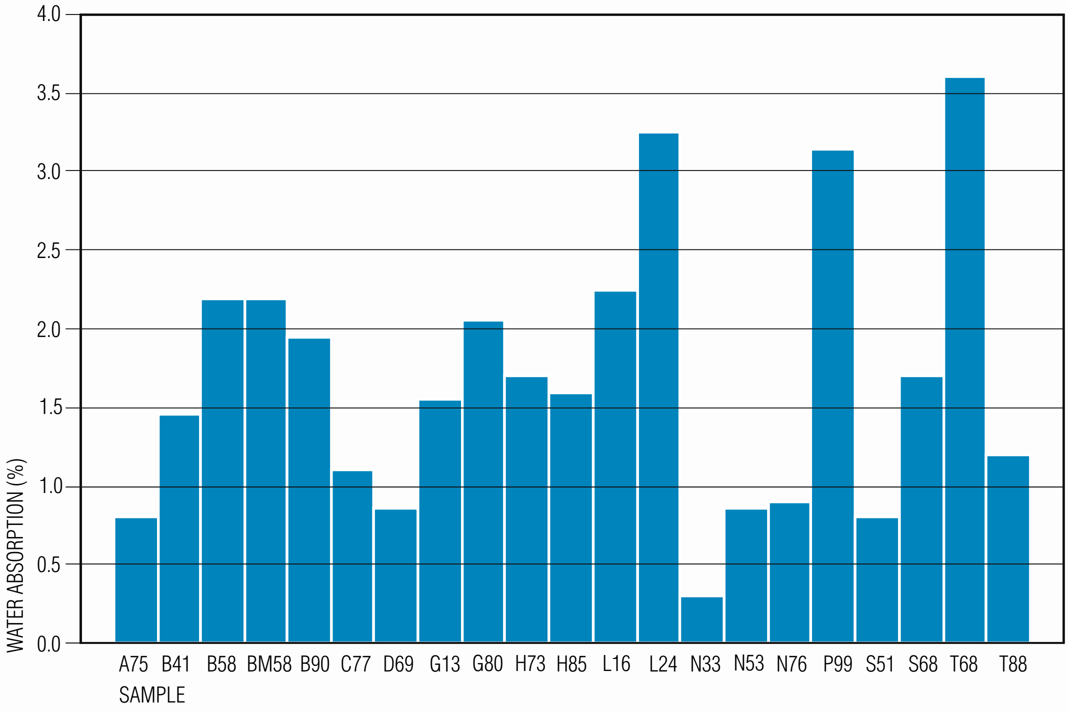

FIGURE 13 – Water Absorption of test samples

As shown in **Figure 13**, seven of the twenty-one samples tested for this project are above the 2% limit that is generally set for natural materials in specifications. Included in these seven samples is G80, one of the two samples that are currently used as 100% of the fine aggregate in concrete mixes.

There is no relationship between particle density and water absorption, as is shown in **Figure 14**.

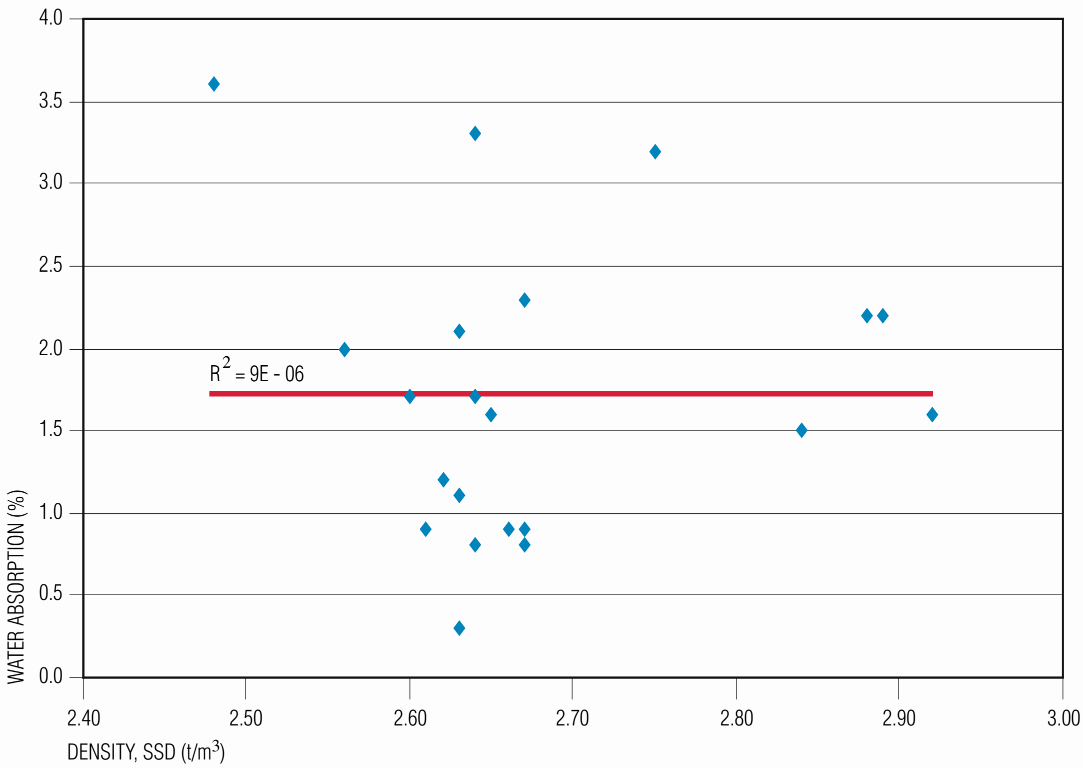

FIGURE 14 – Lack of correlation, water absorption and particle density

Although particle density and water absorption are measured, for convenience, in the same test procedure, the properties are unrelated. Particle density uses water displacement and mass measurements to determine the solid density of the material, although the volume measurement must include non-permeable pores. The water absorption performed at the same time simply measures the mass of water capable of penetrating permeable pores in 24 hours. It is perfectly possible to have a dense rock with high absorption (eg vesicular basalt) or a less dense rock of high absorption (eg a vesicular blastfurnace slag)

As has been noted, water absorption has been used as an indicator of altered or weathered rocks. In these instances, the test may be measuring penetration of water into micro fractures in the rock mass that are the result of stress fracturing. Or the test may be measuring water absorption of clay particles or other hydrophilic alteration minerals. One relationship of water absorption to durability is discussed in relation to the sodium sulphate test.

LCPC Packing Density

Results for the LCPC Packing Density test are reported in **Table 4** and in **Appendix 2**. The results are shown in **Figure 15**.

There is no specification for this test procedure, either in Australia or in France, because the test is not used as a means of selection of suitable material or for rejection of deleterious material. The test provides design data necessary for the use of the Betonlab design method and was included in this programme in anticipation of trialling mixes design by Betonlab in a later part of the CCAA research into manufactured sand.

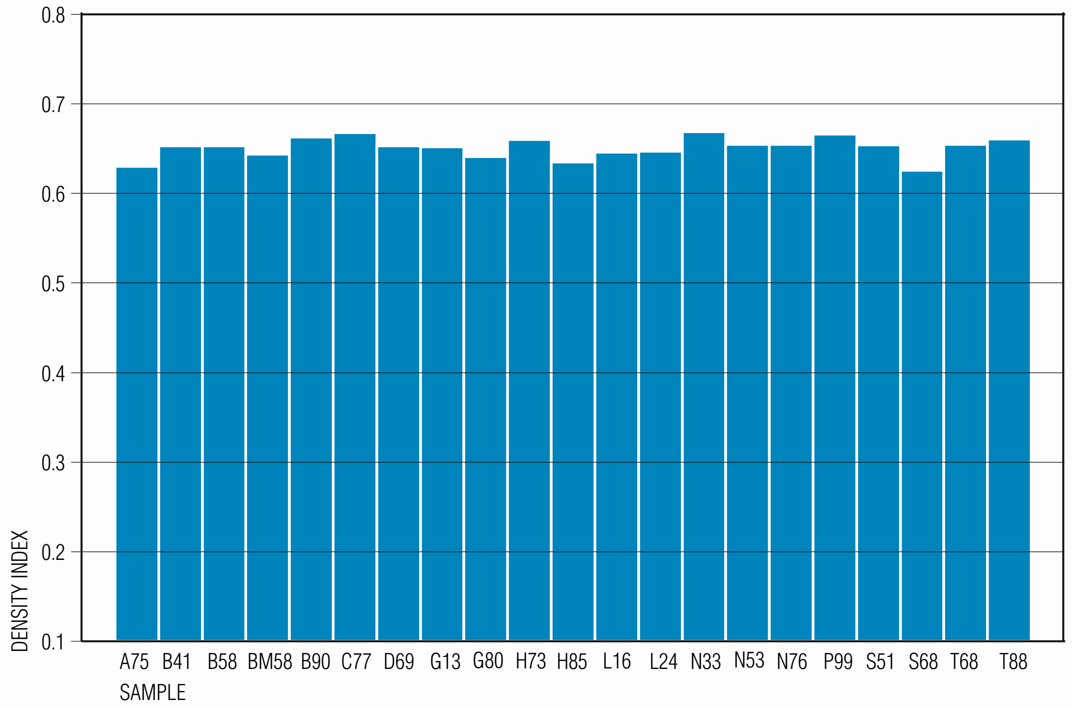

FIGURE 15 – LCPC Packing Density test results

The results cover a fairly limited range, this is not unexpected as the manufactured sands are of similar top size and are produced from comparable processes. Any dry aggregate compacted into a cylinder will form a skeleton of solid particles and the remainder of the space will be voids. Measurement of the unit mass of the aggregate and knowing the particle density of the aggregate allows for calculation of the voids. The scope of AS 1141.16 *Angularity Number* states *... after compaction in the prescribed manner. The least angular (most rounded) aggregates have about 33% voids.* In terms of the LCPC results, 33% voids would be equal to a packing density of 0.67, while higher voids caused by more angular material or significant changes in grading would result in lower density ratios. The LCPC numbers appear a little high in comparison with the information from Method 16 (the expectation would have been for numbers perhaps as low as 0.57). However, it is probable that this difference is the result of different compaction techniques.

7.3 Mineralogical Properties

X-Ray Diffraction

The reported results are given in **Appendix 2**. The following is a summary showing only the dominant , co-dominant or sub-dominant minerals for each sand sample by tested fraction of –2 micron (Mica (M), Chlorite (C), Smectite (S) and Kaolinite (K) ordered by apparent presence where more than one co-dominates):

TABLE 9

Sample ID	Dominant, Co- and Sub-Dominant Minerals in –2 micron Fractions: Full Sample	–75 micron sample	Comments
A75	M	M	Most probable fine mica not illite
B41	S	M, C, S	
B58	S	M, C	
BM58	S, K	S, C	
B90	M, S, K	S, K	
C77	–	S	
D69	M	M	Most probable fine mica not illite
G13	M	M	Most probable fine mica not illite
G80	C, M, S	C, M	
H73	M, C	C, M	
H85	S, C	S, C	
L16	S, K	S, K	
L24	S	S,K	
N33	M	M	Most probable fine mica not illite
N53	M, S	M	Most probable fine mica not illite
N76	M	M	Most probable fine mica not illite
P99	C, S	C, S, M	
S51	K	K, M	
S68	M, C	M, C	
T68	M, K	M, K	Most probable fine mica not illite
T88	M	M	Most probable fine mica not illite

One issue that stands out from this is that there are some significant differences between the –2 micron fractions of the –75 micron sample as opposed to the full sample. This suggests that either the processing to obtain the –75 micron sample has altered the concentration of minerals or that the method lacks a high degree of consistency in its results.

At present there are no specifications applying this test, it is therefore difficult to make any comparison with existing specifications.

At its best XRD would be a useful tool for defining the quality of the fine fraction of manufactured sand. The presence of proportions of deleterious clay minerals on its own will not determine the acceptability or otherwise of a manufactured sand. In view of this there needs to be some way of not only determining what types of minerals make up the –2 micron fraction in a sand but this would need to be linked to quantity of these minerals by way of combining this test with other tests such as –2 micron proportion and Methylene Blue Value. From this research data an interesting correlation (**Figure 16**) is found to exist between the MBV test and the relative proportion of –2 micron to –75 micron material (this normalises the –2 um to the same base as the MBV) when the data is split between samples with dominance of smectite clays as opposed to others:

As can be seen from **Figure 16**, the MBV of the –75 micron fraction is largely relatively higher for sands with clay fractions dominated by smectite than for others at the same relative –2 micron to –75 micron proportion. This may mean that the XRD can be useful in further categorising the –2 micron or MBV tests.

A similar relationship can be developed when comparing the ratios of silt content to –75 micron and –2 micron to –75 micron. When the data is split between samples with dominance of smectite clays as opposed to others:

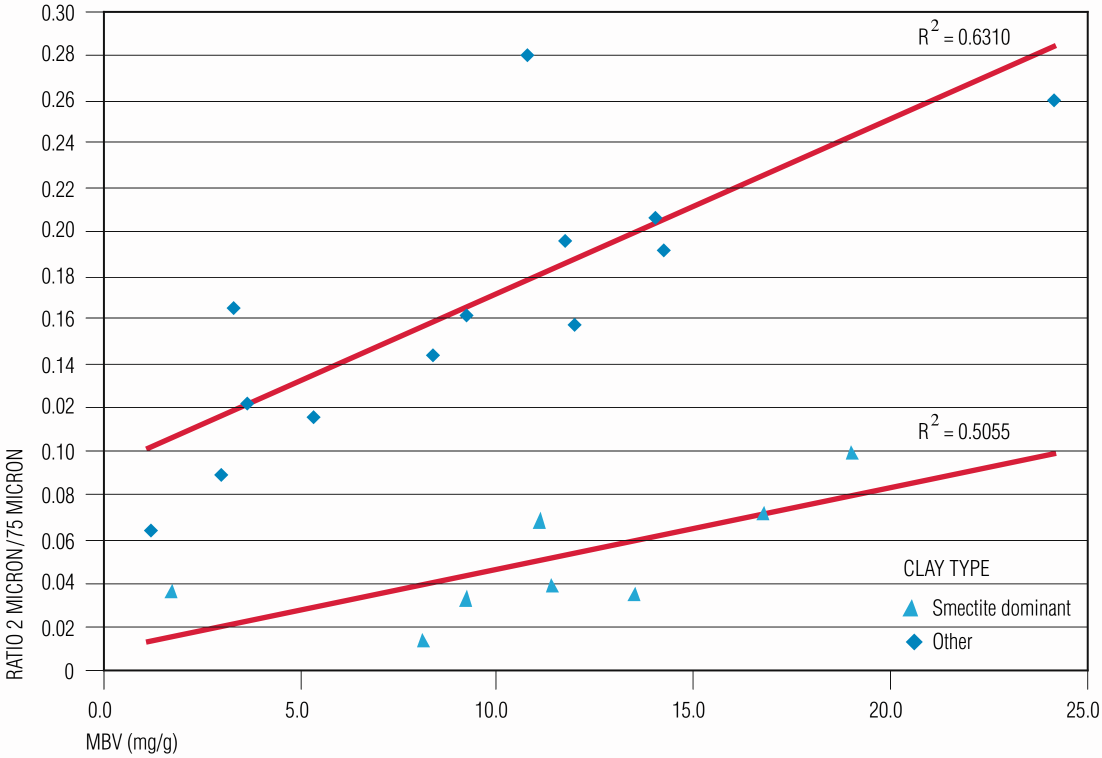

FIGURE 16 – Clay activity related to MBV

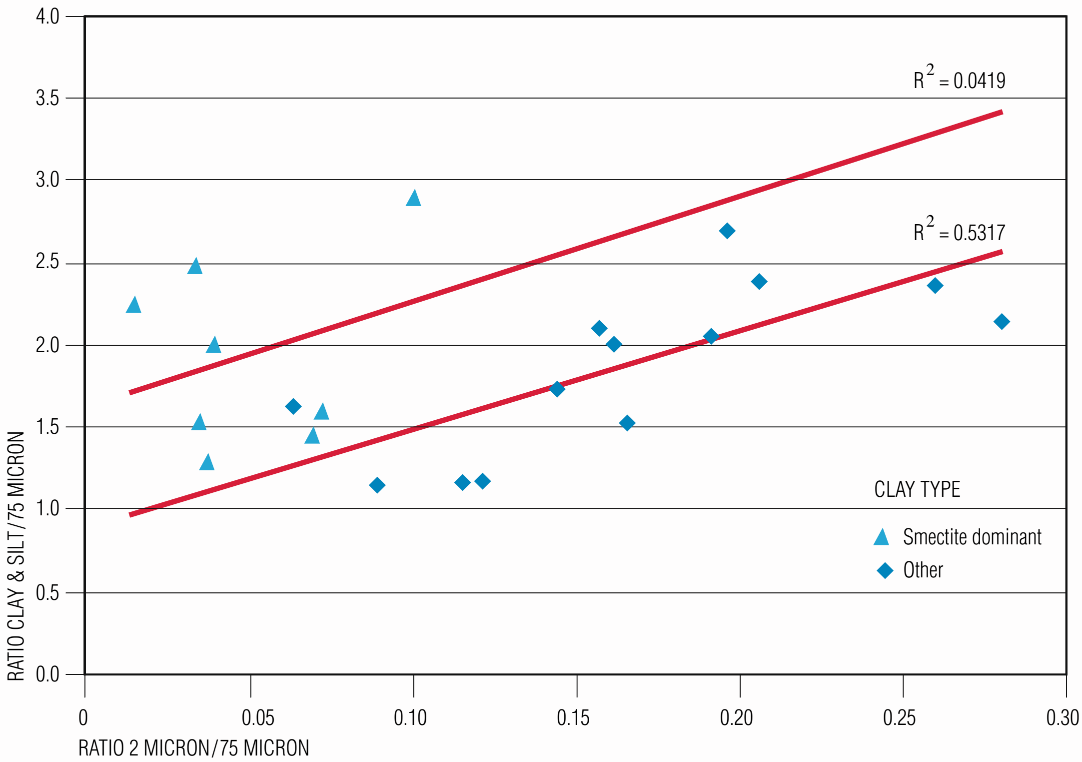

FIGURE 17 – Clay type related to Volumetric Silt content

Again, **Figure 17** demonstrates the impact of the mineral makeup of the sand fines fraction on the silt content to –75 micron ratio. Clearly the effect of smectite clay is to increase the apparent settled volume of fines for a given –2 micron content.

MBV

The results of the Methylene Blue Absorption test are given in **Table 4**, **Appendix 2** and in **Figure 18**.

The ISSA procedure (Bulletin 145) recommends that Mineral aggregate fillers and fines be rejected if the MBV (Methylene Blue Value) exceeds 10 mg/g for basalt rocks or 7 mg/g for gritstones (meta- Greywackes). RTA specifications for fines used in hot mix require further investigation of an aggregate if the MBV exceeds 8 mg/g.

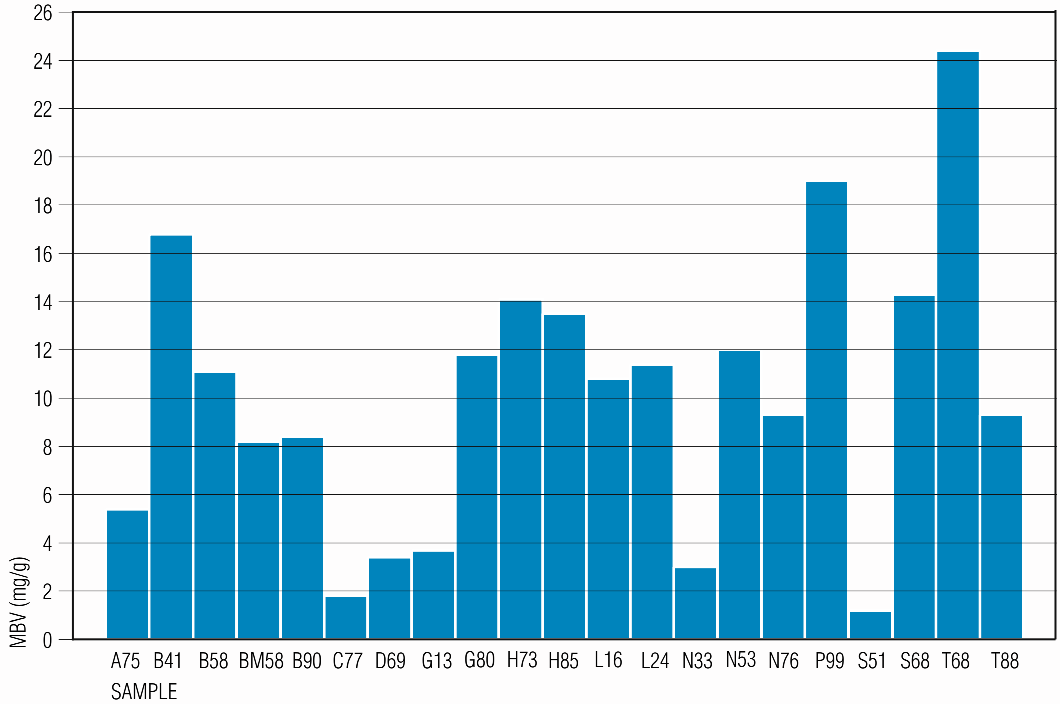

FIGURE 18 – MBV results all samples

Based on the specification and using 8 mg/g MBV as an action limit, fourteen of the twenty-one samples, as indicated in Table 10, would require investigation or would be rejected by specification. The samples assessed in this way would include the two manufactured sands, G80 and T88 already being used as 100% of the fine aggregate in concrete

It appears that the specifications mentioned are failing to recognise that the possible consequences of clay activity in fine aggregate is dependent, not only on the activity of the clay (as measured by the MBV) but also on the quantity of active clay present in the sample. The MBV is given in units of mg/g which implies that if there is a greater quantity of passing 75-µm material, more active clay will be present in the material. But the MBV value will remain the same, because the result is normalised for quantity. The industry suggests that specifications should consider both the activity of the fines and the quantity present and for this purpose has proposed a measure which is the multiple of the passing 75 micron and the MBV. This value is given for all samples in **Table 10**. The table shows that it is possible to have a higher MBV but a lower risk material if the quantity of material is low (samples H73 and L24)

TABLE 10 – MBV results and supporting data

				XRD DATA			
		CALCULATED VALUES		Mica and illite in –75 µm sample	Chlorite in in –75 µm sample	Kaolinite in –75 µm sample	Smectite in in –75 µm sample
Sample ID	**MBV**	MBV x –75 µm	ACI				
A75	5.4	54.0	4.2	65	30		5
B41	16.8	218.4	11.2			40	60
B58	11.1	166.5	9.6	50		10	40
B90	8.4	75.6	5.3	60		30	10
BM58	8.2	114.8	1.9	40		20	40
C77	1.8	25.2	8.1			20	80
D69	3.4	30.6	4.2	80	20		
G13	3.7	44.4	4.5	80	20		
G80	11.8	141.6	10.8	30	60		10
H73	14.1	112.8	10.9	30	50		20
H85	13.5	135.0	4.6	20	30		50
L16	10.8	108.0	34.7			40	60
L24	11.4	193.8	2.1	30	70		
N33	3.0	42.0	5.0	90	5		5
N53	12.0	132.0	9.4	80	5		15
N76	9.3	55.8	0.8	90	4	1	5
P99	19.0	228.0	10.7	35	30		35
S51	1.2	9.6	1.0	50		50	
S68	14.3	328.9	28.2	50	30		20
T68	24.2	459.8	14.6	55		40	5
T88	9.3	83.7	5.8	75	20		5
Equivalent clay activity (reference)		3	3	1	20		

The test determines the quantity of methylene blue dye required to coat the active agents in the soil in a mono molecular layer. In soil science this is a measure of the cationic exchange capacity of the soil, the most active agents in soils are the colloidal humic materials followed by the double-layer clays. The MBV result will be affected by all active agents present in the sample, but, if these agents have been identified, it should be possible to correlate the MBV with the soil activity. In this research, the active clay agents were identified in the 75 micron material by XRD analysis. Organic material, zeolites, and iron hydroxides, all of which will affect the MBV result, were not identified.

Several research papers have attempted to determine a relationship between clay type and clay activity. In the paper *Improvements to the Methylene Blue Dye Test for Harmful Clay in Aggregates for Concrete and Mortar* Yool, Lees, Fried; Cement and Concrete Research Vol. 28 No. 10, pp 1417–1428 1998, the ratios are given as kaolinite:(illite or chlorite):smectite = 1:5:20. For this project, the correlation with MBV is better if the value for the illites and chlorites are taken as 3 rather than 5.

From the data generated in the programme, an Active Clay Index (ACI) was calculated and is given by:

ACI = $\sum$ [(% of each clay in XRD x % finer than 2 micron) / 100 x ratio value of Equivalent Clay Activity)]

This value for all samples except L16 and S68 is plotted against the MBV result in **Figure 19**.

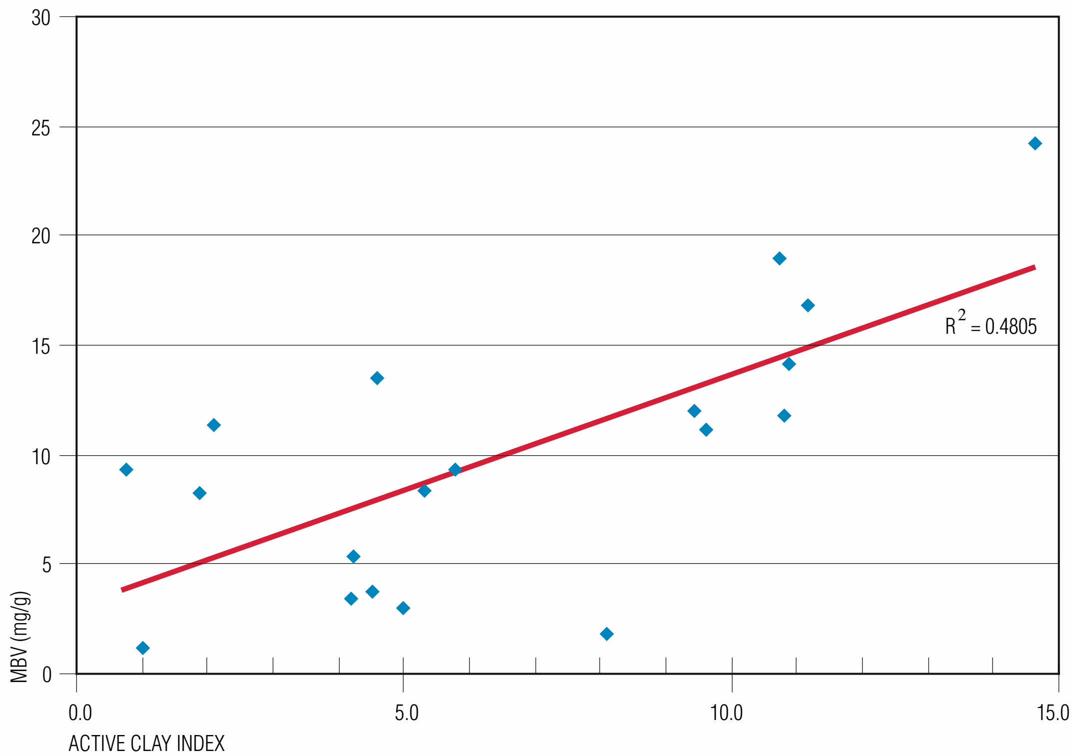

FIGURE 19 – Correlation of clay activity and MBV

Although the correlation is not strong, the expected relationship is demonstrated. Divergence from the correlation could be the result of the limited precision of both methods, the validity of general ratios for the clay activity, and the presence of active materials that were not identified in the XRD analysis.

Samples L16 and S68 do not appear to fit the pattern of the remaining samples. If the results from these two samples are included in the analysis, the R^2 value falls to 0.174.

7.4 Durability Tests

Sand Equivalent and Degradation Factor (Fines)

The average results for Sand Equivalent tests and for Degradation Factor (Fines) for the twenty-one samples tested in this programme are summarised in **Table 11** along with data from other tests which will assist in the discussion. The Sand Equivalent test and the Degradation Factor (Fines) test are considered to measure material durability or, at the least, to measure the presence of deleterious mineralogy that, by its presence, would impact on the durability of the aggregate or the durability of product in which the aggregate was incorporated. Both tests have been compared with other measures of durability or measures of adverse mineralogy, including the Sodium Sulphate test, MBV and XRD clay analysis.

All samples tested would pass known acceptance specification limits for Degradation Factor and Sand Equivalent except samples P99 and T68, both these samples being identified by both methods as suspect. In addition, sample S68 is identified by sand equivalent only as being suspect. The current AS 1258.1 would not reject any sample on the basis of sodium sulphate result, but, as is argued in

TABLE 11 – Comparison of durability test data

Sample ID	Degradation factor fine aggregate	Sand equivalent	Sodium sulphate loss %	Mass % passing 75 micron	MBV x % passing 75µm	Mica & illite in head sample	Chlorite in head sample	Kaolinite in head sample	Smectite in head sample
A75	94.00	79.00	0.90	10	54	85	10		5
B41	86.00	65.00	1.20	13	218.4			30	70
B58	80.00	61.00	1.40	15	166.5	20		20	60
B90	87.00	68.00	0.60	9	75.6	50		25	25
BM58	84.00	69.00	0.80	14	114.8	5		30	65
C77	94.00	73.00	0.10	14	25.2	No clays identified			
D69	85.00	74.00	0.40	9	30.6	90	10		
G13	88.00	60.00	0.30	12	44.4	80	20		
G80	86.00	66.00	0.70	12	141.6	40	40		20
H73	86.00	69.00	1.60	8	112.8	50	25		25
H85	90.00	66.00	0.80	10	135		40		60
L16	88.00	76.00	1.40	10	108			30	70
L24	84.00	60.00	1.10	17	193.8	20	80		
N33	96.00	72.00	0.40	14	42	80	10		10
N53	90.00	70.00	0.70	11	132	50	10		40
N76	87.00	78.00	1.00	6	55.8	90	4	1	5
P99	58.00	51.00	12.40	12	228		50		50
S51	89.00	81.00	0.20	8	9.6			100	
S68	74.00	40.00	1.30	23	328.9	50	30		20
T68	53.00	25.00	6.00	19	459.8	55		40	5
T88	94.00	71.00	0.40	9	83.7	80	20		

the discussion of the sodium sulphate test, this is probably because the specification value is set too high. The two highest sodium sulphate test results correspond to the samples rejected by the Degradation Factor and Sand Equivalent results, samples P99 and T68.

A possible explanation for this difference in 'specification' compliance is that the SE tests the sample as received and is therefore more influenced by the clays and other deleterious material that might be present in the original grading, The Sodium Sulphate and Degradation Factor tests both reject the finer part of the sample grading (for the sodium sulphate, all –0.3mm, and for the Degradation Factor, all –0.425 mm) and commence the test with clean aggregate particles. These latter tests will be only influenced by deleterious material contained within the rock fabric that is liberated by the test procedure.

All three samples identified by the Sand Equivalent as being of concern, are also identified by a proposed measure of the multiple of the passing 75 micron x MBV. This multiple should identify samples with high quantities of fines where those fines are probably reactive. In addition to the samples noted, the multiple also identifies samples B41, B58 and L24 as of possible concern. These samples would pass a specification limit of Sand Equivalent not less than 60 but it is interesting to note that the multiple has identified the three samples with the next lowest SE values. Clearly, because the Sand Equivalent and the multiple of passing 75 micron and MBV both measure the quantity of fines and the activity of the fines component, the correlation between the tests will be strong.

For this series of samples, there is a fairly strong correlation between the Sand Equivalent and the Degradation Factor results as shown in **Figure 20**.

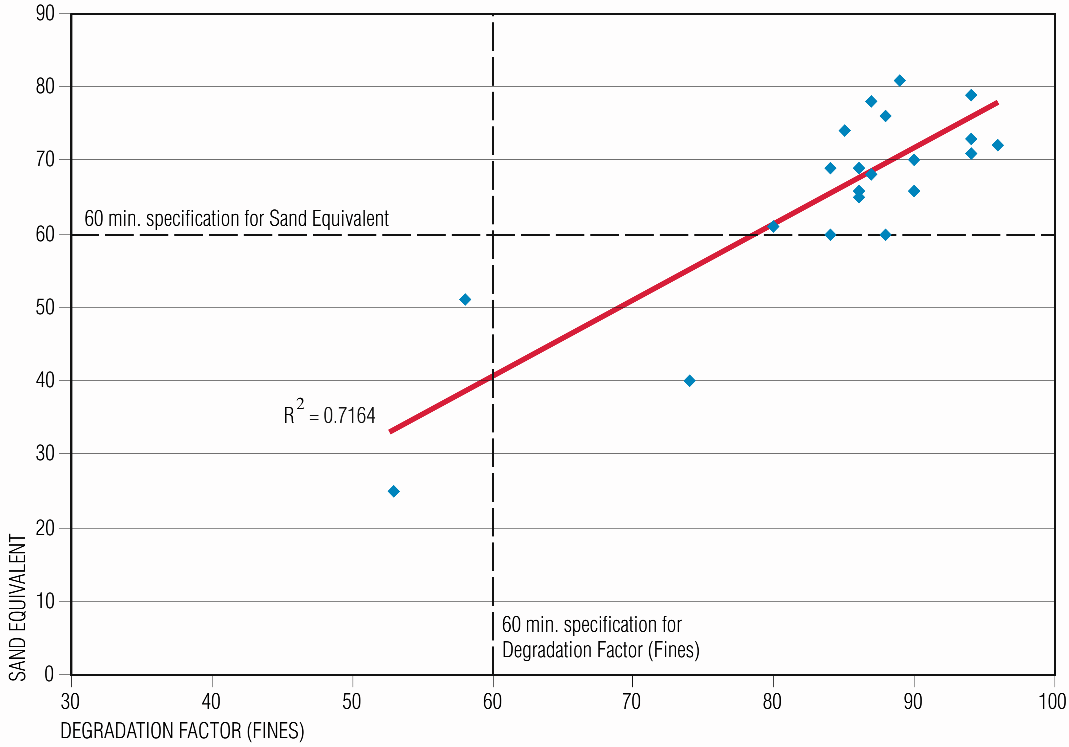

FIGURE 20 – Sand Equivalent v Degradation Factor

However, the correlation is dependant on the three extreme values, the results for samples P99, T68 and S68. If these results were eliminated, then the remainder of the sample population (18 results of the 21) would have a correlation coefficient R^2 of only 0.23. This lower correlation is more anticipated as the tests are measuring differing properties, with the sand equivalent affected by the clay mineralogy in the fine tail of the sand grading while the Degradation Factor measures only the clay in the rock fabric.

The fact that all three 'durability' tests are affected by the presence of clay and the clay activity is demonstrated in **Figure 21**. Each of the three durability tests has been plotted against MBV which measures the presence of clays, the activity of the clay and, to a limited degree, the quantity of clay present. For ease of plotting, the sodium sulphate result was multiplied by a constant, 10.

All durability measures have an expected but weak correlation with clay activity as measured by the MBV test, indicating that the presence and type of clay is a significant, but not the only, factor in the assessment of aggregate durability.

As expected, neither the sodium sulphate loss nor the Degradation Factor has a correlation with the original grading of the samples. This is because the tests are conducted on a limited portion of the original grading, and in particular, the fine fraction of the grading has been removed as part of the test sample preparation. By contrast, the Sand Equivalent test is conducted on the full sample grading; a moderately strong correlation between the fines in the grading and the Sand Equivalent is demonstrated in **Figure 22**. As might be expected, the Sand Equivalent result falls as the percentage passing the 75 micron increases.

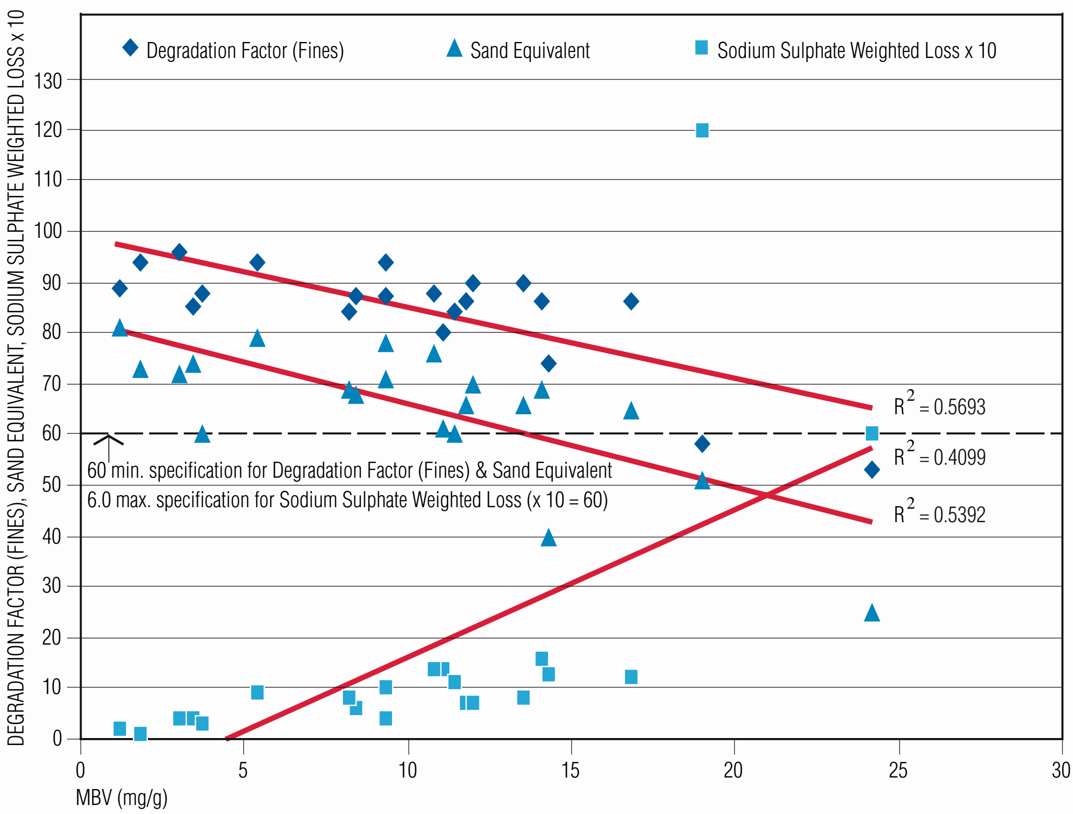

FIGURE 21 – Effect of clay activity on durability tests

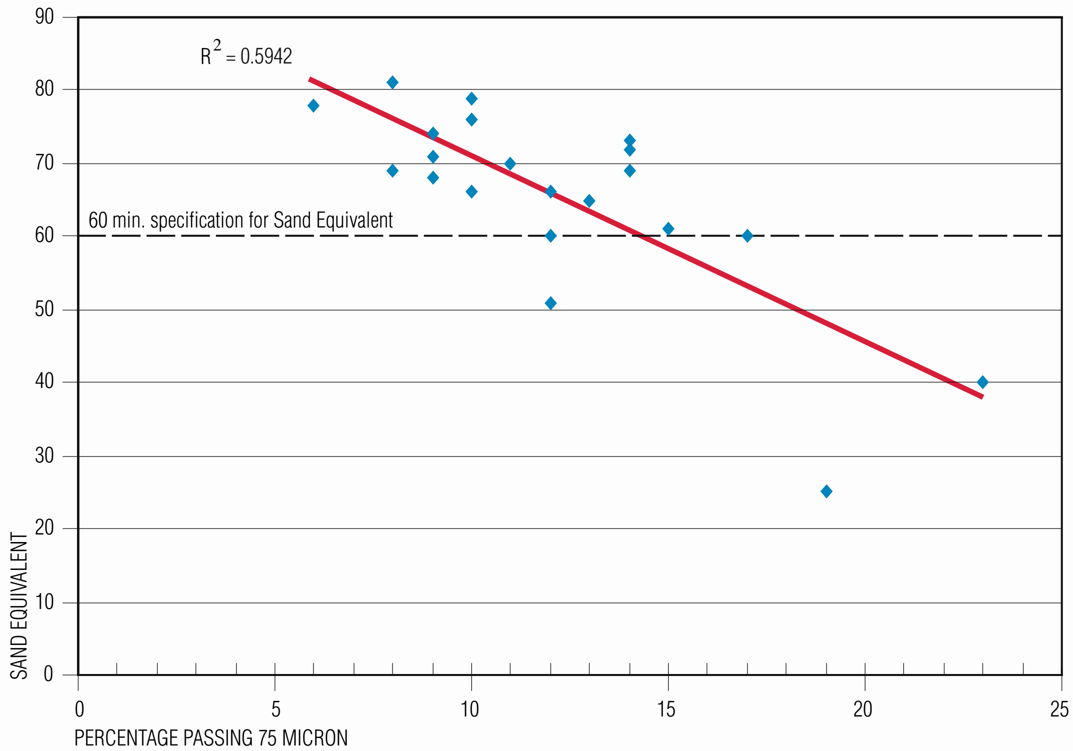

FIGURE 22 – Correlation between fines in the grading and the Sand Equivalent

Overseas references note that the Sand Equivalent correlates poorly with the passing 75 micron in manufactured sands but correlates well in natural sands. The data from this project does not support this finding but again it is worth noting that if the two extreme values were ignored then the correlation coefficient R^2 of the remaining population would drop to 0.3.

However, when the activity of the clay contained in the fines is taken into account, the correlation with the Sand Equivalent result is very strong, as shown in **Figure 23**. The purpose of the Sand Equivalent is clearly to measure the quantity and activity of clays and active silts in the sand. This project has not identified if there are interference factors that might affect the results (for example metal oxide colloids or fine micas). The effect of sericite as an interference has been reported in Victoria and led to the abandonment of the test in that state. It also appears easier to measure the same factor of concern, fines quantity and clay activity by the easier techniques of MBV and passing 75 micron rather than testing for Sand Equivalent. However, this conclusion requires considerably more data than that presented in this study.

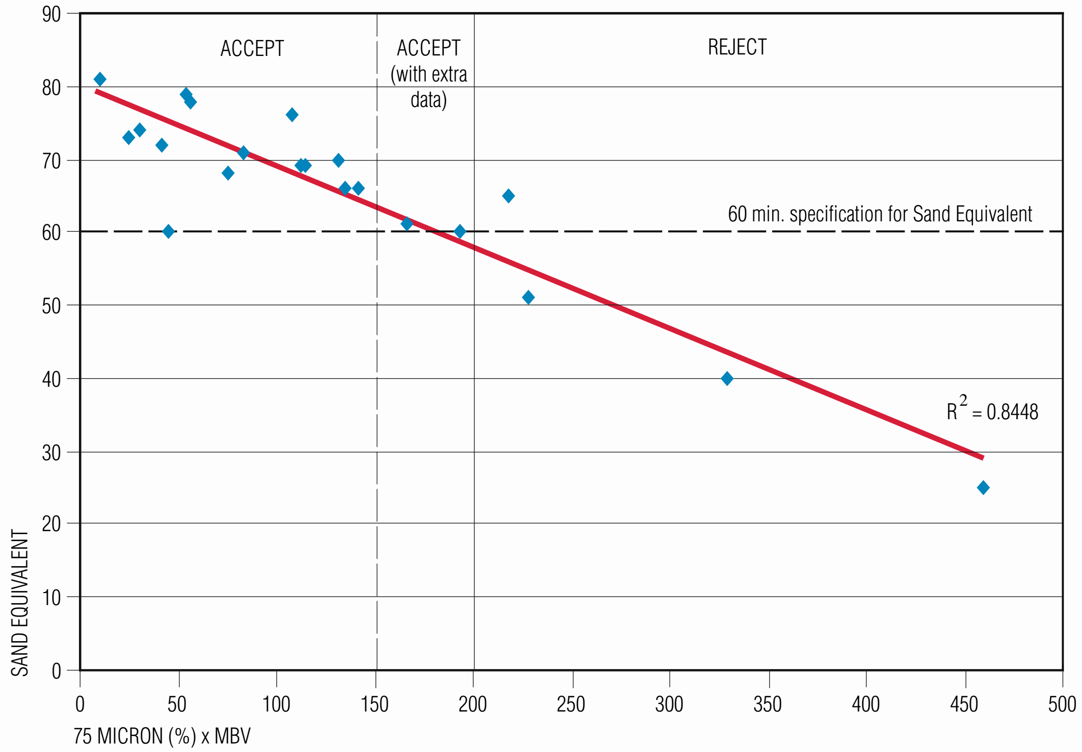

FIGURE 23 – Correlation taking into account clay activity

Sodium Sulphate

A summary of the average results for Sodium Sulphate Soundness and for tests relating to the method or used for comparison are included in **Table 12**. The results demonstrate that compared with the current specification for fine aggregate, only sample p99 would be rejected for Exposure Classes C and B_2, while all samples would be acceptable for other concrete exposure classifications and for use as asphalt aggregate

If the more-stringent requirements applied to coarse aggregate were applied to the fine aggregate then sample P99 would be rejected for all use and T68 would be rejected for Exposure classification C only. Under current specifications sample P99 would be rejected as asphalt aggregate.

Samples rejected by the Sodium Sulphate test are also rejected by the Degradation Factor fine aggregate, and by the Sand Equivalent test procedure (taking minimum values for both tests to be 60). If the Sand Equivalent minimum limit used in the US of between 40 and 50 is used (slightly different minimum limits used in different States) then the SE would reject samples S68 and T68 but would accept sample P99, the sample with the highest Soundness loss. Only the SE identifies sample S68 as a material of concern. A possible explanation for this difference in 'specification' compliance is that the SE tests the sample as received and is therefore more influenced by the clays and other deleterious material that might be present in the original grading, The Sodium Sulphate and Degradation factor tests both reject the finer part of the sample grading (for the sodium sulphate, all –0.3 mm and for the Degradation Factor, all –0.425 mm) and commence the test with clean aggregate particles. These latter tests will be influenced only by deleterious material contained with the rock fabric that is liberated by the test procedure.

TABLE 12 – Sodium sulphate loss average data and related durability test data

	TEST DATA					**XRD DATA**			
Sample ID	**Sodium sulphate loss %**	**Degradation factor fine aggregate**	**Sand equivalent**	**Water abs %**	**MBV X water abs**	**Mica & illite in head sample**	**Chlorite in head sample**	**Kaolinite in head sample**	**Smectite in head sample**
A75	0.90	94.00	79.00	0.90	4.32	85	10		5
B41	1.20	86.00	65.00	1.20	25.2			30	70
B58	1.40	80.00	61.00	1.40	24.42	20		20	60
B90	0.60	87.00	68.00	0.60	16.8	50		25	25
BM58	0.80	84.00	69.00	0.80	24.6	5		30	65
C77	0.10	94.00	73.00	0.10	1.98				
D69	0.40	85.00	74.00	0.40	3.06	90	10		
G13	0.30	88.00	60.00	0.30	8.14	80	20		
G80	0.70	86.00	66.00	0.70	24.78	40	40		20
H73	1.60	86.00	69.00	1.60	23.97	50	25		25
H85	0.80	90.00	66.00	0.80	21.6		40		60
L16	1.40	88.00	76.00	1.40	24.84			30	70
L24	1.10	84.00	60.00	1.10	37.62	20	80		
N33	0.40	96.00	72.00	0.40	0.9	80	10		10
N53	0.70	90.00	70.00	0.70	10.8	50	10		40
N76	1.00	87.00	78.00	1.00	8.37	90	4	1	5
P99	12.40	58.00	51.00	12.40	66.5		50		50
S51	0.20	89.00	81.00	0.20	0.96			100	
S68	1.30	74.00	40.00	1.30	24.31	50	30		20
T68	6.00	53.00	25.00	6.00	53.24	55		40	5
T88	0.40	94.00	71.00	0.40	11.16	80	20		

Figure 24 plots the alternate durability test results against the Soundness result. The expected result is apparent, ie that higher Soundness results are associated with lower SE or Degradation Factor values. However, the correlation is poor. If the results for sample P99 are excluded then the correlation coefficients are increased to 0.80 for the Degradation Factor and to 0.59 for the Sand Equivalent. There

is no particularly valid reason for rejecting the results of P99 but the improved correlation might be indicative of a high Sodium Sulphate result. Care should be exercised in making too much of the correlations as they are highly dependent on the two extreme values, samples P99 and T68. If both these values are excluded, then the data reduces to a scatter plot with the correlation coefficient for Sand Equivalent dropping to 0.12 and for the Degradation Factor dropping to 0.32.

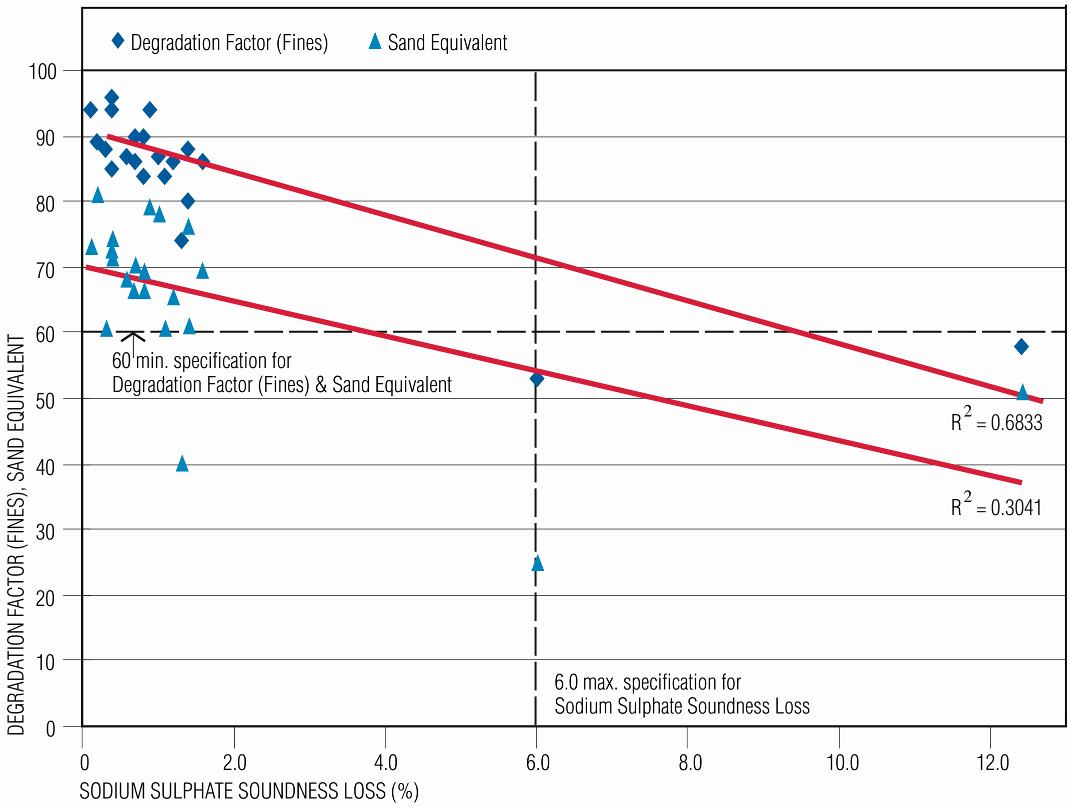

FIGURE 24

Much is made in the literature of the correlation between Sodium Sulphate Soundness and the absorption of the aggregate. This relationship holds particularly well for rock material with fine pore sizes but as the pore diameter becomes coarse, the effect of swelling pressures of either freezing water or of crystallising salts is significantly reduced. This phenomenon is one explanation why Soundness results for vesicular blastfurnace slag and many vesicular basalts are so good. Overseas research suggests that critical pore sizes for freeze/thaw damage were in the range of 0.2 to 0.04 µm.

The Soundness results from these samples were plotted (**Figure 25**) against Water absorption results generated from the density testing; the correlation is quite poor. Whether this is because the water absorption test is incapable of measuring fine diameter pores or whether the poor correlation has other causes is unknown. However, one potential model of sodium sulphate attack (discussed above) suggests that not only the availability of pores but also the presence of clays within the rock were both causes of higher sodium sulphate losses.

To test this possibility, the Soundness loss was plotted against a factor given by the multiple of MBV and Water Absorption (**Figure 26**).

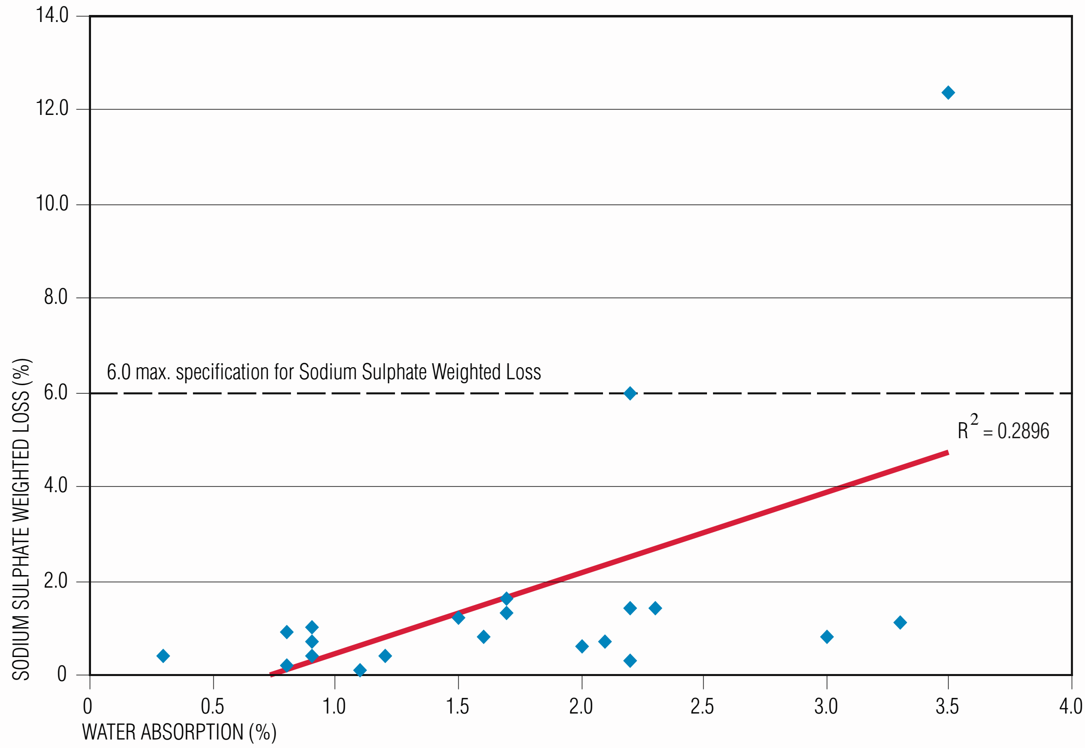

FIGURE 25

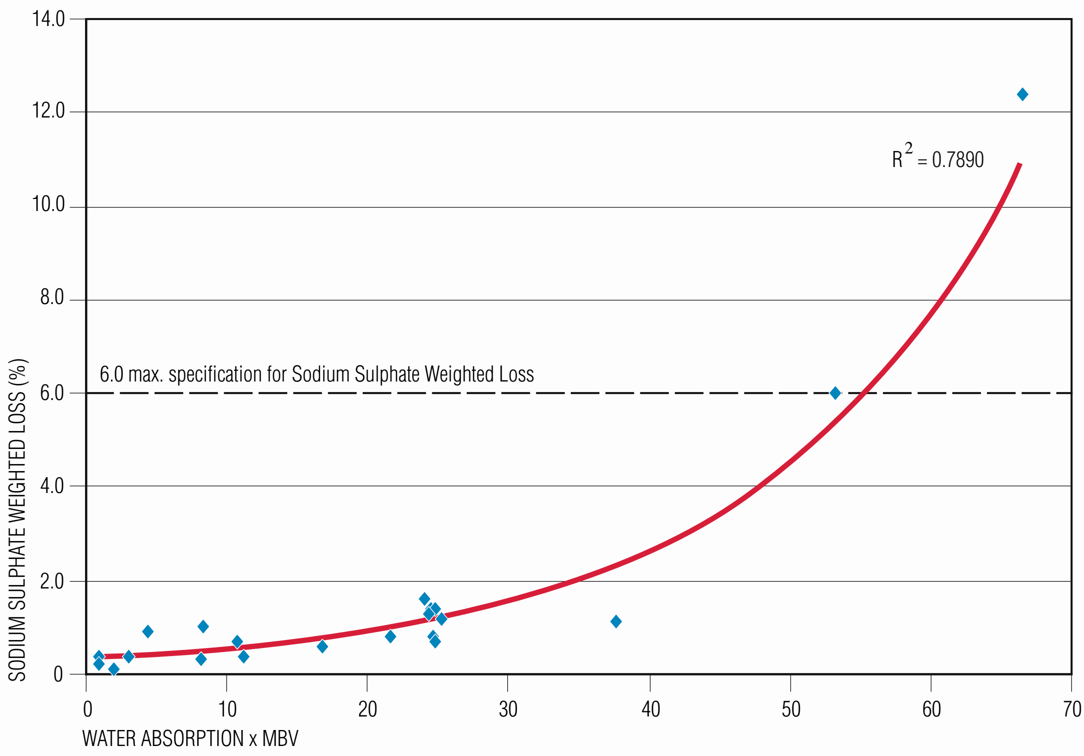

FIGURE 26

Here the correlation coefficient increases to 0.789 which lends a good deal of credence to the model of Sodium Sulphate action. Again, a degree of caution should be exercised because the correlation is strongly influenced by the three results with a multiple above 30. Nevertheless, if the relationship were confirmed with additional research, the result would point to a simpler and quicker method of assessing the 'durability' of the crushed fine aggregate.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 General

Tests and results were analysed to determine if:

- a test was useful for specifying manufactured sand or whether it should be limited to a quality control procedure, with limits and application to only some sources;
- a test should be used on its own or should be considered in combination with other tests;
- when a test was to be used for specification, what acceptance criteria should be required;

and concluded as follows:

8.2 Product Sizing

Grading

In traditional concrete mix design methods, gradings conducted on manufactured sands, down to the 75 micron size fraction, are useful as a means of determining the impact the sand may have on the total combined particle distribution, and hence as an indicator of appropriate particle packing within a concrete mix. From this perspective, grading is considered a reportable test, and is regularly specified in any supply agreement. In assessing a manufactured sand, grading is a necessary test for assisting in design and quality control of concrete. However, AS 2758.1 has attempted to encompass all those materials that may be used, either alone or as components of fine aggregate blends. As a consequence, the standard is so broad that it does not define or control anything. Control may be achieved by specifying variation around an average or submitted grading.

Control of grading variation is important for specifiers to develop confidence in the predictability of the engineering properties of manufactured sand. Nominated grading with tolerances would be the most practical for specifier and supplier but manufactured sand must also meet a broad envelope of grading in order to be defined as sand (as opposed to a coarse aggregate). Experience has shown that most manufactured sands are not used as the only source of fine aggregate particles in most concrete mix designs. Specifying a tighter limit for sand grading will work only where this is applied to the blend of sand constituents used in a concrete mix and not the individual constituents (this is also recognised in clause 5 of ASTM C33).

If a specification on grading is to be developed for individual manufactured sand components, then certain key sieve sizes need to be selected. The committee recommends that a top, mid and bottom sieve are used to ensure that the manufactured sand is actually a fine aggregate and is usable alone or in conjunction with other fine materials.

Successful manufactured sands are generally –4 mm or smaller. This is reflected in the submitted samples, where all but one sample (C77) ranged from 95% to 100% passing the 4.75-mm sieve. An excess of material retained on the 4.75-mm sieve is regularly reported to have a negative impact on concrete flat slab finishing processes, as well as reducing concrete workability. The percentage passing

0.600-mm and 75-micron sieves will define necessary elements of an acceptable sand particle size distribution.

It is recommended that manufactured sand gradings be specified in the Australian Standard as follows:

- That the supplier is required to submit a full target manufactured sand grading to 75-micron sieve size and that test results are reported as part of a supply agreement (standard sieve sizes being 6.7 mm, 4.75 mm, 2.36 mm, 1.18 mm. 0.6 mm, 0.3 mm, 0.15 mm and passing 75 micron (by washing). However, the specification of a full grading envelope is not recommended as part of AS 2758.1 but a suggested envelope for the total fine aggregate component of a concrete mix may be included as part of an informative appendix to the specification.
- That variability limits for that 'submitted' grading be specified on each sieve size, including 75 micron.
- That a minimum specification for an individual manufactured sand constituent of concrete be based on percentage passing 4.75-mm, 0.6-mm and 75-micron sieves. This specification is to ensure only that the constituent can be referred to as a 'Fine Aggregate'. The suggested limits for fine aggregate components are:

Sieve size	Min % passing	Max % passing
4.75 mm	90 to	100
0.6 mm	15 to	80
0.075 mm	0 to	20

For additional details relating to limits on passing 75 micron refer to the attached draft specification.

- Procedures for applying deviation limits to the broad range of possible product gradings will require careful consideration. The period over which a submitted grading might apply and how submitted gradings could be altered would also require consideration.
- Gradings will obviously become part of a quality control measure with results of interest to the individual suppliers and their customers.

Deleterious Fines

The committee recognized that the amount and quality of the material finer than 75 micron, within manufactured sand, has significant impact on the plastic properties of concrete. However, two different sands, both containing the same passing 75 micron amounts may have radically different clay contents both in terms of the quantity of clay-sized material and activity of the clay minerals present (**Figures 4, 5 and 6**). As stated above, the type of clay present in manufactured sand is critical to the performance of a concrete mix.

A range of procedures attempt to control the quantity or quality of fines in the sand grading. Measures of quantity include the passing 75 micron, material less than 2 micron (both these measures are specified in AS 2758 and numerous other specifications) and the Clay and Fine Silt test. Measures of quality include the Methylene Blue Value and X-ray Diffraction.

The project demonstrated that a combination measure that identifies not only the quantity but also the quality of fines appears to offer the best possibilities of control for manufactured sand. The committee recommends specification of the individual components of the concrete fine aggregate with perhaps a recommendation of limit for the total fine aggregate in an informative appendix.

For ease of use and greatest accuracy the combination of passing 75 µm multiplied by MBV offers promise. Manufactured sand or individual components would be accepted to a value of 150 with materials up to a value of 200 considered when there is further supporting evidence of successful performance. Materials with a value over 200 would be considered unacceptable.

The current simplistic procedure of specifying the passing 75 micron or material finer than 2 micron without reference to other tests defining clay activity has been demonstrated to be misleading. Without the inclusion of a measure of clay mineralogy, the specification must be extremely restrictive to control the adverse performance of the smectite-type clays. The specification may then discard the potential benefits of less active clays or rock flour in the mix. It should be remembered that kaolin is added to concrete mixes as a pumping aid.

The 75-micron test should be used only as part of a definition of manufactured sand. The submitted grading in combination with variation limits at the 75-micron size is used to specify product consistency. The 75-micron test in combination with a measure of clay activity is recommended for specifying the performance of manufactured sand in concrete.

It is recommended that the 2 micron test is not used as a specification test. It may be used for Quality Control procedure on individual sources where the type of clay present has been identified and the quantity of passing 2 micron can be defined for the individual source.

The ability to control the effects of deleterious fines by blending with 'clean' natural sands has not been addressed by this project. A suitable control value for the fine aggregate component of a concrete mix may be determined in further research and may be recommended in a model specification for the total fine aggregate.

Clay and Fine Silt Test

It is recommended, considering the data obtained in this programme and the level of published knowledge on the test, that this test not be used as a specification parameter for concrete sands. There is very limited knowledge of the effects of either natural or manufactured sands of known Clay and Fine Silt values on the properties of plastic or hardened concrete. Although the principles of the test are understood and there is some appreciation of the material variables that might affect the result, there is no body of data (and little expectation that the data might be generated) on which specification limits might be based. By contrast, data on the effects of high quantities of clay and fine silt in mixes is already available in measurement and specification of mass percent passing 75 micron. Information on the activity of clays may be derived from the Methylene Blue Value; European standards are suggesting that the combination of these two values may be used as a specification control.

However, the Clay and Fine Silt test retains the advantage of producing a rapid result using simple equipment. The limited data from this programme has indicated that this test also measures the properties of quantity of clay and silt material and some measure of the clay activity. The test may continue to find use as a quality control procedure for individual sources or for specific plant blends.

8.3 Shape and Density Properties

Shape and surface texture

Shape and surface texture are measured indirectly by the Flow Cone procedure; other techniques used to measure these properties are difficult to perform and require professional staff. There are no specifications for the procedure and the classification charts provided in the New Zealand method are based on the performance of natural sands. The current equipment specified in the method is not appropriate for use with manufactured sands; many manufactured sands will not return a valid result because material will not flow through the equipment orifice. The equipment could be modified or the samples changed to obtain results but this would invalidate the current design charts.

Further, changes in grading will also influence the Flow Cone result. The test would report the overall influence of grading, shape and surface texture, but a change in any-one of these properties would change the result. It would not be possible to design a test specification that could, for instance, control particle shape over a range of products, because a difference in grading over the range would change results without shape having been affected.

Therefore the Flow Cone test should not be used as a specification procedure. The flow cone is best used as a design procedure to help determine suitable workability in fine aggregate blends. The test might also be used as a quality control procedure on specific sources where changes in results would indicate possible changes in crushing characteristics if the grading were constant. Conversely, constant crushing characteristics with a change in the Flow Cone would indicate either a change of grading or change in rock character causing a change in surface texture.

Density Measurement

The results of testing in this programme have confirmed that there is no particular need to change the current specifications for particle density and water absorption for manufactured sand used as fine aggregate in concrete. However, the testing did demonstrate the difficulty of completing the test with sand-sized materials that had significant amounts of material retained above the 1.18 mm size. With these materials it was very difficult to determine the SSD condition as the material collapsed prematurely when the mould was withdrawn. As a consequence, the SSD moisture condition had to be determined by visual means, and the accuracy of the water absorption and some of the density determinations may be questioned.

It is recommended that the limitations of the test method be drawn to the attention of the Standards Committee for aggregate tests.

The LCPC Packing Density test was not considered sensitive enough to act as either a specification or a quality control test. The test is intended to develop a necessary design parameter for the LCPC mix design method.

8.4 Mineralogy

X-Ray Diffraction

XRD, if used, should be used only in conjunction with other tests such as the –2 micron, MBV and clay and fine silt tests. At best it provides guidance as to the relationship between other tests. Due to its qualitative output the test should really be used only as a research tool and, at the most, as part of a quality control regime.

The test should not be used for specification. In its present format, the test lacks precision and, although many research papers have been published, the correlation between clay types, clay quantity and aggregate or concrete performance is difficult to evaluate. There does not appear to be a standardised method for the testing of material, or the methods tend to be equipment specific.

The test is best used as part of ongoing research assessing the –2 micron fraction of manufactured sands. There is a need to set realistic specification values on the presence of clay fines and these limits should be set based on an understanding of the activity of the dominant minerals present. Even with this information, specification limits are likely to be determined by a technique such as MBV which takes into account the activity of all clays present, rather than the XRD technique that identifies the individual clay components without advising on the overall performance effects of the totality of clays present.

To be truly effective, the XRD method needs to be developed to improve the estimate of clay quantities more accurately.

MBV

There is sufficient evidence from this project and from other research to accept that the MBV procedure is valuable in identifying all active components in the microfines and reporting the result as a single value. However, it is believed that it is not correct to specify the MBV as a standalone limit. The specification must account for both the activity of the clay materials present in the microfines and for the quantity of these active agents. For the purpose of specification, the committee proposes a value determined by the multiple of the passing 75 micron and the MBV. Based on the data of this programme, the committee suggests that for any material intended as a component of concrete fine aggregate, materials with a multiple greater than 200 be rejected. Materials with a multiple less than 150 be accepted, while materials with a multiple between 150 and 200 may be accepted with submission of additional information indicating successful performance. These values may not ensure successful use if applied to the total fine aggregate. The suggested values are based on the successful use of the samples in this programme, most of which are being used in blends with clean natural sands. One might anticipate that the natural sands would have a 'dilution' effect on the multiple for the total fine aggregate. The value of the multiple that should be specified for successful performance of the total fine aggregate should be investigated further.

8.5 Durability Tests

For this project, durability tests included Sodium Sulphate Soundness, Sand Equivalent and Degradation Factor (fines). Both the Sodium Sulphate and Degradation Factor are limited in that they test only a portion of the sand grading and may therefore be limited as product control tests unless combined with a measure that evaluates deleterious fines. The Sodium Sulphate test maximum limit in the Standard appears to be high. A lower limit is recommended to identify higher quality materials. The Sand Equivalent test is a true product test, but has been reported to be adversely affected by sericite. Both the Degradation Factor and the Sand Equivalent appear to measure clay activity and clay quantity contained either in the product grading or liberated from rock particles by agitation. Only the Sodium Sulphate may also measure rock strength (as resistance to swelling pressure)

It is considered that the Micro Deval test may eventually prove a useful fine aggregate durability test. Until this can be demonstrated, the use of a selection from a number of durability tests, with a choice made based on local experience, is recommended.

Sodium Sulphate Soundness should be combined with a control measure for deleterious fines. The specification limit for Sodium Sulphate should be maximum 6% weighted loss for all exposure classifications. It is recommended to continue with the use of the sodium sulphate test for the present until other procedures are developed that have better repeatability and reproducibility.

There is no proven correlation between SE and Degradation Factor Fines – they are best considered as two different tests with quite different outcomes. Both tests should be considered further when the other fundamental rock tests and the durability tests are being considered.

The Sand Equivalent limit would be 60 minimum. The application of the test in acid igneous and metamorphic rocks (particularly greywackes) that contain significant sericite and mica would need careful consideration. The test is a product measure and should stand alone as a control. However, it may not evaluate particle strength and may need to be combined eventually with a measure such as the Micro Deval.

The Degradation Factor (fines) is considered a source rock test and may need to be combined with a control measure for deleterious fines. Where used, the suggested specification is minimum 60. The test may not evaluate particle strength and may need to be combined eventually with a measure such as the Micro Deval.

The Sand Equivalent test, which measures the presence and activity of silt and clay fines in the total grading, may be applied to individual components of the fine aggregate grading for convenience, but control of the fines by blending with inert fine sands should be recognised, so the specification limit should really be applied to the total fine aggregate.

The Sodium Sulphate Soundness and Degradation Factor (fines) tests can be seen to be influenced by weak or altered particles and it is reasonable that these particles are not included in the concrete mix in any significant quantity. The suggested specification limits should therefore apply to the individual components of the fine aggregate.

At the conclusion of this project it still remains true that no one durability test for fine aggregate will assess all parameters of durability required for aggregate and product performance. The parameters that need determination are:

- Resistance of the aggregate to abrasion and breakdown while being handled and placed and resistance to abrasion in place. This is of particular significance for asphalt aggregate and fine filter aggregates but has some significance for concrete aggregate. At the present time the Micro Deval appears to have the greatest promise in evaluating this parameter.
- Resistance to oxidation, erosion, salt exposure, water penetration or chemical attack. These durability parameters are controlled by the absorption potential of the aggregate and the presence within the aggregate of deleterious/ expansive clays. At this time the Sodium Sulphate test appears to be the best test for these parameters. The degradation factor for fine aggregate will identify clay activity, while the abrasion of the material will identify soft materials prone to erosion or perhaps even salt attack. However, it is not as strongly influenced by water absorption as the Sodium Sulphate test and therefore perhaps not as good an indicator of salt attack, water penetration or chemical attack.
- Finally, durability measures need to account for the detrimental effects on the performance of concrete mixes of clays or fine silts carried in the tail of crushed fine aggregates or natural sands, particularly if it is not possible to remove these materials by washing. Neither the Sodium Sulphate nor Degradation Factor Fines can adequately assess this parameter because both tests remove these materials from the test portion. The Sand Equivalent test may assist here, but there does not appear to be any correlation between Sand Equivalent and the clays identified in the head sample. Also, the possible limitation of the Sand Equivalent in testing materials high in sericite must be taken into account. At this time, the MBV test combined with the Passing 75 micron appears to offer the best possibility for controlling this issue.

Finally, the effects of these durability properties on concrete mortar need to be evaluated in further research. This research would confirm or reset specification limits and would determine critical design values, enabling the usage rates of manufactured sands in fine aggregate blends to be determined.

Appendix 1

AMDEL TEST PROCEDURE FOR X-RAY DIFFRACTION
Quantitative mineralogy of samples

1 INTRODUCTION

Samples were received from Janine Herzig of Amdel Mineral Processing with a request for determination of their mineralogy. They were from Job No: N1860GE06.

2 PROCEDURE

Subsamples were taken and dispersed in water with the aid of deflocculants and allowed to settle to produce –2 μm size fractions by the pipette method. The resulting dispersions were used to prepare oriented clay preparations on ceramic plates. When air-dry, these were examined in the X-ray diffractometer. Selected plates were additionally treated with glycerol in order to confirm the presence of smectite. The relative amounts of the clay minerals in the –2 μm size fraction were estimated from the XRD trace using the peak areas of the first order basal diffraction peaks of kaolinite, mica and glyceroled smectite and the second order basal diffraction peak of chlorite and their corrected areas summed to 100%.

3 RESULTS

The estimated percentage of the clay minerals in the –2 μm size fraction are as follows:

Note that although the mineral contents are quoted to one unit for convenience, such a degree of accuracy is not implied; this is because the calculated values are dependent on the assumptions given in the 'Procedure' section and measurements from XRD traces can have an error of up to ±20% relative for major minerals and up to ±50% relative for minor minerals. For samples C77 and C77 –75 μm no clay minerals were detected.

	SAMPLE ID						
CLAY MINERAL	**A75**	**B41**	**B58**	**BM58**	**B90**	**C77**	**D69**
Mica (illite)	85		20	5	50		90
Chlorite	10						10
Kaolinite		30	20	30	25		
Smectite	5	70	60	65	25		
	G13	**G80**	**H73**	**H85**	**L16**	**L24**	**N33**
Mica (illite)	80	40	50				80
Chlorite	20	40	25	40			10
Kaolinite					30	20	
Smectite		20	25	60	70	80	10
	N53	**N76**	**P99**	**S51**	**S68**	**T68**	**T88**
Mica (illite)	50	90			50	55	80
Chlorite	10	4	50		30		20
Kaolinite		1		100		40	
Smectite	40	5	50		20	5	

CLAY MINERAL	SAMPLE ID A75 –75 µm	B41 –75 µm	B58 –75 µm	BM58 –75 µm	B90 –75 µm	C77 –75 µm	D69 –75 µm
Mica (illite)	65		50	40	60		80
Chlorite	30						20
Kaolinite		40	10	20	30		
Smectite	5	60	40	40	10		
	G13	**G80**	**H73**	**H85**	**L16**	**L24**	**N33**
Mica (illite)	80	30	30	20			90
Chlorite	20	60	50	30			5
Kaolinite					40	30	
Smectite		10	20	50	60	70	5
	N53	**N76**	**P99**	**S51**	**S68**	**T68**	**T88**
Mica (illite)	80	90	35	50	50	55	75
Chlorite	5	4	30		30		20
Kaolinite		1		50		40	
Smectite	15	5	35		20	5	5

Appendix 2 DETAILED SUMMARY OF PROJECT RESULTS – Samples A75, B41, B58, BM58, B90

	A75			B41			B58			BM58			B90		
	A	B	Average	A	B	Average	A	B	Average	A	B	Average	A	B	Average
SERIES 1															
AS1141.11 - washed grading															
9.5mm															
6.7mm	100	100	100				100	100	100				100	100	100
4.75mm	99	99	99	100	100	100	95	95	95	100	100	100	95	97	96
2.36mm	69	68	69	84	80	82	70	69	70	92	93	93	73	74	74
1.18mm	39	39	39	56	52	54	46	45	46	57	57	57	47	50	49
600um	23	23	23	36	34	35	33	32	33	37	37	37	32	34	33
425um	19	19	19	29	28	29	28	27	28	30	30	30	26	27	27
300um	15	15	15	24	22	23	25	24	25	25	25	25	21	22	22
150um	13	12	13	17	16	17	19	18	19	19	19	19	13	14	14
75um	10	9	10	13	12	13	15	14	15	14	14	14	9	9	9
AS1141.25.3 - Degradation Factor, fine Agg.	93	94	94	86	86	86	79	81	80	82	86	84	87	87	87
AS1289.3.7.1 - Sand Equivalent Value	81	77	79	66	64	65	58	63	61	69	69	69	68	68	68
AS1141.5 - Particle Density/Absorption															
-4.75mm Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.9	2.9	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.6	2.6	2.6
-4.75mm Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.5	2.5	2.5
-4.75mm SSD Particle Density (kg/m3)	2.6	2.7	2.6	2.8	2.8	2.8	2.9	2.9	2.9	2.9	2.9	2.9	2.6	2.6	2.6
-4.75mm Absorption (%)	1.0	0.6	0.8	1.3	1.6	1.5	2.2	2.2	2.2	2.3	2.1	2.2	1.9	2.0	2.0
-4.75mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.9	2.9	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.6	2.6	2.6
-4.75mm +75um Dry Particle Density (kg/m3)	2.7	2.7	2.7	2.8	2.8	2.8	2.9	2.9	2.9	2.9	2.9	2.9	2.6	2.5	2.5
-4.75mm +75um SSD Particle Density (kg/m3)	2.7	2.7	2.7	2.9	2.9	2.9	3.0	3.0	3.0	2.9	2.9	2.9	2.6	2.5	2.6
-4.75mm +75um Absorption (%)	0.4	0.4	0.4	1.3	1.3	1.3	1.1	1.2	1.2	1.1	1.1	1.1	1.4	1.4	1.4
-2.36mm Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.9	2.9	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.6	2.6	2.6
-2.36mm Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.8	2.8	2.8	2.8	2.8	2.8	2.9	2.8	2.9	2.5	2.5	2.5
-2.36mm SSD Particle Density (kg/m3)	2.6	2.6	2.6	2.8	2.8	2.8	2.9	2.9	2.9	2.9	2.9	2.9	2.6	2.6	2.6
-2.36mm Absorption (%)	1.0	0.8	0.9	1.8	1.5	1.7	1.6	2.1	1.9	1.4	1.9	1.7	2.1	2.0	2.1
-2.36mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.9	2.9	2.9	3.0	3.0	3.0	3.0	3.0	3.0	2.6	2.6	2.6
-2.36mm +75um Dry Particle Density (kg/m3)	2.7	2.7	2.7	2.8	2.8	2.8	2.9	2.9	2.9	2.9	2.9	2.9	2.5	2.5	2.5
-2.36mm +75um SSD Particle Density (kg/m3)	2.7	2.7	2.7	2.8	2.9	2.8	3.0	3.0	3.0	2.9	2.9	2.9	2.6	2.6	2.6
-2.36mm +75um Absorption (%)	0.4	0.5	0.5	1.4	1.4	1.4	1.3	1.2	1.3	1.1	1.2	1.2	1.4	1.4	1.4
AS1141.24 - Sodium Sulphate Soundness															
<9.5 + 4.75mm Fraction							0.7	0.7	0.7				0.4	0	0.2
<4.75 + 2.36mm Fraction	0.2	0.5	0.4	0.8	0.9	0.9	1.3	1.1	1.2	0.8	0.7	0.8	1.0	0.7	0.9
<2.36 + 1.18mm Fraction	0.7	0.9	0.8	0.9	1.1	1.0	1.3	1.3	1.3	0.7	0.7	0.7	0.5	0.5	0.5
<1.18 + 600um Fraction	1.0	1.3	1.2	1.5	1.3	1.4	1.7	1.5	1.6	0.8	0.8	0.8	0.5	0.5	0.5
<600 + 300um Fraction	2.3	4.2	3.3	1.5	1.7	1.6	2.6	2.4	2.5	1.0	1.2	1.1	0.4	0.7	0.6
Total weighted loss (%)	0.7	1.1	0.9	1.1	1.2	1.2	1.5	1.3	1.4	0.8	0.8	0.8	0.6	0.6	0.6
SERIES 2															
4.75mm Voids Content (%)	IF*	IF*	Note 1	39.8	IF*	39.8	IF*	IF*	Note 1	IF*	45.3	45.3	IF*	IF*	Note 1
4.75mm Flow Time (sec)	IF*	IF*	Note 1	23.8	IF*	23.8	IF*	IF*	Note 1	IF*	27.0	27.0	IF*	IF*	Note 1
4.75mm +75um Voids Content (%)	IF*	IF*	Note 1	45.8	45.5	45.6	IF*	IF*	Note 1	45.9	46.1	46.0	IF*	IF*	Note 1
4.75mm +75um Flow Time (sec)	IF*	IF*	Note 1	26.6	26.2	26.4	IF*	IF*	Note 1	24.3	24.2	24.2	IF*	IF*	Note 1
2.36mm Voids Content (%)	45.2	44.9	45.1	39.9	40.0	40.0	41.1	41.1	41.1	41.9	42.1	42.0	42.8	42.9	42.8
2.36mm Flow Time (sec)	29.0	28.6	28.8	22.8	22.6	22.7	23.5	23.2	23.4	21.6	21.7	21.6	25.9	26.1	26.0
2.36mm +75um Voids Content (%)	46.9	47.1	47.0	46.8	46.8	46.8	47.1	47.2	47.2	46.6	46.9	46.8	47.4	47.5	47.5
2.36mm +75um Flow Time (sec)	30.0	30.3	30.1	24.2	24.4	24.3	23.9	24.4	24.1	22.9	23.6	23.2	27.3	28.3	27.8
SERIES 3															
XRD Analysis - See Attached Spreadsheet															
MBA - ISSA Bull 145 Procedure	5.3	5.4	5.4	17.0	16.5	16.8	11.2	11.0	11.1	8.3	8.0	8.2	8.2	8.6	8.4
OPTIONAL															
LCPC Packing Density	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.7	0.7	0.7

NOTE 1 (IF*) - Interrupted flow sample would not flow without assistance.

DETAILED SUMMARY OF PROJECT RESULTS – Samples C77, D69, G13, G80, H73

	C77			D69			G13			G80			H73		
	A	B	Average	A	B	Average	A	B	Average	A	B	Average	A	B	Average
SERIES 1															
AS1141.11 - washed grading															
9.5mm															
6.7mm	100	100	100							100	100	100	100	100	100
4.75mm	91	91	91	100	100	100	100	100	100	98	99	99	94	95	95
2.36mm	56	55	56	76	80	78	70	74	72	68	70	69	63	60	62
1.18mm	36	35	36	46	44	45	48	49	49	43	44	44	37	36	37
600um	26	26	26	29	28	29	33	33	33	29	25	27	22	22	22
425um	23	22	23	24	22	23	27	28	28	25	23	24	18	18	18
300um	20	20	20	19	18	19	22	23	23	20	21	21	15	14	15
150um	16	17	17	13	12	13	17	16	17	15	16	16	10	11	11
75um	13	14	14	9	8	9	12	12	12	11	12	12	8	8	8
AS1141.25.3 - Degradation Factor, fine Agg.	92	96	94	85	84	85	89	87	88	85	87	86	86	85	86
AS1289.3.7.1 - Sand Equivalent Value	73	73	73	74	74	74	57	62	60	65	66	66	67	71	69
AS1141.5 - Particle Density/Absorption															
-4.75mm Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
-4.75mm Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.7	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
-4.75mm SSD Particle Density (kg/m3)	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
-4.75mm Absorption (%)	0.9	1.3	1.1	0.9	0.8	0.9	1.4	1.7	1.6	2.0	2.1	2.1	1.8	1.6	1.7
-4.75mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
-4.75mm +75um Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.6	2.6	2.6
-4.75mm +75um SSD Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.6	2.6	2.6
-4.75mm +75um Absorption (%)	1.0	0.9	1.0	0.6	0.7	0.7	0.4	0.4	0.4	0.5	0.5	0.5	0.8	0.9	0.9
-2.36mm Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
-2.36mm Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.7	2.6	2.6	2.7	2.7	2.7	2.6	2.6	2.6	2.5	2.5	2.5
-2.36mm SSD Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.6	2.7	2.6	2.6	2.6	2.6
-2.36mm Absorption (%)	0.8	0.7	0.8	0.9	0.9	0.9	0.5	1.0	0.8	2.5	1.5	2.0	2.4	1.9	2.2
-2.36mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
-2.36mm +75um Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.6	2.6	2.6
-2.36mm +75um SSD Particle Density (kg/m3)	2.6	2.6	2.6	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.6	2.6	2.6
-2.36mm +75um Absorption (%)	0.9	1.0	1.0	0.6	0.6	0.6	0.3	0.3	0.3	0.7	0.7	0.7	1.1	1.0	1.1
AS1141.24 - Sodium Sulphate Soundness															
<9.5 + 4.75mm Fraction	0.1	0.4	0.3										2.3	4.1	3.2
<4.75 + 2.36mm Fraction	0.1	0.1	0.1	0.5	0.4	0.5	0.3	0.3	0.3	0.8	0.8	0.8	1.3	2.3	1.8
<2.36 + 1.18mm Fraction	0.0	0.1	0.1	0.4	0.3	0.4	0.1	0.1	0.1	0.8	0.9	0.9	1.0	1.8	1.4
<1.18 + 600um Fraction	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.3	0.3	0.7	0.3	0.5	0.9	0.9	0.9
<600 + 300um Fraction	0.8	0.2	0.5	0.3	0.5	0.4	0.6	0.4	0.5	0.2	0.5	0.4	2.8	0.9	1.9
Total weighted loss (%)	0.1	0.1	0.1	0.4	0.3	0.4	0.3	0.2	0.3	0.7	0.7	0.7	1.3	1.9	1.6
SERIES 2															
4.75mm Voids Content (%)	IF*	IF*	Note 1	IF*	42.8	42.8	IF*	IF*	Note 1	IF*	IF*	Note 1	IF*	IF*	Note 1
4.75mm Flow Time (sec)	IF*	IF*	Note 1	IF*	28.2	28.2	IF*	IF*	Note 1	IF*	IF*	Note 1	IF*	IF*	Note 1
4.75mm +75um Voids Content (%)	IF*	IF*	Note 1	44.7	44.6	44.7	IF*	IF*	Note 1	IF*	IF*	Note 1	IF*	IF*	Note 1
4.75mm +75um Flow Time (sec)	IF*	IF*	Note 1	30.1	29.7	29.9	IF*	IF*	Note 1	IF*	IF*	Note 1	IF*	IF*	Note 1
2.36mm Voids Content (%)	40.8	41.1	41.0	44.0	44.0	44.0	46.2	46.4	46.3	43.2	43.1	43.2	42.3	42.3	42.3
2.36mm Flow Time (sec)	32.5	34.2	33.4	27.9	27.9	27.9	30.6	30.6	30.6	26.5	26.5	26.5	25.7	25.8	25.8
2.36mm +75um Voids Content (%)	45.7	45.9	45.8	46.7	46.5	46.6	47.7	47.8	47.8	47.4	47.5	47.5	45.3	45.4	45.3
2.36mm +75um Flow Time (sec)	25.9	25.9	25.9	26.5	25.7	26.1	26.4	26.3	26.4	26.7	26.9	26.8	25.6	25.9	25.8
SERIES 3															
XRD Analysis - See Attached Spreadsheet															
MBA - ISSA Bull 145 Procedure	1.7	1.8	1.8	3.3	3.4	3.4	3.8	3.5	3.7	11.8	11.7	11.8	14.2	13.9	14.1
OPTIONAL															
LCPC Packing Density	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.7	0.7	0.7

NOTE 1 (IF*) - Interrupted flow sample would not flow without assistance.

DETAILED SUMMARY OF PROJECT RESULTS – Samples H85, L16, L24

	H85			L16			L24		
	A	B	Average	A	B	Average	A	B	Average
SERIES 1									
AS1141.11 - washed grading									
9.5mm									
6.7mm	100	100	100	100	100	100	100	100	100
4.75mm	96	96	96	99	99	99	97	97	97
2.36mm	68	68	68	90	91	91	74	73	74
1.18mm	40	39	40	55	55	55	49	48	49
600um	25	24	25	35	34	35	34	34	34
425um	21	20	21	28	27	28	29	29	29
300um	18	17	18	23	22	23	26	25	26
150um	13	12	13	15	15	15	21	20	21
75um	10	10	10	10	10	10	17	16	17
AS1141.25.3 - Degradation Factor, fine Agg.	89	90	90	88	87	88	83	84	84
AS1289.3.7.1 - Sand Equivalent Value	66	66	66	76	76	76	59	60	60
AS1141.5 - Particle Density/Absorption									
-4.75mm Apparent Particle Density (kg/m3)	3.0	3.0	3.0	2.8	2.8	2.8	2.8	2.8	2.8
-4.75mm Dry Particle Density (kg/m3)	2.9	2.9	2.9	2.6	2.6	2.6	2.5	2.6	2.6
-4.75mm SSD Particle Density (kg/m3)	2.9	2.9	2.9	2.7	2.7	2.7	2.6	2.6	2.6
-4.75mm Absorption (%)	1.4	1.8	1.6	2.2	2.3	2.3	3.4	3.1	3.3
-4.75mm +75um Apparent Particle Density (kg/m3)	3.0	3.0	3.0	2.8	2.8	2.8	2.8	2.8	2.8
-4.75mm +75um Dry Particle Density (kg/m3)	2.9	2.9	2.9	2.7	2.7	2.7	2.7	2.7	2.7
-4.75mm +75um SSD Particle Density (kg/m3)	3.0	3.0	3.0	2.7	2.7	2.7	2.7	2.7	2.7
-4.75mm +75um Absorption (%)	0.7	0.7	0.7	1.6	1.8	1.7	1.6	1.8	1.7
-2.36mm Apparent Particle Density (kg/m3)	3.0	3.0	3.0	2.8	2.8	2.8	2.8	2.8	2.8
-2.36mm Dry Particle Density (kg/m3)	2.9	2.9	2.9	2.6	2.6	2.6	2.6	2.6	2.6
-2.36mm SSD Particle Density (kg/m3)	2.9	2.9	2.9	2.7	2.7	2.7	2.7	2.6	2.6
-2.36mm Absorption (%)	1.7	1.7	1.7	1.8	1.7	1.8	2.6	2.7	2.7
-2.36mm +75um Apparent Particle Density (kg/m3)	3.0	3.0	3.0	2.8	2.8	2.8	2.8	2.8	2.8
-2.36mm +75um Dry Particle Density (kg/m3)	2.9	2.9	2.9	2.7	2.7	2.7	2.7	2.7	2.7
-2.36mm +75um SSD Particle Density (kg/m3)	3.0	3.0	3.0	2.7	2.7	2.7	2.7	2.7	2.7
-2.36mm +75um Absorption (%)	0.9	0.9	0.9	1.6	1.6	1.6	1.6	1.8	1.7
AS1141.24 - Sodium Sulphate Soundness									
<9.5 + 4.75mm Fraction									
<4.75 + 2.36mm Fraction	0.7	1.0	0.9	1.0	1.2	1.1	0.8	0.9	0.9
<2.36 + 1.18mm Fraction	0.8	0.7	0.8	1.5	1.3	1.4	0.9	1.3	1.1
<1.18 + 600um Fraction	0.6	0.6	0.6	1.6	1.5	1.6	1.1	1.1	1.1
<600 + 300um Fraction	1.1	0.9	1.0	1.1	1.2	1.2	1.6	1.9	1.8
Total weighted loss (%)	0.8	0.8	0.8	1.4	1.3	1.4	1.0	1.2	1.1
SERIES 2									
4.75mm Voids Content (%)	IF*	IF*	Note 1	43.0	41.5	42.2	IF*	IF*	Note 1
4.75mm Flow Time (sec)	IF*	IF*	Note 1	27.4	25.8	26.6	IF*	IF*	Note 1
4.75mm +75um Voids Content (%)	IF*	IF*	Note 1	45.6	46.0	45.8	IF*	IF*	Note 1
4.75mm +75um Flow Time (sec)	IF*	IF*	Note 1	27.0	28.2	27.6	IF*	IF*	Note 1
2.36mm Voids Content (%)	42.1	42.4	42.2	41.6	41.9	41.8	38.8	38.8	38.8
2.36mm Flow Time (sec)	22.2	22.3	22.2	23.4	23.8	23.6	24.6	24.2	24.4
2.36mm +75um Voids Content (%)	48.2	48.3	48.2	47.1	47.2	47.2	48.0	48.1	48.1
2.36mm +75um Flow Time (sec)	25.1	25.8	25.5	26.1	26.3	26.2	26.7	27.4	27.1
SERIES 3									
XRD Analysis - See Attached Spreadsheet									
MBA - ISSA Bull 145 Procedure	13.3	13.7	13.5	11.0	10.6	10.8	11.0	11.8	11.4
OPTIONAL									
LCPC Packing Density	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.6	0.6

NOTE 1 (IF*) - Interrupted flow sample would not flow without assistance.

DETAILED SUMMARY OF PROJECT RESULTS – Samples N33, N53, N76

	N33			N53			N76		
	A	B	Average	A	B	Average	A	B	Average
SERIES 1									
AS1141.11 - washed grading									
9.5mm					100	100			
6.7mm				100	99	100			
4.75mm	100	100	100	94	95	95	100	100	100
2.36mm	93	92	93	75	72	74	88	88	88
1.18mm	66	66	66	52	53	53	61	61	61
600um	46	46	46	36	37	37	38	38	38
425um	38	37	38	30	31	31	29	29	29
300um	32	31	32	25	25	25	22	22	22
150um	20	20	20	15	16	16	11	11	11
75um	14	14	14	10	11	11	6	6	6
AS1141.25.3 - Degradation Factor, fine Agg.	96	96	96	90	90	90	87	86	87
AS1289.3.7.1 - Sand Equivalent Value	69	74	72	70	70	70	78	77	78
AS1141.5 - Particle Density/Absorption									
-4.75mm Apparent Particle Density (kg/m3)	2.7	2.6	2.6	2.6	2.7	2.6	2.7	2.7	2.7
-4.75mm Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
-4.75mm SSD Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.7	2.7
-4.75mm Absorption (%)	0.5	0.1	0.3	0.6	1.1	0.9	0.9	0.9	0.9
-4.75mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
-4.75mm +75um Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.7	2.7
-4.75mm +75um SSD Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.7	2.7
-4.75mm +75um Absorption (%)	0.3	0.4	0.4	0.5	0.5	0.5	0.4	0.4	0.4
-2.36mm Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
-2.36mm Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
-2.36mm SSD Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.7	2.7
-2.36mm Absorption (%)	0.3	0.3	0.3	0.7	0.8	0.8	0.8	0.8	0.8
-2.36mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
-2.36mm +75um Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.7	2.7
-2.36mm +75um SSD Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.7	2.7
-2.36mm +75um Absorption (%)	0.3	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6
AS1141.24 - Sodium Sulphate Soundness									
<9.5 + 4.75mm Fraction				0.5	0.3	0.4			
<4.75 + 2.36mm Fraction	0.2	0.5	0.4	0.9	0.8	0.9	1.2	1.0	1.1
<2.36 + 1.18mm Fraction	0.3	0.2	0.3	0.6	0.7	0.7	1.0	0.9	1.0
<1.18 + 600um Fraction	0.5	0.3	0.4	0.5	0.4	0.5	0.7	0.8	0.8
<600 + 300um Fraction	0.6	0.7	0.7	1.1	0.8	1.0	1.1	1.0	1.1
Total weighted loss (%)	0.4	0.4	0.4	0.7	0.7	0.7	1.0	0.9	1.0
SERIES 2									
4.75mm Voids Content (%)	43.8	43.9	43.8	IF*	IF*	Note 1	IF*	43.4	43.4
4.75mm Flow Time (sec)	30.7	30.3	30.5	IF*	IF*	Note 1	IF*	24.7	24.7
4.75mm +75um Voids Content (%)	45.1	45.1	45.1	IF*	IF*	Note 1	45.3	45.2	45.2
4.75mm +75um Flow Time (sec)	27.2	27.0	27.1	IF*	IF*	Note 1	24.7	24.8	24.8
2.36mm Voids Content (%)	44.8	44.9	44.8	45.4	45.3	45.3	44.5	44.4	44.5
2.36mm Flow Time (sec)	33.9	33.5	33.7	25.7	25.7	25.7	22.4	22.5	22.4
2.36mm +75um Voids Content (%)	46.8	46.7	46.8	47.3	47.2	47.2	46.8	46.9	46.8
2.36mm +75um Flow Time (sec)	25.0	25.0	25.0	24.8	24.9	24.9	23.4	23.2	23.3
SERIES 3									
XRD Analysis - See Attached Spreadsheet									
MBA - ISSA Bull 145 Procedure	3.0	3.0	3.0	12.0	12.0	12.0	9.5	9.0	9.3
OPTIONAL									
LCPC Packing Density	0.7	0.7	0.7	0.6	0.7	0.7	0.7	0.7	0.7

NOTE 1 (IF*) - Interrupted flow sample would not flow without assistance.

DETAILED SUMMARY OF PROJECT RESULTS – Samples P99, S51, S68

	P99			S51			S68		
	A	B	Average	A	B	Average	A	B	Average
SERIES 1									
AS1141.11 - washed grading									
9.5mm					100	100			
6.7mm	100	100	100	100	99	100			
4.75mm	96	96	96	99	99	99	100	100	100
2.36mm	77	79	78	78	78	78	94	98	96
1.18mm	53	53	53	38	38	38	64	65	65
600um	38	39	39	21	21	21	46	47	47
425um	33	33	33	16	16	16	40	40	40
300um	28	28	28	13	13	13	34	35	35
150um	18	18	18	10	10	10	28	28	28
75um	12	12	12	8	8	8	23	23	23
AS1141.25.3 - Degradation Factor, fine Agg.	60	55	58	90	88	89	74	74	74
AS1289.3.7.1 - Sand Equivalent Value	51	51	51	80	82	81	39	41	40
AS1141.5 - Particle Density/Absorption									
-4.75mm Apparent Particle Density (kg/m3)	2.9	2.9	2.9	2.7	2.7	2.7	2.7	2.7	2.7
-4.75mm Dry Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.6	2.6	2.6
-4.75mm SSD Particle Density (kg/m3)	2.8	2.7	2.8	2.7	2.7	2.7	2.6	2.7	2.6
-4.75mm Absorption (%)	3.0	3.3	3.2	0.7	0.9	0.8	2.2	1.2	1.7
-4.75mm +75um Apparent Particle Density (kg/m3)	2.9	2.9	2.9	2.7	2.7	2.7	2.7	2.7	2.7
-4.75mm +75um Dry Particle Density (kg/m3)	2.8	2.8	2.8	2.7	2.7	2.7	2.6	2.6	2.6
-4.75mm +75um SSD Particle Density (kg/m3)	2.8	2.8	2.8	2.7	2.7	2.7	2.7	2.7	2.7
-4.75mm +75um Absorption (%)	1.8	1.7	1.8	0.3	0.3	0.3	1.3	1.4	1.4
-2.36mm Apparent Particle Density (kg/m3)	2.9	2.9	2.9	2.7	2.7	2.7	2.7	2.7	2.7
-2.36mm Dry Particle Density (kg/m3)	2.7	2.7	2.7	2.7	2.7	2.7	2.5	2.6	2.5
-2.36mm SSD Particle Density (kg/m3)	2.8	2.8	2.8	2.7	2.7	2.7	2.6	2.6	2.6
-2.36mm Absorption (%)	2.5	2.7	2.6	0.5	0.7	0.6	2.2	2.4	2.3
-2.36mm +75um Apparent Particle Density (kg/m3)	2.9	2.9	2.9	2.7	2.7	2.7	2.7	2.7	2.7
-2.36mm +75um Dry Particle Density (kg/m3)	2.8	2.8	2.8	2.7	2.7	2.7	2.6	2.6	2.6
-2.36mm +75um SSD Particle Density (kg/m3)	2.8	2.8	2.8	2.7	2.7	2.7	2.6	2.7	2.6
-2.36mm +75um Absorption (%)	1.9	2.0	2.0	0.4	0.4	0.4	1.5	1.6	1.6
AS1141.24 - Sodium Sulphate Soundness									
<9.5 + 4.75mm Fraction									
<4.75 + 2.36mm Fraction	20.0	16.8	18.4	0.1	0.2	0.2	1.3	0.0	0.7
<2.36 + 1.18mm Fraction	12.3	12.3	12.3	0.1	0.1	0.1	1.0	1.0	1.0
<1.18 + 600um Fraction	9.3	10.7	10.0	0.3	0.3	0.3	1.7	1.2	1.5
<600 + 300um Fraction	5.8	5.4	5.6	0.3	0.3	0.3	2.0	2.0	2.0
Total weighted loss (%)	12.8	12.0	12.4	0.2	0.2	0.2	1.4	1.2	1.3
SERIES 2									
4.75mm Voids Content (%)	IF*	IF*	Note 1	41.3	41.2	41.2	45.5	IF*	45.5
4.75mm Flow Time (sec)	IF*	IF*	Note 1	27.9	27.8	27.9	35.7	IF*	35.7
4.75mm +75um Voids Content (%)	IF*	IF*	Note 1	43.4	43.8	43.6	47.6	47.8	47.7
4.75mm +75um Flow Time (sec)	IF*	IF*	Note 1	28.3	29.0	28.6	30.3	30.4	30.4
2.36mm Voids Content (%)	44.8	44.9	44.8	42.2	42.1	42.2	44.7	44.7	44.7
2.36mm Flow Time (sec)	23.0	23.1	23.1	26.5	26.7	26.6	36.8	37.5	37.1
2.36mm +75um Voids Content (%)	46.6	46.8	46.7	44.6	44.6	44.6	48.5	48.3	48.4
2.36mm +75um Flow Time (sec)	22.7	23.2	22.9	26.4	26.2	26.3	28.9	28.5	28.7
SERIES 3									
XRD Analysis - See Attached Spreadsheet									
MBA - ISSA Bull 145 Procedure	19.5	18.5	19.0	1.2	1.2	1.2	14.0	14.5	14.3
OPTIONAL									
LCPC Packing Density	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6

NOTE 1 (IF*) - Interrupted flow sample would not flow without assistance.

DETAILED SUMMARY OF PROJECT RESULTS – Samples T68, T88

	T68			T88		
	A	B	Average	A	B	Average
SERIES 1						
AS1141.11 - washed grading						
9.5mm						
6.7mm	100	100	100	100	100	100
4.75mm	97	98	98	99	99	99
2.36mm	84	85	85	79	78	79
1.18mm	72	74	73	48	49	49
600um	59	60	60	30	31	31
425um	48	49	49	24	24	24
300um	37	37	37	19	20	20
150um	25	25	25	12	13	13
75um	18	19	19	9	9	9
AS1141.25.3 - Degradation Factor, fine Agg.	53	53	53	94	93	94
AS1289.3.7.1 - Sand Equivalent Value	25	25	25	71	71	71
AS1141.5 - Particle Density/Absorption						
-4.75mm Apparent Particle Density (kg/m3)	2.6	2.6	2.6	2.7	2.7	2.7
-4.75mm Dry Particle Density (kg/m3)	2.4	2.4	2.4	2.6	2.6	2.6
-4.75mm SSD Particle Density (kg/m3)	2.5	2.5	2.5	2.6	2.6	2.6
-4.75mm Absorption (%)	3.6	3.6	3.6	1.3	1.1	1.2
-4.75mm +75um Apparent Particle Density (kg/m3)	2.6	2.7	2.6	2.7	2.7	2.7
-4.75mm +75um Dry Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.6	2.6
-4.75mm +75um SSD Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.6	2.6
-4.75mm +75um Absorption (%)	1.4	1.5	1.5	0.5	0.6	0.6
-2.36mm Apparent Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.7	2.7
-2.36mm Dry Particle Density (kg/m3)	2.4	2.4	2.4	2.5	2.5	2.5
-2.36mm SSD Particle Density (kg/m3)	2.5	2.5	2.5	2.6	2.6	2.6
-2.36mm Absorption (%)	3.8	4.0	3.9	1.7	2.3	2.0
-2.36mm +75um Apparent Particle Density (kg/m3)	2.6	2.6	2.6	2.7	2.7	2.7
-2.36mm +75um Dry Particle Density (kg/m3)	2.6	2.5	2.5	2.6	2.6	2.6
-2.36mm +75um SSD Particle Density (kg/m3)	2.6	2.6	2.6	2.6	2.7	2.6
-2.36mm +75um Absorption (%)	1.4	1.5	1.5	0.5	0.6	0.6
AS1141.24 - Sodium Sulphate Soundness						
<9.5 + 4.75mm Fraction						
<4.75 + 2.36mm Fraction	9.9	13.7	11.8	0.6	0.7	0.7
<2.36 + 1.18mm Fraction	6.5	9.1	7.8	0.6	0.6	0.6
<1.18 + 600um Fraction	4.6	5.2	4.9	0.4	0.4	0.4
<600 + 300um Fraction	2.3	2.3	2.3	0.4	0.0	0.2
Total weighted loss (%)	5.3	6.6	6.0	0.5	0.2	0.4
SERIES 2						
4.75mm Voids Content (%)	IF*	41.3	41.3	IF*	IF*	Note 1
4.75mm Flow Time (sec)	IF*	25.0	25.0	IF*	IF*	Note 1
4.75mm +75um Voids Content (%)	44.9	45.0	45.0	IF*	IF*	Note 1
4.75mm +75um Flow Time (sec)	25.6	24.9	25.2	IF*	IF*	Note 1
2.36mm Voids Content (%)	42.2	42.2	42.2	42.4	42.6	42.5
2.36mm Flow Time (sec)	22.8	22.8	22.8	27.2	27.8	27.5
2.36mm +75um Voids Content (%)	47.7	47.7	47.7	47.0	47.1	47.1
2.36mm +75um Flow Time (sec)	23.2	23.4	23.3	26.3	26.9	26.6
SERIES 3						
XRD Analysis - See Attached Spreadsheet						
MBA - ISSA Bull 145 Procedure	24.0	24.4	24.2	9.0	9.5	9.3
OPTIONAL						
LCPC Packing Density	0.7	0.7	0.7	0.7	0.7	0.7

NOTE 1 (IF*) - Interrupted flow sample would not flow without assistance.

Appendix 3 TEST REPEATABILITY – Samples A75 to H73

	A75			B41			B58			BM58			B90		
	A	B	%Dev from mean	A	B	%Dev from mean	A	B	%Dev from mean	A	B	%Dev from mean	A	B	%Dev from mean
SERIES 1															
AS1141.11 - washed grading															
9.5mm															
6.7mm	100	100	0				100	100	0				100	100	0
4.75mm	99	99	0	100	100	0	95	95	0	100	100	0	95	97	0.3
2.36mm	69	68	0.2	84	80	0.6	70	69	0.2	92	93	0.1	73	74	0.2
1.18mm	39	39	0	56	52	0.9	46	45	0.3	57	57	0	47	50	0.8
600um	23	23	0	36	34	0.7	33	32	0.4	37	37	0	32	34	0.8
425um	19	19	0	29	28	0.4	28	27	0.5	30	30	0	26	27	0.5
300um	15	15	0	24	22	1.1	25	24	0.5	25	25	0	21	22	0.6
150um	13	12	1	17	16	0.8	19	18	0.7	19	19	0	13	14	0.9
75um	10	9	1.3	13	12	1	15	14	0.9	14	14	0	9	9	0
AS1141.25.3 - Degradation Factor, fine Agg.	93	94	0.1	86	86	0	79	81	0.3	82	86	0.6	87	87	0
AS1289.3.7.1 - Sand Equivalent Value	81	77	0.6	66	64	0.4	58	63	1.0	69	69	0	68	68	0
AS1141.5 - Particle Density/Absorption															
-4.75mm Apparent Particle Density (kg/m3)	2.7	2.7	0.0	2.9	2.9	0	3.0	3.0	0.0	3.0	3.0	0.1	2.6	2.6	0.0
-4.75mm Dry Particle Density (kg/m3)	2.6	2.6	0.2	2.8	2.8	0.1	2.8	2.8	0	2.8	2.8	0.2	2.5	2.5	0
-4.75mm SSD Particle Density (kg/m3)	2.6	2.7	0.1	2.8	2.8	0.0	2.9	2.9	0	2.9	2.9	0.1	2.6	2.6	0
-4.75mm Absorption (%)	1.0	0.6	6.3	1.3	1.6	2.6	2.2	2.2	0	2.3	2.1	1.1	1.9	2.0	0.6
-4.75mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	0	2.9	2.9	0.0	3.0	3.0	0	3.0	3.0	0	2.6	2.6	0.2
-4.75mm +75um Dry Particle Density (kg/m3)	2.7	2.7	0.0	2.8	2.8	0.0	2.9	2.9	0.0	2.9	2.9	0	2.6	2.5	0.2
-4.75mm +75um SSD Particle Density (kg/m3)	2.7	2.7	0.0	2.9	2.9	0	3.0	3.0	0.0	2.9	2.9	0	2.6	2.5	0.2
-4.75mm +75um Absorption (%)	0.4	0.4	0	1.3	1.3	0	1.1	1.2	1.1	1.1	1.1	0	1.4	1.4	0
-2.36mm Apparent Particle Density (kg/m3)	2.7	2.7	0	2.9	2.9	0.1	3.0	3.0	0.3	3.0	3.0	0	2.6	2.6	0.0
-2.36mm Dry Particle Density (kg/m3)	2.6	2.6	0.1	2.8	2.8	0	2.8	2.8	0.0	2.9	2.8	0.2	2.5	2.5	0
-2.36mm SSD Particle Density (kg/m3)	2.6	2.6	0.0	2.8	2.8	0.0	2.9	2.9	0.1	2.9	2.9	0.1	2.6	2.6	0
-2.36mm Absorption (%)	1.0	0.8	2.8	1.8	1.5	2.3	1.6	2.1	3.4	1.4	1.9	3.8	2.1	2.0	0.6
-2.36mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	0	2.9	2.9	0	3.0	3.0	0.0	3.0	3.0	0	2.6	2.6	0
-2.36mm +75um Dry Particle Density (kg/m3)	2.7	2.7	0	2.8	2.8	0.0	2.9	2.9	0	2.9	2.9	0.0	2.5	2.5	0
-2.36mm +75um SSD Particle Density (kg/m3)	2.7	2.7	0	2.8	2.9	0.0	3.0	3.0	0.0	2.9	2.9	0	2.6	2.6	0.0
-2.36mm +75um Absorption (%)	0.4	0.5	2.8	1.4	1.4	0	1.3	1.2	1	1.1	1.2	1.1	1.4	1.4	0
AS1141.24 - Sodium Sulphate Soundness															
<9.5 + 4.75mm Fraction							0.7	0.7	0				0.4	0	25
<4.75 + 2.36mm Fraction	0.2	0.5	10.7	0.8	0.9	1.5	1.3	1.1	2.1	0.8	0.7	1.7	1.0	0.7	4.4
<2.36 + 1.18mm Fraction	0.7	0.9	3.1	0.9	1.1	2.5	1.3	1.3	0	0.7	0.7	0	0.5	0.5	0
<1.18 + 600um Fraction	1.0	1.3	3.3	1.5	1.3	1.8	1.7	1.5	1.6	0.8	0.8	0	0.5	0.5	0
<600 + 300um Fraction	2.3	4.2	7.3	1.5	1.7	1.6	2.6	2.4	1	1.0	1.2	2.3	0.4	0.7	6.8
Total weighted loss (%)	0.7	1.1	5.6	1.1	1.2	1.1	1.5	1.3	1.8	0.8	0.8	0	0.6	0.6	0
SERIES 2															
2.36mm Voids Content (%)	45.2	44.9	0.1	39.9	40.0	0.0	41.1	41.1	0	41.9	42.1	0.1	42.8	42.9	0.0
2.36mm Flow Time (sec)	29.0	28.6	0.2	22.8	22.6	0.1	23.5	23.2	0.2	21.6	21.7	0.1	25.9	26.1	0.1
2.36mm +75um Voids Content (%)	46.9	47.1	0.1	46.8	46.8	0	47.1	47.2	0.0	46.6	46.9	0.1	47.4	47.5	0.0
2.36mm +75um Flow Time (sec)	30.0	30.3	0.1	24.2	24.4	0.1	23.9	24.4	0.3	22.9	23.6	0.4	27.3	28.3	0.4
SERIES 3															
XRD Analysis - See Attached Spreadsheet															
MBA - ISSA Bull 145 Procedure	5.3	5.4	0.2	17.0	16.5	0.4	11.2	11.0	0.2	8.3	8.0	0.5	8.2	8.6	0.6
OPTIONAL															
LCPC Packing Density	0.6	0.6	0	0.7	0.7	0.0	0.7	0.7	0.1	0.6	0.6	0.1	0.7	0.7	0.0

continues

TEST REPEATABILITY – Samples A75 to H73 *continued*

	C77			D69			G13			G80		
	A	B	%Dev from mean	A	B	%Dev from mean	A	B	%Dev from mean	A	B	%Dev from mean
SERIES 1												
AS1141.11 - washed grading												
9.5mm												
6.7mm	100	100	0							100	100	0
4.75mm	91	91	0	100	100	0	100	100	0	98	99	0.1
2.36mm	56	55	0.2	76	80	0.6	70	74	0.7	68	70	0.4
1.18mm	36	35	0.4	46	44	0.6	48	49	0.3	43	44	0.3
600um	26	26	0	29	28	0.4	33	33	0	29	25	1.9
425um	23	22	0.6	24	22	1.1	27	28	0.5	25	23	1.0
300um	20	20	0	19	18	0.7	22	23	0.6	20	21	0.6
150um	16	17	0.8	13	12	1	17	16	0.8	15	16	0.8
75um	13	14	0.9	9	8	1.5	12	12	0	11	12	1.1
AS1141.25.3 - Degradation Factor, fine Agg.	92	96	0.5	85	84	0.1	89	87	0.3	85	87	0.3
AS1289.3.7.1 - Sand Equivalent Value	73	73	0	74	74	0	57	62	1.1	65	66	0.2
AS1141.5 - Particle Density/Absorption												
-4.75mm Apparent Particle Density (kg/m3)	2.7	2.7	0	2.7	2.7	0	2.7	2.7	0.0	2.7	2.7	0
-4.75mm Dry Particle Density (kg/m3)	2.6	2.6	0.1	2.6	2.7	0.0	2.6	2.6	0.1	2.6	2.6	0.0
-4.75mm SSD Particle Density (kg/m3)	2.6	2.6	0.1	2.7	2.7	0.0	2.7	2.6	0.0	2.6	2.6	0.0
-4.75mm Absorption (%)	0.9	1.3	4.5	0.9	0.8	1.5	1.4	1.7	2.4	2.0	2.1	0.6
-4.75mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	0	2.7	2.7	0	2.7	2.7	0	2.7	2.7	0.0
-4.75mm +75um Dry Particle Density (kg/m3)	2.6	2.6	0	2.7	2.7	0.0	2.7	2.7	0	2.7	2.7	0
-4.75mm +75um SSD Particle Density (kg/m3)	2.7	2.7	0	2.7	2.7	0	2.7	2.7	0	2.7	2.7	0
-4.75mm +75um Absorption (%)	1.0	0.9	1.3	0.6	0.7	1.9	0.4	0.4	0	0.5	0.5	0
-2.36mm Apparent Particle Density (kg/m3)	2.7	2.7	0.0	2.7	2.7	0	2.7	2.7	0.0	2.7	2.7	0
-2.36mm Dry Particle Density (kg/m3)	2.6	2.6	0	2.7	2.6	0.0	2.7	2.7	0.1	2.6	2.6	0.3
-2.36mm SSD Particle Density (kg/m3)	2.7	2.7	0	2.7	2.7	0	2.7	2.7	0.1	2.6	2.7	0.2
-2.36mm Absorption (%)	0.8	0.7	1.7	0.9	0.9	0	0.5	1.0	8.3	2.5	1.5	6.3
-2.36mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	0	2.7	2.7	0	2.7	2.7	0	2.7	2.7	0.0
-2.36mm +75um Dry Particle Density (kg/m3)	2.6	2.6	0.0	2.7	2.7	0.0	2.7	2.7	0	2.7	2.7	0.0
-2.36mm +75um SSD Particle Density (kg/m3)	2.6	2.6	0	2.7	2.7	0	2.7	2.7	0.0	2.7	2.7	0.0
-2.36mm +75um Absorption (%)	0.9	1.0	1.3	0.6	0.6	0	0.3	0.3	0	0.7	0.7	0
AS1141.24 - Sodium Sulphate Soundness												
<9.5 + 4.75mm Fraction	0.1	0.4	15									
<4.75 + 2.36mm Fraction	0.1	0.1	0	0.5	0.4	2.8	0.3	0.3	0	0.8	0.8	0
<2.36 + 1.18mm Fraction	0.0	0.1	25	0.4	0.3	3.6	0.1	0.1	0	0.8	0.9	1.5
<1.18 + 600um Fraction	0.0	0.0		0.3	0.3	0	0.3	0.3	0	0.7	0.3	10
<600 + 300um Fraction	0.8	0.2	15	0.3	0.5	6.3	0.6	0.4	5	0.2	0.5	10.7
Total weighted loss (%)	0.1	0.1	0	0.4	0.3	3.6	0.3	0.2	5	0.7	0.7	0
SERIES 2												
2.36mm Voids Content (%)	40.8	41.1	0.1	44.0	44.0	0	46.2	46.4	0.1	43.2	43.1	0.0
2.36mm Flow Time (sec)	32.5	34.2	0.6	27.9	27.9	0	30.6	30.6	0	26.5	26.5	0
2.36mm +75um Voids Content (%)	45.7	45.9	0.1	46.7	46.5	0.1	47.7	47.8	0.0	47.4	47.5	0.0
2.36mm +75um Flow Time (sec)	25.9	25.9	0	26.5	25.7	0.4	26.4	26.3	0.0	26.7	26.9	0.1
SERIES 3												
XRD Analysis - See Attached Spreadsheet												
MBA - ISSA Bull 145 Procedure	1.7	1.8	0.7	3.3	3.4	0.4	3.8	3.5	1.0	11.8	11.7	0.1
OPTIONAL												
LCPC Packing Density	0.7	0.7	0.0	0.7	0.7	0.1	0.7	0.7	0.1	0.6	0.6	0.1

continues

TEST REPEATABILITY – Samples A75 to H73 *continued*

	H73					
	A	B	%Dev from mean	∑ %dev	Number of results	Ave % Dev
SERIES 1						
AS1141.11 - washed grading						
9.5mm						
6.7mm	100	100	0	0	6	0
4.75mm	94	95	0.1	0.5	10	0.1
2.36mm	63	60	0.6	3.8	10	0.4
1.18mm	37	36	0.3	3.7	10	0.4
600um	22	22	0	4.5	10	0.5
425um	18	18	0	4.4	10	0.4
300um	15	14	0.9	5.4	10	0.5
150um	10	11	1.2	7.8	10	0.8
75um	8	8	0	6.6	10	0.7
AS1141.25.3 - Degradation Factor, fine Agg.	86	85	0.1	2.2	10	0.2
AS1289.3.7.1 - Sand Equivalent Value	67	71	0.7	5.0	10	0.5
AS1141.5 - Particle Density/Absorption						
-4.75mm Apparent Particle Density (kg/m3)	2.7	2.7	0	0.3	10.0	0.0
-4.75mm Dry Particle Density (kg/m3)	2.6	2.6	0.0	0.7	10.0	0.1
-4.75mm SSD Particle Density (kg/m3)	2.6	2.6	0	0.5	10.0	0.0
-4.75mm Absorption (%)	1.8	1.6	1.5	16.6	10.0	1.7
-4.75mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	0	0.3	10.0	0.0
-4.75mm +75um Dry Particle Density (kg/m3)	2.6	2.6	0.0	0.5	10.0	0.0
-4.75mm +75um SSD Particle Density (kg/m3)	2.6	2.6	0	0.3	10.0	0.0
-4.75mm +75um Absorption (%)	0.8	0.9	1.5	5.6	10.0	0.6
-2.36mm Apparent Particle Density (kg/m3)	2.7	2.7	0.0	0.7	10.0	0.1
-2.36mm Dry Particle Density (kg/m3)	2.5	2.5	0.1	0.1	10.0	0.1
-2.36mm SSD Particle Density (kg/m3)	2.6	2.6	0.0	0.8	10.0	0.1
-2.36mm Absorption (%)	2.4	1.9	2.9	33.7	10.0	3.4
-2.36mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	0.0	0.2	10.0	0.0
-2.36mm +75um Dry Particle Density (kg/m3)	2.6	2.6	0	0.2	10.0	0.0
-2.36mm +75um SSD Particle Density (kg/m3)	2.6	2.6	0	0.3	10.0	0.0
-2.36mm +75um Absorption (%)	1.1	1.0	1.2	7.1	10.0	0.7
AS1141.24 - Sodium Sulphate Soundness						
<9.5 + 4.75mm Fraction	2.3	4.1	7.0	32.0	4.0	8.0
<4.75 + 2.36mm Fraction	1.3	2.3	6.9	32.2	10.0	3.2
<2.36 + 1.18mm Fraction	1.0	1.8	7.1	17.8	10.0	1.8
<1.18 + 600um Fraction	0.9	0.9	0	18.2	10.0	1.8
<600 + 300um Fraction	2.8	0.9	12.8	54.8	10.0	5.5
Total weighted loss (%)	1.3	1.9	4.7	23.5	10.0	2.3
SERIES 2						
2.36mm Voids Content (%)	42.3	42.3	0	0.3	10.0	0.0
2.36mm Flow Time (sec)	25.7	25.8	0.0	0.8	10.0	0.1
2.36mm +75um Voids Content (%)	45.3	45.4	0.0	0.3	10.0	0.0
2.36mm +75um Flow Time (sec)	25.6	25.9	0.1	2.2	10.0	0.2
SERIES 3						
XRD Analysis - See Attached Spreadsheet						
MBA - ISSA Bull 145 Procedure	14.2	13.9	0.3	3.9	10	0.4
OPTIONAL						
LCPC Packing Density	0.7	0.7	0.1	0.7	10	0.1

TEST REPEATABILITY – Samples H85 to T88

	H85			L16			L24		
	A	B	%Dev from mean	A	B	%Dev from mean	A	B	%Dev from mean
SERIES 1									
AS1141.11 - washed grading									
9.5mm									
6.7mm	100	100	0	100	100	0	100	100	0
4.75mm	96	96	0	99	99	0	97	97	0
2.36mm	68	68	0	90	91	0.1	74	73	0.2
1.18mm	40	39	0.3	55	55	0	49	48	0.3
600um	25	24	0.5	35	34	0.4	34	34	0
425um	21	20	0.6	28	27	0.5	29	29	0
300um	18	17	0.7	23	22	0.6	26	25	0.5
150um	13	12	1	15	15	0	21	20	0.6
75um	10	10	0	10	10	0	17	16	0.8
AS1141.25.3 - Degradation Factor, fine Agg.	89	90	0.1	88	87	0.1	83	84	0.1
AS1289.3.7.1 - Sand Equivalent Value	66	66	0	76	76	0	59	60	0.2
AS1141.5 - Particle Density/Absorption									
-4.75mm Apparent Particle Density (kg/m3)	3.0	3.0	0.0	2.8	2.8	0	2.8	2.8	0.0
-4.75mm Dry Particle Density (kg/m3)	2.9	2.9	0.2	2.6	2.6	0.0	2.5	2.6	0.1
-4.75mm SSD Particle Density (kg/m3)	2.9	2.9	0.1	2.7	2.7	0	2.6	2.6	0.0
-4.75mm Absorption (%)	1.4	1.8	3.1	2.2	2.3	0.6	3.4	3.1	1.2
-4.75mm +75um Apparent Particle Density (kg/m3)	3.0	3.0	0	2.8	2.8	0.0	2.8	2.8	0
-4.75mm +75um Dry Particle Density (kg/m3)	2.9	2.9	0	2.7	2.7	0	2.7	2.7	0.0
-4.75mm +75um SSD Particle Density (kg/m3)	3.0	3.0	0	2.7	2.7	0	2.7	2.7	0
-4.75mm +75um Absorption (%)	0.7	0.7	0	1.6	1.8	1.5	1.6	1.8	1.5
-2.36mm Apparent Particle Density (kg/m3)	3.0	3.0	0	2.8	2.8	0	2.8	2.8	0
-2.36mm Dry Particle Density (kg/m3)	2.9	2.9	0.0	2.6	2.6	0.0	2.6	2.6	0.0
-2.36mm SSD Particle Density (kg/m3)	2.9	2.9	0	2.7	2.7	0	2.7	2.6	0.0
-2.36mm Absorption (%)	1.7	1.7	0	1.8	1.7	0.7	2.6	2.7	0.5
-2.36mm +75um Apparent Particle Density (kg/m3)	3.0	3.0	0	2.8	2.8	0	2.8	2.8	0.0
-2.36mm +75um Dry Particle Density (kg/m3)	2.9	2.9	0	2.7	2.7	0	2.7	2.7	0.1
-2.36mm +75um SSD Particle Density (kg/m3)	3.0	3.0	0	2.7	2.7	0	2.7	2.7	0.0
-2.36mm +75um Absorption (%)	0.9	0.9	0	1.6	1.6	0	1.6	1.8	1.5
AS1141.24 - Sodium Sulphate Soundness									
<9.5 + 4.75mm Fraction									
<4.75 + 2.36mm Fraction	0.7	1.0	4.4	1.0	1.2	2.3	0.8	0.9	1.5
<2.36 + 1.18mm Fraction	0.8	0.7	1.7	1.5	1.3	1.8	0.9	1.3	4.5
<1.18 + 600um Fraction	0.6	0.6	0	1.6	1.5	0.8	1.1	1.1	0
<600 + 300um Fraction	1.1	0.9	2.5	1.1	1.2	1.1	1.6	1.9	2.1
Total weighted loss (%)	0.8	0.8	0	1.4	1.3	0.9	1.0	1.2	2.3
SERIES 2									
2.36mm Voids Content (%)	42.1	42.4	0.1	41.6	41.9	0.1	38.8	38.8	0
2.36mm Flow Time (sec)	22.2	22.3	0.1	23.4	23.8	0.2	24.6	24.2	0.2
2.36mm +75um Voids Content (%)	48.2	48.3	0.0	47.1	47.2	0.0	48.0	48.1	0.0
2.36mm +75um Flow Time (sec)	25.1	25.8	0.3	26.1	26.3	0.1	26.7	27.4	0.3
SERIES 3									
XRD Analysis - See Attached Spreadsheet									
MBA - ISSA Bull 145 Procedure	13.3	13.7	0.4	11.0	10.6	0.5	11.0	11.8	0.9
OPTIONAL									
LCPC Packing Density	0.6	0.6	0.1	0.6	0.6	0.1	0.7	0.6	0.1

continues

TEST REPEATABILITY – Samples H85 to T88 *continued*

	N33			N53			N76		
	A	B	%Dev from mean	A	B	%Dev from mean	A	B	%Dev from mean
SERIES 1									
AS1141.11 - washed grading									
9.5mm					100				
6.7mm				100	99	0.1			
4.75mm	100	100	0	94	95	0.1	100	100	0
2.36mm	93	92	0.1	75	72	0.5	88	88	0
1.18mm	66	66	0	52	53	0.2	61	61	0
600um	46	46	0	36	37	0.3	38	38	0
425um	38	37	0.3	30	31	0.4	29	29	0
300um	32	31	0.4	25	25	0	22	22	0
150um	20	20	0	15	16	0.8	11	11	0
75um	14	14	0	10	11	1.2	6	6	0
AS1141.25.3 - Degradation Factor, fine Agg.	96	96	0	90	90	0	87	86	0.1
AS1289.3.7.1 - Sand Equivalent Value	69	74	0.9	70	70	0	78	77	0.2
AS1141.5 - Particle Density/Absorption									
-4.75mm Apparent Particle Density (kg/m3)	2.7	2.6	0.0	2.6	2.7	0.1	2.7	2.7	0
-4.75mm Dry Particle Density (kg/m3)	2.6	2.6	0.0	2.6	2.6	0.0	2.6	2.6	0
-4.75mm SSD Particle Density (kg/m3)	2.6	2.6	0	2.6	2.6	0.0	2.7	2.7	0
-4.75mm Absorption (%)	0.5	0.1	16.7	0.6	1.1	7.4	0.9	0.9	0
-4.75mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	0	2.7	2.7	0	2.7	2.7	0
-4.75mm +75um Dry Particle Density (kg/m3)	2.6	2.6	0	2.6	2.6	0	2.7	2.7	0.0
-4.75mm +75um SSD Particle Density (kg/m3)	2.6	2.6	0	2.6	2.6	0	2.7	2.7	0.0
-4.75mm +75um Absorption (%)	0.3	0.4	3.6	0.5	0.5	0	0.4	0.4	0
-2.36mm Apparent Particle Density (kg/m3)	2.7	2.7	0.0	2.7	2.7	0	2.7	2.7	0.0
-2.36mm Dry Particle Density (kg/m3)	2.6	2.6	0	2.6	2.6	0.0	2.6	2.6	0.0
-2.36mm SSD Particle Density (kg/m3)	2.6	2.6	0	2.6	2.6	0.0	2.7	2.7	0.0
-2.36mm Absorption (%)	0.3	0.3	0	0.7	0.8	1.7	0.8	0.8	0
-2.36mm +75um Apparent Particle Density (kg/m3)	2.7	2.7	0.0	2.7	2.7	0	2.7	2.7	0.0
-2.36mm +75um Dry Particle Density (kg/m3)	2.6	2.6	0	2.6	2.6	0	2.7	2.7	0.0
-2.36mm +75um SSD Particle Density (kg/m3)	2.6	2.6	0	2.6	2.6	0	2.7	2.7	0
-2.36mm +75um Absorption (%)	0.3	0.4	3.6	0.5	0.5	0	0.6	0.6	0
AS1141.24 - Sodium Sulphate Soundness									
<9.5 + 4.75mm Fraction				0.5	0.3	6.3			
<4.75 + 2.36mm Fraction	0.2	0.5	10.7	0.9	0.8	1.5	1.2	1.0	2.3
<2.36 + 1.18mm Fraction	0.3	0.2	5	0.6	0.7	1.9	1.0	0.9	1.3
<1.18 + 600um Fraction	0.5	0.3	6.9	0.5	0.4	2.8	0.7	0.8	1.7
<600 + 300um Fraction	0.6	0.7	1.9	1.1	0.8	3.9	1.1	1.0	1.2
Total weighted loss (%)	0.4	0.4	0	0.7	0.7	0	1.0	0.9	1.3
SERIES 2									
2.36mm Voids Content (%)	44.8	44.9	0.0	45.4	45.3	0.0	44.5	44.4	0.0
2.36mm Flow Time (sec)	33.9	33.5	0.1	25.7	25.7	0	22.4	22.5	0.1
2.36mm +75um Voids Content (%)	46.8	46.7	0.0	47.3	47.2	0.0	46.8	46.9	0.0
2.36mm +75um Flow Time (sec)	25.0	25.0	0	24.8	24.9	0.1	23.4	23.2	0.1
SERIES 3									
XRD Analysis - See Attached Spreadsheet									
MBA - ISSA Bull 145 Procedure	3.0	3.0	0	12.0	12.0	0	9.5	9.0	0.7
OPTIONAL									
LCPC Packing Density	0.7	0.7	0.0	0.6	0.7	0.4	0.7	0.7	0.1

continues

TEST REPEATABILITY – Samples H85 to T88 *continued*

	P99			S51			S68		
	A	B	%Dev from mean	A	B	%Dev from mean	A	B	%Dev from mean
SERIES 1									
AS1141.11 - washed grading									
9.5mm					100				
6.7mm	100	100	0	100	99	0.1			
4.75mm	96	96	0	99	99	0	100	100	0
2.36mm	77	79	0.3	78	78	0	94	98	0.5
1.18mm	53	53	0	38	38	0	64	65	0.2
600um	38	39	0.3	21	21	0	46	47	0.3
425um	33	33	0	16	16	0	40	40	0
300um	28	28	0	13	13	0	34	35	0.4
150um	18	18	0	10	10	0	28	28	0
75um	12	12	0	8	8	0	23	23	0
AS1141.25.3 - Degradation Factor, fine Agg.	60	55	1.1	90	88	0.3	74	74	0
AS1289.3.7.1 - Sand Equivalent Value	51	51	0	80	82	0.3	39	41	0.6
AS1141.5 - Particle Density/Absorption									
-4.75mm Apparent Particle Density (kg/m3)	2.9	2.9	0	2.7	2.7	0	2.7	2.7	0
-4.75mm Dry Particle Density (kg/m3)	2.7	2.7	0.0	2.7	2.7	0.0	2.6	2.6	0.3
-4.75mm SSD Particle Density (kg/m3)	2.8	2.7	0.1	2.7	2.7	0	2.6	2.7	0.2
-4.75mm Absorption (%)	3.0	3.3	1.2	0.7	0.9	3.1	2.2	1.2	7.4
-4.75mm +75um Apparent Particle Density (kg/m3)	2.9	2.9	0	2.7	2.7	0	2.7	2.7	0.0
-4.75mm +75um Dry Particle Density (kg/m3)	2.8	2.8	0	2.7	2.7	0	2.6	2.6	0
-4.75mm +75um SSD Particle Density (kg/m3)	2.8	2.8	0	2.7	2.7	0	2.7	2.7	0.0
-4.75mm +75um Absorption (%)	1.8	1.7	0.7	0.3	0.3	0	1.3	1.4	0.9
-2.36mm Apparent Particle Density (kg/m3)	2.9	2.9	0	2.7	2.7	0	2.7	2.7	0.1
-2.36mm Dry Particle Density (kg/m3)	2.7	2.7	0.0	2.7	2.7	0.1	2.5	2.6	0.0
-2.36mm SSD Particle Density (kg/m3)	2.8	2.8	0.0	2.7	2.7	0.0	2.6	2.6	0.0
-2.36mm Absorption (%)	2.5	2.7	0.1	0.5	0.7	4.2	2.2	2.4	1.1
-2.36mm +75um Apparent Particle Density (kg/m3)	2.9	2.9	0	2.7	2.7	0	2.7	2.7	0
-2.36mm +75um Dry Particle Density (kg/m3)	2.8	2.8	0	2.7	2.7	0	2.6	2.6	0.0
-2.36mm +75um SSD Particle Density (kg/m3)	2.8	2.8	0.0	2.7	2.7	0	2.6	2.7	0.0
-2.36mm +75um Absorption (%)	1.9	2.0	0.6	0.4	0.4	0	1.5	1.6	0.8
AS1141.24 - Sodium Sulphate Soundness									
<9.5 + 4.75mm Fraction									
<4.75 + 2.36mm Fraction	20.0	16.8	2.2	0.1	0.2	8.3	1.3	0.0	
<2.36 + 1.18mm Fraction	12.3	12.3	0	0.1	0.1	0	1.0	1.0	0
<1.18 + 600um Fraction	9.3	10.7	1.8	0.3	0.3	0	1.7	1.2	4.3
<600 + 300um Fraction	5.8	5.4	0.9	0.3	0.3	0	2.0	2.0	0
Total weighted loss (%)	12.8	12.0	0.8	0.2	0.2	0	1.4	1.2	1.9
SERIES 2									
2.36mm Voids Content (%)	44.8	44.9	0.0	42.2	42.1	0.0	44.7	44.7	0
2.36mm Flow Time (sec)	23.0	23.1	0.1	26.5	26.7	0.1	36.8	37.5	0.2
2.36mm +75um Voids Content (%)	46.6	46.8	0.1	44.6	44.6	0	48.5	48.3	0.1
2.36mm +75um Flow Time (sec)	22.7	23.2	0.3	26.4	26.2	0.1	28.9	28.5	0.2
SERIES 3									
XRD Analysis - See Attached Spreadsheet									
MBA - ISSA Bull 145 Procedure	19.5	18.5	0.7	1.2	1.2	0	14.0	14.5	0.4
OPTIONAL									
LCPC Packing Density	0.7	0.7	0.0	0.7	0.7	0.0	0.6	0.6	0

continues

TEST REPEATABILITY – Samples H85 to T88 *continued*

	T68			T88					
	A	B	%Dev from mean	A	B	%Dev from mean	∑ %dev	Number of results	Ave % Dev
SERIES 1									
AS1141.11 - washed grading									
9.5mm									
6.7mm	100	100	0	100	100	0	0.3	7	0.0
4.75mm	97	98	0.1	99	99	0	0.3	11	0.0
2.36mm	84	85	0.1	79	78	0.2	1.9	11	0.2
1.18mm	72	74	0.3	48	49	0.3	1.6	11	0.1
600um	59	60	0.2	30	31	0.4	2.1	11	0.2
425um	48	49	0.3	24	24	0	2.4	11	0.2
300um	37	37	0	19	20	0.6	3.6	11	0.3
150um	25	25	0	12	13	1	3.4	11	0.3
75um	18	19	0.7	9	9	0	2.6	11	0.2
AS1141.25.3 - Degradation Factor, fine Agg.	53	53	0	94	93	0.1	0.1	11	0.1
AS1289.3.7.1 - Sand Equivalent Value	25	25	0	71	71	0	3.1	11	0.3
AS1141.5 - Particle Density/Absorption									
-4.75mm Apparent Particle Density (kg/m3)	2.6	2.6	0.0	2.7	2.7	0	0.3	11.0	0.0
-4.75mm Dry Particle Density (kg/m3)	2.4	2.4	0.1	2.6	2.6	0.1	0.1	11.0	0.1
-4.75mm SSD Particle Density (kg/m3)	2.5	2.5	0.1	2.6	2.6	0.1	0.6	11.0	0.1
-4.75mm Absorption (%)	3.6	3.6	0	1.3	1.1	2.1	58.1	11.0	5.3
-4.75mm +75um Apparent Particle Density (kg/m3)	2.6	2.7	0.0	2.7	2.7	0	0.1	11.0	0.0
-4.75mm +75um Dry Particle Density (kg/m3)	2.6	2.6	0	2.6	2.6	0.0	0.1	11.0	0.0
-4.75mm +75um SSD Particle Density (kg/m3)	2.6	2.6	0.0	2.6	2.6	0	0.1	11.0	0.0
-4.75mm +75um Absorption (%)	1.4	1.5	0.9	0.5	0.6	2.3	14.1	11.0	1.3
-2.36mm Apparent Particle Density (kg/m3)	2.6	2.6	0.0	2.6	2.7	0.1	0.4	11.0	0.0
-2.36mm Dry Particle Density (kg/m3)	2.4	2.4	0.1	2.5	2.5	0.0	0.5	11.0	0.0
-2.36mm SSD Particle Density (kg/m3)	2.5	2.5	0.1	2.6	2.6	0	0.3	11.0	0.0
-2.36mm Absorption (%)	3.8	4.0	0.6	1.7	2.3	3.8	12.5	11.0	1.1
-2.36mm +75um Apparent Particle Density (kg/m3)	2.6	2.6	0	2.7	2.7	0.0	0.2	11.0	0.0
-2.36mm +75um Dry Particle Density (kg/m3)	2.6	2.5	0.0	2.6	2.6	0	0.2	11.0	0.0
-2.36mm +75um SSD Particle Density (kg/m3)	2.6	2.6	0.0	2.6	2.7	0.0	0.2	11.0	0.0
-2.36mm +75um Absorption (%)	1.4	1.5	0.9	0.5	0.6	2.3	12.6	11.0	1.1
AS1141.24 - Sodium Sulphate Soundness									
<9.5 + 4.75mm Fraction							6.3	1	6.3
<4.75 + 2.36mm Fraction	9.9	13.7	4.0	0.6	0.7	1.9	47.6	10	4.8
<2.36 + 1.18mm Fraction	6.5	9.1	4.2	0.6	0.6	0	25.4	11	2.3
<1.18 + 600um Fraction	4.6	5.2	1.5	0.4	0.4	0	24.9	11	2.3
<600 + 300um Fraction	2.3	2.3	0	0.4	0.0	25	39.7	11	3.6
Total weighted loss (%)	5.3	6.6	2.7	0.5	0.2	10.7	19.9	11	1.8
SERIES 2									
2.36mm Voids Content (%)	42.2	42.2	0	42.4	42.6	0.1	0.4	11	0.0
2.36mm Flow Time (sec)	22.8	22.8	0	27.2	27.8	0.3	1.4	11	0.1
2.36mm +75um Voids Content (%)	47.7	47.7	0	47.0	47.1	0.0	0.3	11	0.0
2.36mm +75um Flow Time (sec)	23.2	23.4	0.1	26.3	26.9	0.3	1.6	11	0.1
SERIES 3									
XRD Analysis - See Attached Spreadsheet									
MBA - ISSA Bull 145 Procedure	24.0	24.4	0.2	9.0	9.5	0.7	3.7	11	0.3
OPTIONAL									
LCPC Packing Density	0.7	0.7	0.0	0.7	0.7	0.1	0.9	11	0.1

Appendix 4

SPECIFICATION FOR MANUFACTURED SAND FOR USE AS CONCRETE FINE AGGREGATE

Scope:

This specification defines the acceptance criteria for manufactured sands supplied for use in the fine aggregate of concrete. The manufactured sand may be one component of a fine aggregate blend, or it may comprise the total fine aggregate for the mix. This specification defines properties determined from manufactured sands that have been used successfully in fine aggregate. However, it provides no guidance on the extent of the addition of the manufactured sand. A material complying with this specification will be acceptable for blending, but the blend proportions must be determined by trials. The effects of a sand complying with this specification on the water demand, plastic or hardened properties of concrete cannot be predicted and are not addressed by this specification.

Definitions:

Manufactured sand: A purposeful made crushed fine aggregate produced from a suitable source material designed for use in concrete or for other specific products. Only source materials with suitable strength, durability and shape characteristics should be considered. Production generally involves crushing, screening and possibly washing. Separation into discrete fractions, recombining and blending may be necessary.

Sound, durable stone or source: For the purposes of this specification sound and durable stone or a sound and durable source shall mean source rock or stone that can be shown to comply with the durability clause (Clause 9) of Australian Standard AS 2758.1 for exposure classification B1 or B2.

General:

Manufactured sand shall be produced from crushing and screening of sound and durable source rock. Crushing shall include processes to improve the particle shape of the manufactured sand. Production processes shall ensure that sand stockpiles are not contaminated with weathered or highly altered rock or with clay seams or other contaminants. Crushing of multiple source rocks into a single sand stockpile shall not be permitted unless it can be demonstrated that such a process is under blend control and produces a consistent product. In accordance with Clause 13 of AS 2758.1, volcanic breccia, mudstones, shales and highly weathered or altered rocks shall not be used as source rock for manufactured sand.

Sampling:

The sampling of aggregate and of source rock shall be carried out in accordance with the methods described in AS 1141.3.1.

Note: Unless otherwise stated in this specification, the frequency of testing should be agreed between the producer of the manufactured sand and the concrete producer.

Testing:

Testing shall be conducted in accordance with the methods specified in each clause of this document. Proportions, ratios and percentages are expressed in relation to units described in the test methods and are specified in comparable units in this document.

Density and Water Absorption:

When determined in accordance with AS 1141.5, the particle density of manufactured sand, expressed as the saturated, surface dry value, shall not exceed 3.2 t/m^3 and shall be greater than or equal to 2.1 t/m^3.

Particle Size Distribution

Because of the wide variation in crushing characteristics of natural materials, and significant variation in the design of crushing plant, it is not practical to define an overall grading specification for manufactured sands. Instead, the grading of individual components of a fine aggregate shall be determined by the concrete manufacturer and the variation of the individual gradings shall be controlled by the Producer of the component, whether natural or manufactured sand.

The Producer of manufactured sand shall provide a history of grading results to indicate the average grading and variation the manufactured sand proposed for supply. In addition, the Producer shall nominate a grading envelope for the product that shall be known as the 'submitted grading'. Nevertheless, manufactured sand, by definition, shall conform to the general grading limits given in **Table A4.1**. Consideration may be given to manufactured sands with a greater than 20% passing the 75 micron fraction providing they are used in combination with another sand where the total % passing 75 micron for the combination does not exceed 15% and providing they meet the limits of deviation in every respect.

The 'limits of deviation' (see **Table A4.2**) are the maximum variations in percentage units between the submitted grading and any particular test result during the course of the contract.

NOTES:

1 *Consideration may be given to Manufactured Sands with a greater than 20% passing the 75 micron size fraction providing they are used in combination with another sand where the total % passing 75 micron for the combination does not exceed 15.0% and providing they meet the limits of deviation in every respect.*

2 *Reasonably consistent grading is necessary for aggregate supplied under any one contract to ensure practical control of concrete manufacture.*

3 *It is recognized that smaller deviation values than those specified in **Tables A4.1 and A4.2** may be more appropriate to particular projects. Where smaller deviations are required, values should be nominated in the works specification.*

TABLE A4.1 – General grading limits

Sieve size	Cumulative percentage passing
4.75 mm	90% to 100%
0.6 mm	15% to 80%
0.075 mm	0% to 20%

The producer of manufactured sand shall review the current 'submitted grading' and shall advise all customers whenever a grading result departs from the submitted grading by more than the deviation limits given in **Table A2** at any sieve size.

TABLE A4.2 – Grading variation limits

Sieve size	Maximum deviation, percent
9.5 mm	–
4.75 mm	± 5
2.36 mm	±10
1.18 mm	±15
0.60 mm	±15
0.30 mm	±10
0.15 mm	±5
0.075 mm	±3

Particle Shape:

If the shape of particles in manufactured sand is to be specified, the test procedures and the applicable limits shall be detailed in the supply specification.

Deleterious Fines:

Manufactured sand may be tested for the presence of unacceptable quantities of deleterious fines by either of the following two procedures.

PROCEDURE 1

When tested for Methylene Blue Value (MBV) by the procedure of the International Slurry Seal Association (ISSA) Bulletin 145, the multiple of the MBV and the passing 75 micron value of any sample shall not exceed 150.

Note 1: *The effect of fines on the mix properties of concrete depends on the quantity of fines present in the aggregate grading, and the cationic exchange capacity of the fines.*

Note 2: *Manufactured sands with higher measured activities have been used successfully but generally in low addition rates. Sands with multiples up to 200 may be used if mix design data exists which demonstrates acceptable concrete performance. Sands with multiples over 200 are unlikely to produce acceptable concrete.*

PROCEDURE 2

The Sand Equivalent of a manufactured sand, when determined in accordance with AS 1289.3.7.1 shall be equal to or greater than 60.

Note 1: *The Sand Equivalent test is known to be affected by high levels of sericite. When present, sericite may lower the value of the Sand Equivalent without significantly affecting concrete mix properties or concrete performance. Where mineralogical data indicates the presence of sericite in otherwise acceptable manufactured sands, it may be preferable to use Procedure 1 for the assessment of fines.*

Note 2: *Where the Sand Equivalent is less than 60, it may still be possible to use the manufactured sand in low blend ratios if the sand is blended with a clean natural sand. In this case, it would be appropriate to apply the specification limit of 60 to the total fine aggregate blend rather than to the manufactured sand component. However, the concrete manufacturing process must be capable of accurate and consistent blending if the specification is applied to the fine aggregate blend rather than the individual components.*

Durability

General

Aggregate durability limits are given in PROCEDURE 3 or PROCEDURE 4 and ideally only one procedure should be used to avoid conflicting interpretations. Any newly proposed manufactured sand shall be tested for both properties in order to determine which procedure is most relevant for the ongoing test plan and specification.(see Note 5) Unlike the specification for coarse aggregates in AS 2758.1, manufactured sands have been specified to a single limit for all concrete exposure classifications.

NOTES:

1 *Aggregates conforming to the requirements of this Clause are expected to have sufficient durability to withstand the conditions of service of the concrete member for an estimated design life of 40 to 60 years. More stringent requirements than those specified would be required for a design life exceeding 60 years.*

2 *Aggregate durability characteristics should not be taken as a direct predictor of the mechanical and physical properties of the concrete. The true impact of the aggregate on concrete properties can only be evaluated effectively in concrete mix trials and from concrete performance records.*

3 *Classification U in Appendix A represents an exposure environment not specified in Tables A1 and A2 but for which a degree of severity of exposure should be assessed and appropriate durability limits provided in the works specification.*

4 *Manufactured sand may influence the abrasion and skid resistance of concrete. Additional properties may need to be specified in the works specification where abrasion and skid resistance of the finished concrete are important.*

5 *The method of durability assessment would normally be specified in the supply specification and should be chosen on the basis that it has been shown by experience to be appropriate for the rock sources to be used. In some cases experience may show that the pass criteria needs to be adjusted for a particular rock source or the end use intended. Regional knowledge based on the experience of local road and engineering authorities and the experience local suppliers will also assist in determining the most appropriate assessment procedure.*

6 *Unlike coarse aggregates, there is currently no data in Australia for selecting a test procedure for fine aggregates that will assess particle strength or the resistance of manufactured sand particles to abrasion. Where this property is of significance to the performance of concrete, additional procedures may need to be specified in works specifications. Currently, work is being undertaken to determine the appropriate method to assess abrasion resistance (physical durability) of manufactured sand.*

PROCEDURE 3

The sodium sulphate loss for manufactured sand when assessed in accordance with AS 1141.24 shall not exceed a weighted total loss of 6% for all concrete exposure classifications.

PROCEDURE 4

The Degradation Factor (Fines) for manufactured sand, when assessed in accordance with AS 1141.25.3 shall not be less than 60 for all concrete exposure classifications. (Drafting Note: In the revision of AS 2758.1 an entry for fine aggregate needs to be made in the table listing Degradation Factor.)

Alkali-Reactive Materials

General

Fine aggregate combinations intended for use in concrete that will be subjected to frequent wetting, extended exposure to humid atmosphere, or contact with moist ground, shall not react with alkalis in the concrete to an extent that may result in excessive expansion.

Requirements

The producer of manufactured sand shall provide appropriate documentation to the concrete producer to allow assessment of the potential reactivity of the aggregate.

NOTE: Guidance on assessment and mix design is given in SAA HB79.

Impurities

Soluble salts

NOTE: Excessive quantities of some soluble salts may cause efflorescence on the concrete, corrosion of the reinforcing steel or disintegration of the mass of the concrete. Permissible levels of soluble salts are generally expressed as the proportion of the relevant ion present in the concrete by mass of concrete or by mass of Portland cement.

Chlorides *The chloride ion content of manufactured sand and determined quantitatively in accordance with AS 1012.20 and reported. (See Note).*

NOTE: Water soluble chlorides in aggregates are more relevant to the corrosion of the reinforcement. Work is currently being undertaken to establish a water soluble chloride test for inclusion in Australian Standards.

Sulphates *The sulphate ion content of manufactured sand shall be determined quantitatively in accordance with AS 1012.20 and reported.*

Other salts Manufactured sands which contain other strongly ionized salts, such as nitrates, shall not be used unless it can be shown that they do not adversely affect concrete durability. Restrictions on the presence of these salts may be specified in the works specification.