Comparison of Gyratory & Marshall Asphalt Design Methods for New Zealand Pavement Mixes

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Executive Summary

Introduction

During the past three decades, traffic loadings and speeds have increased dramatically in New Zealand, but the New Zealand asphalt mix design procedure has not changed much in that time. New and innovative mix designs and materials are being produced, and road authorities, including Transit New Zealand, are adopting performance-related specifications and implementing performance contracts for road maintenance and construction. In addition, road user expectations have risen. To meet these challenges, a better understanding of the behaviour of the asphalt mixes used on New Zealand pavements, and their integration with pavement designs and specifications are necessary.

APRG18 performance-related mix design procedure, developed in Australia, could be useful in achieving the above goals, but as there can be significant differences between Australian and New Zealand materials, conditions and specifications, APRG 18 could not be applied to New Zealand without validation. Thus, research was carried out in 2002 to test the APRG18 procedure using local materials.

As part of the research described in this report, the historical development of the traditional Marshall and the modern gyratory compaction-based, performance-related asphalt mix design procedures was reviewed and compared.

Asphalt mixes sourced from a range of asphalt manufacturers located around New Zealand were subjected to a comprehensive laboratory testing regime, to determine their volumetric and performance-related properties such as modulus.

Asphalt test specimens were created using Marshall and gyratory compaction procedures, based on existing mix designs. They were tested using the Marshall apparatus and the MATerials Testing Apparatus (MATTA). As most asphalt mixes currently used in New Zealand pavements are designed using the Marshall-based procedure, and the goal was to compare the results of the APRG18 performance-related method with the Marshall method, Marshall mix designs were used as the control specimens for experimental purposes.

Testing Marshall and Gyratory Specimens

As volumetric properties are the most important part of the asphalt mix design procedure, their determination is the first stage in carrying out performance-related mix design procedures. Examples of such procedures, based on gyratory compaction, are the AUSTROADS APRG18 and Superpave Mix Design procedures. Volumetric parameters examined included air voids, voids in the mineral aggregate (VMA), voids filled with bitumen (VFB), and total and effective bitumen content, at different compaction levels.

Bitumen Contents

Statistical analysis showed that the correlation between total bitumen content and Marshall specimens was the highest of the data sets considered. This confirms that the Marshall mix design procedure is focused solely on determining bitumen content.

In comparison, the correlation between total bitumen content and modulus of specimens compacted by the gyratory compactor is lower because the gyratory compaction procedure is intended to consider other factors, not just bitumen content. As the mixes tested were all designed using Marshall procedure, it is logical that the Marshall specimens had the highest correlation.

Stiffness Moduli

Stiffness moduli of the Marshall specimens are consistently greater than moduli of the same mixes compacted in the gyratory compactor. The mixes were designed using the Marshall procedure so thus achieve a stiffer specimen when compacted by Marshall compaction apparatus. These mixes are designed to suit the compaction type and effort used in the procedure. In comparison, the same mixes if compacted differently (as in the gyratory compactor which more closely simulates field compaction) produce specimens with moduli that are closer to those achieved by the mix in the field. However, densities of specimens created in the Servopac are greater than densities of Marshall specimens, so density alone cannot be used as an indicator of asphalt stiffness.

Refusal Density

Performance-related mix design procedures such as APRG18 attempt to ensure that adequate rutting resistance is achieved, by compacting the design mix in the gyratory compactor for 350 cycles to refusal density. This is reached near or at the maximum compacted density of the mix. The APRG18 refusal density requirement of 2.5% voids at 350 gyratory compaction cycles is too severe for mixes used in New Zealand, and a more realistic refusal voids limit would be 2% at 250 gyratory cycles.

Recommendations

Adopting AUSTROADS APRG18 procedure

The Marshall mix design procedure is inadequate for the needs of performance-related specifications, so the AUSTROADS APRG18 asphalt mix design procedure, based on gyratory compaction of test specimens, should be adopted in New Zealand.

New Zealand Supplement to AUSTROADS Pavement Design Guide

As an interim step, the New Zealand Supplement to the AUSTROADS *Guide to the Structural Design of Pavements* should be modified to incorporate the results of this research, namely that the range of stiffness moduli for typical dense-graded asphalt mixes, used on New Zealand roads, is 1400 MPa to 3300 MPa.

The values provided in this report are relevant only to the specific mixes tested for this research. Every asphalt mix should be tested to determine its specific properties.

New Zealand Supplement to APRG18

A New Zealand Supplement to APRG18 should be drafted by a joint roading industry–Transit working party to assist with the acceptance and implementation of APRG18.

Comparison of Marshall and APRG18 procedures

The performance of asphalt mixes that have been designed based on tests using the two procedures (Marshall and APRG18) should be compared using both in-service field trials and test sections at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF).

Acceptance criteria based on statistical analysis

The statistical acceptance criteria for asphalt mixes designed, manufactured and constructed under performance-related specifications must include statistical analysis. The potential application to New Zealand asphalt mixes of using the Log_{10} (GPa) concept for quantifying the standard deviation of asphalt stiffness moduli should be investigated further.

Safety

One of the major disadvantages of the Marshall compaction hammer is that it is an inherently noisy and unsafe operation, causing numerous injuries to operators, whereas modern gyratory compactors are substantially safer and quieter to operate. This factor must be considered, given the modern pro-active attitude to worker safety.

Abstract

The historical development of the traditional Marshall and the modern gyratory-based, performance-related asphalt mix design procedures is described. New Zealand is progressively adopting performance-related specifications and implementing performance contracts for road maintenance and construction. Thus, in 2002, asphalt mixes sourced from a range of asphalt manufacturers located around New Zealand were subjected to a comprehensive laboratory testing regime, to determine their volumetric- and performance-related properties, such as modulus. Two sets of asphalt specimens were created, using either Marshall or gyratory compaction procedures, based on existing mix designs. They were then tested by AUSTROADS APRG18 procedures and equipment to provide performance-related data.

The Marshall mix design procedure is inadequate for the needs of performance-related specifications, so the AUSTROADS APRG18 asphalt mix design procedure, based on gyratory compaction of test specimens, should be adopted in New Zealand. As an interim step, the New Zealand Supplement to the AUSTROADS *Guide to the Structural Design of Pavements* should be modified to incorporate the results of this research, namely that the range of stiffness moduli for typical dense-graded asphalt mixes used on New Zealand roads is 1400 MPa to 3300 MPa.

1. Introduction

During the past three decades, traffic loadings and speeds have increased dramatically in New Zealand, but the New Zealand asphalt mix design procedure has not changed much in that time. New and innovative mix designs and materials are being produced, and road authorities, including Transit New Zealand, are adopting performance-related specifications and implementing performance contracts for road maintenance and construction. In addition, road user expectations have risen. To meet these challenges, a better understanding of the behaviour of the asphalt mixes used on New Zealand pavements, and their integration with pavement designs and specifications are necessary.

APRG18 performance-related mix design procedure, developed in Australia, could be useful in achieving the above goals, but as there can be significant differences between Australian and New Zealand materials, conditions and specifications, APRG18 could not be applied to New Zealand without validation. Thus, research was carried out in 2002 to test the APRG18 procedure using local materials.

The trend internationally is to adopt asphalt mix design tools which are directly related to the behaviour and performance of the product in-service on the road. In May 1997, AUSTROADS and the Australian Asphalt Pavement Association (AAPA) jointly issued APRG18 *Selection and Design of Asphalt Mixes: Provisional Guide.* This describes new performance-related asphalt mix design procedures using affordable, accurate and easy-to-use Australian-designed and -manufactured test equipment. Applying the new performance-related mix design procedure should overcome the deficiencies of the existing empirically based Marshall mix design procedure. The latter is acknowledged worldwide to be not directly related to road conditions, and it does not reliably predict pavement mix performance under traffic.

The AUSTROADS *Guide for the Structural Design of Pavements* (2001) widely used by New Zealand pavement designers, contains presumptive stiffness moduli values for stiffness characterisation of asphalt for the six Australian states only, and not for New Zealand. New Zealand pavement designers need such data to apply to New Zealand materials and mixes for use in asphalt pavement design. Before 2002, no such data were available in the public domain.

The ultimate aim of this research is to reduce life cycle costs of pavements by improving the performance of asphalt-surface pavements, and by providing publicly available data. Then pavement and asphalt mix designers will gain confidence in adopting performance-related asphalt mix design procedures in New Zealand, in all contracts, as well as in performance-specified contracts.

The objective of this research was to compare the volumetric and stiffness properties of asphalt specimens created in the laboratory, obtained by using the two procedures of gyratory compaction and Marshall compaction.

2. Background and Literature Review

2.1 Background

Ever since bitumen and aggregate were first mixed together, over a century ago, to create a bitumen-bound aggregate, there has been a constant search for a laboratory-based mix design procedure that adequately quantifies the properties of the mixture. More recently, the development of mix design procedures that can also more accurately predict the performance of the mixture in service has increased, because performance specifications have been progressively introduced in New Zealand, Australia and internationally.

Mix properties are most affected by volume and not by mass. However production and testing of asphalt is by mass of the constituents. Asphalt mix design and analysis focuses on five properties of the asphalt mixture:

1. mix density,
2. air voids,
3. voids in the mineral aggregate (VMA),
4. voids filled with binder (VFB), and
5. binder content.

It is significant that all these are volumetric properties. The objective of mixture design is (Asphalt Institute Manual Series No. 2, 1997):

...to determine... *a cost-effective blend and gradation of aggregates and asphalt* that yields a mix having:

1. *Sufficient asphalt*[1] to ensure a durable pavement.
2. *Sufficient mix stability* to satisfy the demands of traffic without distortion or displacement.
3. *Sufficient voids* in the total compacted mix to allow for a slight amount of additional compaction under traffic loading without flushing, bleeding, and loss of stability.
4. A *maximum void content* to limit the permeability of harmful air and moisture into the mix.
5. *Sufficient workability* to permit efficient placement of the mix without segregation and without sacrificing stability and performance.
6. For surface mixes, *proper aggregate texture and hardness* to provide sufficient skid resistance in unfavourable weather conditions.

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[1] In North America, the term 'asphalt' is used to describe the liquid material that is called 'bitumen' in New Zealand and Australia.

One of the most widely used mix design procedures is the Marshall method of mix design, which was developed over 60 years ago by Bruce Marshall of the Mississippi Highway Department, USA. The Marshall method rapidly became widely used around the world during and after World War II because the US Army Corps of Engineers adopted and improved the Marshall procedure (Leahy & McGennis 1999).

The Marshall procedure was introduced into New Zealand about 1970. The Marshall design and testing procedure, which is described in more detail in Section 2.1 of this report, involves compacting an asphalt sample in a mould using a hand-held 4.5 kg hammer dropped vertically onto the material. While containing the sample being compacted, the mould walls and base respectively are kept vertical and horizontal.

At about the same time as the Marshall procedure was being developed, other engineers were examining asphalt mixes compacted in the field. Of special concern was the particle orientation of the aggregates in the mix while it was being compacted. Specimens prepared by a gyratory compaction process had stress-strain properties that were more representative of those of the actual flexible pavement structure, than specimens produced by impact compaction devices such as the Marshall hammer (Leahy & McGennis 1999).

As a result, gyratory compaction was first developed in Texas in the 1940s, and was further enhanced by the US Army Corp of Engineers to create the gyratory kneading compactor. This device was a result of experience with asphalt airport runways, which showed that wheelpath densities under heavy aircraft were not suitably simulated by Marshall impact compaction (Leahy & McGennis 1999). This device became known as the Gyratory Test Machine (GTM®), and is still in use around the world (Figure 2.1). The concept, operation and mix properties measured by the GTM® are documented in MacRae (2001). Further background is provided in Harman et al. (2002) who comprehensively documented the development of gyratory compaction around the world since 1930.

New Zealand's Ministry of Works Central Laboratories acquired and used a GTM® in the 1970s, which was then transferred to the University of Canterbury, Christchurch, in 1989 where it was refurbished for research and testing of aggregates and asphalt mixes. The components of the GTM® are heavy and extremely robust, which means that even very stiff mixes do not affect its accuracy and performance. However, the disadvantage is that the GTM® components are difficult to repair when they fail. Eventually, the difficulty and cost of repairing the New Zealand GTM® became too great and it was decommissioned.

By the 1970s, despite the development of alternative mix design methods and testing equipment, the Marshall method was the most common asphalt mix design procedure in North America, Australia and New Zealand. However, by 1984, rutting problems in asphalt were widespread throughout the US, and were attributed to a number of causes, including the poor correlation between Marshall Stability and in-situ stability of the asphalt under trafficking.

Even though fatigue cracking is a primary cause of pavement failure in the US and New Zealand, rutting is the most visible and more dangerous for road users, because it allows surface ponding of water which reduces tyre–road friction and allows water to enter the pavement. As a result, mix design standards were reviewed.

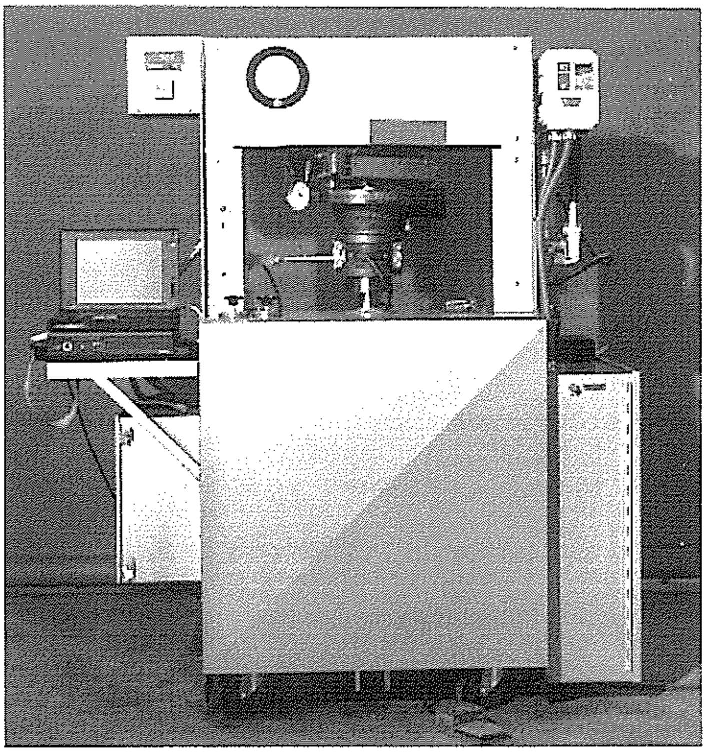


Figure 2.1 Gyratory testing machine (GTM) (from MacRae 2001).

A comprehensive review of international published literature by Abd El Halim et al. (1993) emphasised that all research and experience to date had confirmed that proper compaction of the asphalt is the single most significant factor for achieving satisfactory service life of asphalt-surfaced pavements. So it is important that field compaction is reasonably simulated in the laboratory-compacted specimens used in mix design. The deficiencies of empirical mix design methods, such as the Marshall, are summarised by Haydon (1994):

> *The methods are restricted by the small aggregate sizes used and their compaction techniques, which do not simulate the compaction regime in situ. They do not measure mechanical properties of the mixtures, so cannot be used for performance specifications or design procedures.*

Differences in aggregate particle orientation between field and laboratory-prepared specimens, and between Marshall and gyratory-compacted specimens, were highlighted by work done by Karium & Oliver (1995). The cylindrical samples were cut orthogonally to the circular cross-section (Figure 2.2) so the particle orientation caused by the different compaction techniques could be visually assessed.

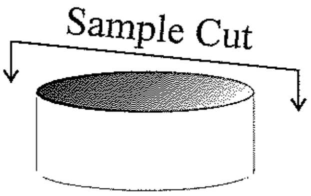


Figure 2.2 Vertical cut through asphalt mix samples.

Karium & Oliver (1995) concluded that:

- Marshall compaction of samples differed from field compaction in terms of particle orientation, and
- Gyratory compaction resulted in particle orientation that was more closely aligned to that resulting from field compaction, than from Marshall compaction.

Tashman et al. (2002) used X-ray computed tomography (CT) and image analysis techniques to examine the distribution of air voids in gyratory-compacted and field core specimens. They found that the vertical distributions of voids within the specimens were the same. In both cases, air voids are non-uniformly distributed, and are two to three times greater in the top of the specimen, compared with the middle of the specimen.

The development of a new mix design method in the US began with the asphalt–aggregate mixture analysis system (AAMAS). This was the forerunner for the Superpave mix design procedure that was an outcome of the Strategic Highway Research Program (SHRP) (Huber 1999). SHRP cost US$150 million over 5 years during 1988-1993, of which US$50 million was allocated to asphalt research. The objectives of SHRP's asphalt research programme were to extend the life or reduce the life cycle costs of asphalt pavements, to reduce maintenance costs, and to minimise premature failures. The Superpave asphalt mix design procedure is explained in more detail in Section 2.3 of this report.

In 1988, the Australian asphalt industry, through AAPA (Australian Asphalt Pavement Association), began an A$750,000 research and development programme to enhance the quality and performance of asphalt mixes. A wide range of laboratory compaction equipment available around the world was evaluated, and gyratory compaction was adopted as the future industry standard in Australia (Bethune 1992). A reliable, automated, rapid and cost-effective gyratory compaction device, the Gyropac, was selected because it was designed to be relatively inexpensive and portable. A second generation version of the Gyropac, called the Servopac, was designed to meet the standards of Superpave gyratory compactors.

Another product of the Australian programme was the MATerials Testing Apparatus (MATTA), based on the Nottingham Asphalt Tester (from the UK). MATTA was designed to measure the fundamental properties of asphalt (stiffness modulus, deformation resistance, and fatigue). The ultimate outcome of the programme was the Australian performance-related asphalt mix design procedure incorporating the above devices, and known as APRG18 (AUSTROADS 1998). The equipment and mix design procedure are described in Section 2.4 of this report.

Cui (1998) conducted an initial evaluation of the appropriateness of performance-related tests for New Zealand asphalt mixes by comparing the Marshall, APRG18 and Superpave mix design methods, and subjecting a limited number of New Zealand-sourced materials to laboratory indirect-tensile testing using standard Marshall and gyratory compaction procedures. He recommended that performance-related mix design procedures should be introduced into New Zealand, but that further testing of both local materials and existing mix designs is necessary to establish adequate criteria for performance properties that suit local material, environmental and traffic conditions.

2.2 Marshall Mix Design and Testing

The Marshall mix design procedure and testing are described in detail in the Asphalt Institute MS-2 (1997), but a brief overview is provided here. For compacting specimens, the Marshall hammer (Figure 2.3) is used. It weighs 4.5 kg and its drop height is 457 mm. The hammer comprises a flat circular tamping face with a diameter of 98 mm. Each side of the sample receives either 50 blows or 75 blows. Generally 50 blows are used for lighter loading conditions and 75 blows are used to simulate heavier load or traffic applications.

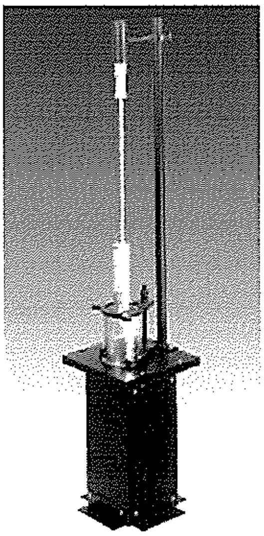


Figure 2.3 Marshall hammer.

The two main types of Marshall hammer are mechanical and manual. The density obtained with a mechanical hammer and that obtained with a manual hammer can be substantially different. If a mechanical hammer is used, it should be calibrated to give the same density as that which would be obtained with a manual hammer, but this is rarely done in practice (Scott 1999).

The Marshall Stability (Compression) test (Figure 2.4) is used as one parameter in determining the optimum bitumen content and is a rough measure of the mixture's stability under loads. The Marshall Stability test is conducted at 60°C because this is considered the maximum temperature to which most asphalt pavements will be subjected to during their life.

Marshall Flow, also measured while carrying out the Marshall Stability test, is a measure of the vertical deformation of an asphalt core specimen from the time that a load is applied until the sample fails.

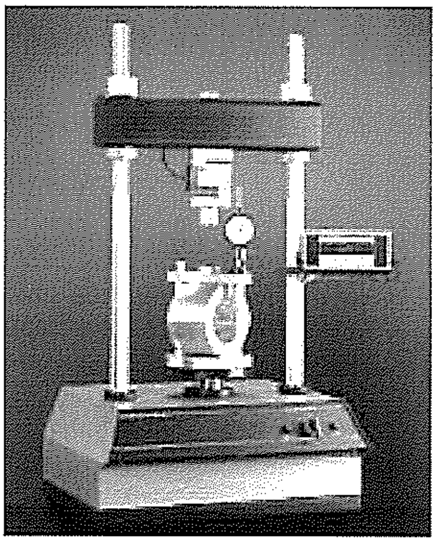


Figure 2.4 Load frame for Marshall Stability (Compression) test.

2.3 Superpave Mix Design and Testing

The Superpave mix design procedure involves (Asphalt Institute SP-2, 2001):

- Selection of component materials;
- Selection of a design aggregate structure;
- Selection of a design binder content;
- Evaluation of the moisture sensitivity of the asphalt design mix

Several trial combinations of aggregates are evaluated to determine an aggregate structure that has appropriate volumetric and densification properties. Once several trial gradations are determined, specimens are mixed and compacted using Superpave gyratory compactors. A number of gyratory compactors satisfy the Superpave standard, but the Servopac is the predominant make of Superpave gyratory compactor used in Australia and New Zealand.

Volumetric and densification properties of the compacted mixture specimens are then determined and the trial gradations are compared with mixture criteria. Volumetric properties consist of determining the percentage of total air voids in a compacted specimen, voids in the mineral aggregate (VMA), and voids in the mineral aggregate filled with binder (VFB).

Volumetric properties can be determined from the densification curves. The most important property is air voids in the compacted specimen, and is fixed at 4% for all mixtures and traffic levels. The VMA criterion changes as the nominal maximum particle size of the mixture changes, and the VFB criterion changes as a function of traffic, in that increasing traffic requires a lower VFB. Low volume roads require higher VFB to increase the durability of the asphalt pavement. Any trial gradation that meets all compacted mixture criteria may be selected as the design aggregate structure.

The Superpave Gyratory Compactor (Servopac) compacts asphalt mixtures in a mould through a combination of constant vertical pressure (600 kPa) and a constant angle of gyration (1.25°). The gyration angle and vertical pressure produce a kneading action while compacting the asphalt specimen, as shown in Figure 2.5. Specimen height is measured during compaction, so the rate of densification can be determined.

Superpave mix design provides data about the compactibility of a mixture. The level of compactive effort is tied to projected traffic levels. A short-term aging procedure is also applied to all test specimens. In comparison, the conventional Marshall mix design procedure determines only optimum binder content for a set particle size distribution of aggregate.

The number of gyrations ($N_{variable}$) selected for each mix design is based on traffic. All the design volumetric properties are determined on compacted mixture specimens at N_{design}. The number of gyrations increases as traffic increases. Therefore, an Auckland motorway would have a higher number of required gyrations than would a rural highway. Increasing the required number of gyrations for increased traffic results in changing the asphalt mixture properties and design binder contents for a given mixture.

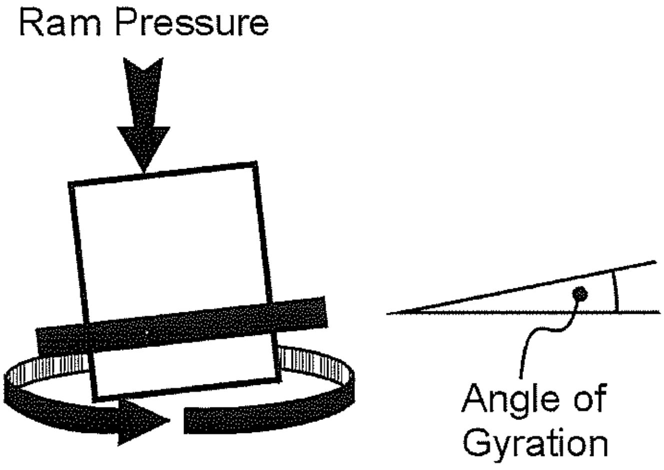


Figure 2.5 Concept underpinning gyratory compaction procedure.

After the selection of the design aggregate structure is completed, the design binder content for the mixture is determined. This involves mixing and compacting design aggregate structure specimens at several asphalt binder contents. Generally four binder contents are used, centered around the estimated design binder content determined from the design aggregate structure phase of testing.

Mixture properties are determined for each binder content, and graphs are generated showing the change in mixture properties with changes in the binder content of the mixture. The design binder content is selected from this data, corresponding to 4% air voids at N_{design}.

All other mixture properties are determined at this binder content. If the mixture meets all criteria, then the design binder content is selected. The combination of design aggregate structure and design binder content then becomes the design asphalt mixture.

The final step in the Superpave mix design system is an evaluation of the moisture sensitivity of the design asphalt mixture, which is done on the design aggregate blend at the design binder content. Specimens for this test are compacted to approximately 7% air voids. One subset, consisting of three specimens, is considered as the control set. The other subset of three specimens is conditioned in an oven.

The conditioned specimens are subjected to partial vacuum saturation followed by an optional freeze cycle, followed by a 24-hour thaw cycle at 60°C. All specimens are tested to determine their indirect tensile strengths. The moisture sensitivity is a ratio of the average tensile strengths of the conditioned subset divided by the average tensile strengths of the control subset. The Superpave criterion for tensile strength ratio is a minimum of 80% (Asphalt Institute SP-2, 2001).

2.4 APRG18 Asphalt Mix Design Procedure

Details of this mix design procedure are in APRG18 (AUSTROADS 1998), and only a summary of the procedure is provided here.

The APRG18 mix design procedure has three levels, as illustrated in Figure 2.6.

During **Level 1** testing, a composition of desirable volumetric proportions is identified by selecting a target grading and materials combination, and then preparing a series of mixes at binder contents that span the expected binder range. Because determining mixture volumetric properties is a very, if not the most, important part of the mix design procedure, determination of volumetric properties is the first stage in both the APRG18 and Superpave Mix Design procedures.

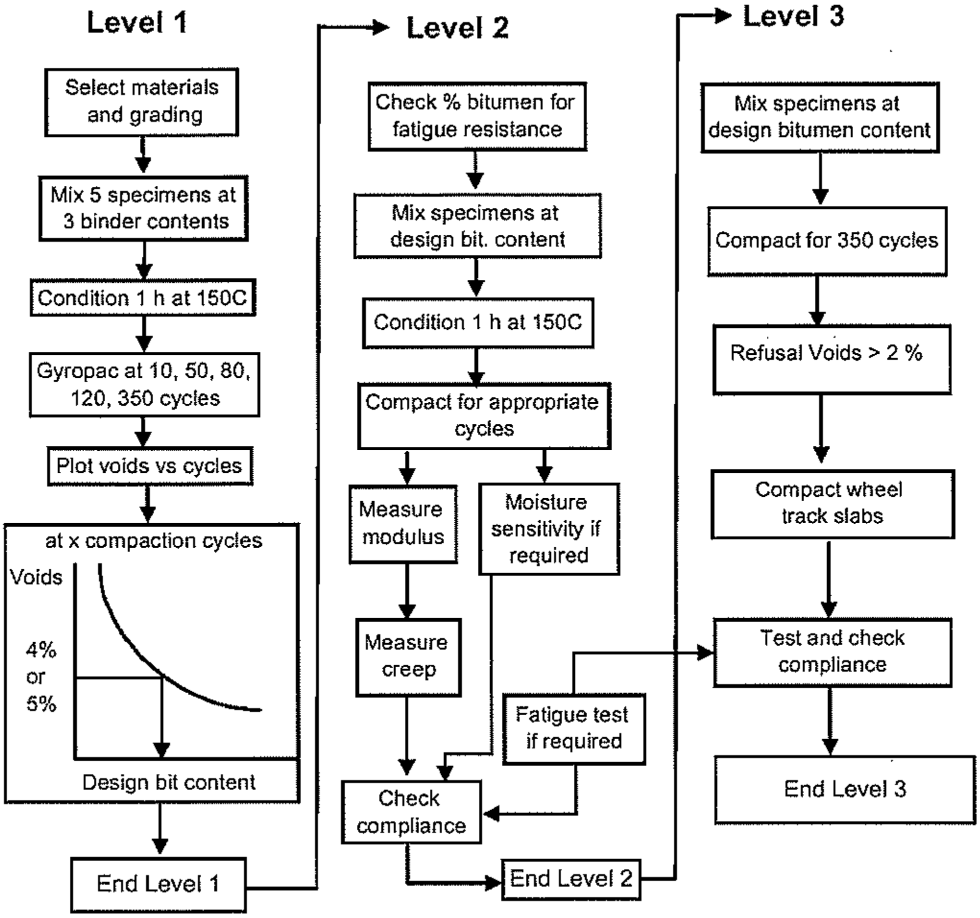


Figure 2.6 APRG18 asphalt mix design procedure.

Each mixture is conditioned in an oven before compaction, to simulate the binder absorption and hardening which occurs during manufacture and placement of a mix, and the first year or two of field service. At each binder content, five samples of mix are compacted in a gyratory compactor, each sample being compacted for a different number of cycles. Compacted samples are tested for density and the results plotted as air void content (%) versus number of gyratory cycles (Figure 2.7).

For each compaction level (different compaction levels are specified for different classes of mix), VMA and other volumetric properties are plotted against binder content. The design binder content is the binder content at which the compacted mix has a specified value of air voids. The required air void content depends on the class of mix and the traffic level. For example, referring to Figure 2.7, for the heaviest traffic condition (corresponding to 120 gyratory compaction cycles), the target design air voids is 4%. The design bitumen content would be 'b'. In comparison, if the intended use was in a lightly trafficked situation (corresponding to 50 gyratory compaction cycles) and a design air voids of 4%, the design binder content would be 'b +1.0%'.

The determination of volumetric properties during Level 1 testing is the most important step. There is some merit in checking refusal density at this level, if the mix is not to be subjected to Level 3. Gathering information on volumetric properties at a range of compaction levels and binder contents permits more than one mix type to be designed from the one set of laboratory volumetric data.

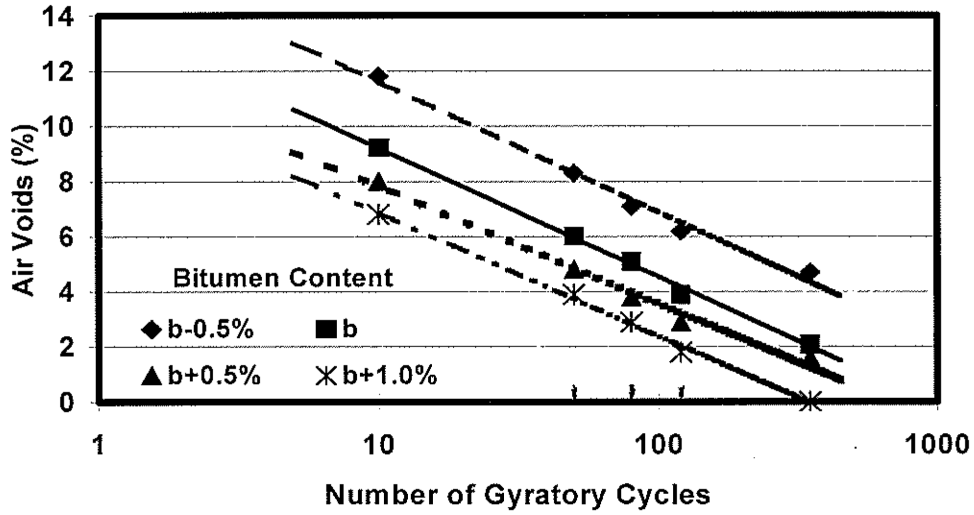


Figure 2.7 Typical compaction lines for determining binder content for a mix.

Figure 2.8 Gyropac compactor.

Two types of gyratory compactors are widely used in New Zealand and Australia. The Gyropac (Figure 2.8) has two fixed gyration angles (which can be set either to 2° for 100 mm moulds or to 3° for 150 mm moulds), and was designed to be lighter and easier to transport. On the Servopac (Figure 2.9) however, the vertical load, gyration angle and other parameters can be altered. Both the Gyropac and Servopac are capable of producing homogeneous asphalt samples, either 100 mm or 150 mm in diameter. The Gyropac is designed to produce 100 mm-diameter specimens that are 65 mm thick, and 150 mm-diameter specimens that are 85 mm thick.

To be adopted as a mix design tool, all Gyropacs must have similar compaction performance, so a procedure for checking the performance of Gyropacs has been developed and trialed in Australasia (Oliver 2000b).

The components of Servopac were designed to be stiffer and more resistant to deformation under heavier loads, so the Servopac is a heavier piece of equipment. Samples were compacted in the Servopac for this research because it collects additional data, and its characteristics make it more appropriate for research use.

For medium trafficked roads where the traffic is slow moving, or heavily trafficked roads, the mechanical properties of candidate mixes must be measured to compare with acceptance criteria.

Level 2 of the mix design procedure involves measuring resilient modulus, which is discussed in Section 2.5 of this report; dynamic creep and moisture sensitivity testing is optional. A check on binder film thickness (index) is included to ensure that sufficient binder is present to provide acceptable fatigue resistance and durability. Binder film is a parameter that dictates minimum binder content.

Figure 2.9 Servopac compactor.

Level 3 testing is performed on mixes to be used in high stress conditions (i.e. heavy loads, slow-moving loads or extremely high numbers of load repetitions) where rutting is more likely to occur, or where a high degree of confidence in the rutting performance of the mix is required. This testing is aimed to ensure that adequate rutting resistance is achieved. It involves compacting the design mix in the gyratory compactor for 350 cycles to refusal density, which is near or at the maximum compacted density of the mix. APRG18 (1998) requires that:

(a) the decrease in voids between 120 and 350 cycles of gyratory compaction be not more than 2% (i.e. if the voids at 120 cycles is 4.5%, then the voids at 350 cycles should be no less than 2.5%), and has:

(b) a minimum void content of 2.5% after 350 cycles.

Oliver (2000a) recommended that item (a) should be replaced with a criterion based on initial voids, in order to identify mixes likely to have low rut resistance, but that item (b) be retained. In later work, Oliver (2002) found that the refusal density requirement of 2.5% at 350 cycles is too severe for Victorian (Australia) mixes, and recommended that the refusal voids limit be relaxed to a minimum of 2% voids at 250 cycles. (This change has since been incorporated into the 2002 version of APRG18.)

Oliver (2002) also recommended that APRG18 be revised to have a requirement for an initial minimum void content of 10% at 10 gyratory compaction cycles, to ensure that a mix contains a strong aggregate skeleton (and, thus, good resistance to deformation). This has also been incorporated into the 2002 version of APRG18.

2.5 Resilient Modulus

Resilient modulus (M_R) of a mix is applied stress (σ) divided by resilient strains (ε_r). In practical terms, resilient modulus is calculated using the following equation (AS 2891.13.1- 1995):

$$M_R = \frac{P\ (\nu + 0.27)}{Ht} \qquad \text{Equation 1}$$

where: P is repeated load (N)
t is mean height (mm) of specimen
ν is Poisson's ratio
H is recovered horizontal deformation (mm) of specimen after load application

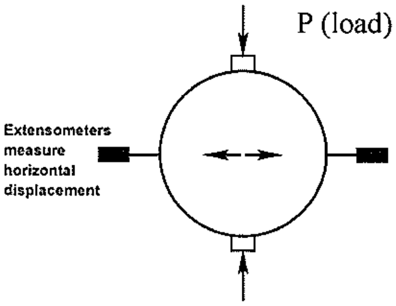
The repeated load is applied vertically to the specimen which has been placed between two loading bars. As the load compresses the specimen, the horizontal deformation of the specimen is measured, as shown in Figure 2.10.

The horizontal tensile stress (σ_t) in the specimen is calculated from (AS 2891.13.1-1995):

$$\sigma_t = \frac{2P}{\pi t D} \qquad \text{Equation 2}$$

where: σ_t is tensile strength (kPa)
D is specimen diameter (mm)

Bitumen (and thus mix) stiffness depends on both the loading time and the temperature, so both the total cycle time and the rise time (the time taken to reach the maximum applied vertical load) must also be specified for each test. Loading time correlates with the speed of vehicles that will be passing over the mix in place.



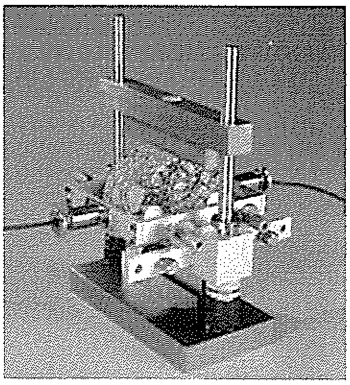


Figure 2.10 Indirect tensile modulus test.

The MATerials Testing Apparatus (MATTA), shown in Figure 2.11, was used to measure resilient modulus in this research. The MATTA is an Industrial Process Controls Ltd (IPC) UTM5P[2] model and is based on a simple reaction frame, comprising a base plate, lateral support columns and a 100 mm-diameter crosshead. The samples are positioned between the base plate and crosshead, and an electro-pneumatic actuator is used to exert dynamic compressive forces. Measurements using force and displacement transducers enable the resultant stress and strain in the sample to be determined (de Vos & Feeley 1998). The apparatus is enclosed in a temperature-controlled cabinet, and all testing is done in the cabinet.

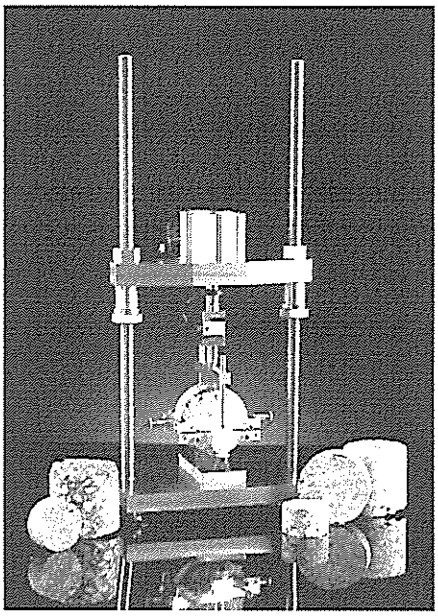


Figure 2.11 Materials Testing Apparatus (MATTA).

The machine is controlled by a control and data acquisition system (CDAS), a compact microprocessor-based unit which provides all the electrical power, control signals, signal conditioning, data acquisition and communication facilities necessary to operate the MATTA. For reliability and accuracy of data acquisition and control, all time-critical parameters are controlled directly by the MATTA CDAS unit. However, overall control of the tests is by a personal computer, which communicates with the MATTA CDAS. Graphical displays enable ready monitoring of transducer outputs and adjustment of zero positions.

The standard rise time is 0.04 ± 0.005 seconds (40 ± 5 milliseconds) (AS 2891.13.1-1995). The peak load is the load required to deform the specimen within the specified recovered horizontal strain of 50 ± 20 microstrain. The testing begins with an estimated modulus as a start point for the MATTA software, which then adjusts the load as needed. Even if there is no start point, the programme calculates one, tries it out, evaluates the result to determine whether it is within specified constraints, makes an adjustment and so on. When it establishes a load that is satisfactory for the set strain and rise time, the indirect tensile test commences.

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[2] Universal Testing Machine 5P.

As asphalt is a visco-elastic material, its properties depend on the temperature at which it is tested. All the moduli tests done in this research were at 25°C.

2.6 Health and Safety

The health and safety of operators and others exposed to laboratory testing equipment is a very important issue which must be considered for these procedures. Both types of Marshall compaction, manual and mechanical, are:

- noisy, and require:
- handling of hot pre-heated hammers (90°C to 140°C),
- handling of the hot moulds,
- manual removal of specimens from the moulds.

In addition, the manual hammer is:

- prone to crushing fingers while using the sliding hammer, and
- physically demanding while operating the sliding hammer.

The gyratory compaction equipment is fully automated and provides an air-driven jack on the same table to make removal of specimens easier. Gyratory compactors have fewer individual parts to be assembled to form the asphalt specimens. In order to sustain the high axial loads and gyratory attitude of the sample while it is being formed, the Servopac mould is one piece, robust and therefore heavy, but considerably less physical input is required to make asphalt specimens in it. Also it enables safe, correct lifting procedure to be used for the heavier moulds.

The Marshall compaction hammer is an inherently unsafe operation and causes injuries to operators, whereas the gyratory compactors are substantially safer and quieter to operate.

3. Laboratory Testing and Results

All the laboratory tests described in this section were conducted in the Fulton Hogan Laboratory in Nelson.

3.1 Selection of Mixes

After all the asphalt plants in New Zealand had been identified, the following criteria were applied for selecting the mixes to be used in the testing:

- geographic location of the plant,
- method of manufacture (continuous or batch),
- the volume of the material used,
- the mix's applications (structural asphalt pavements, wearing courses),
- traffic loadings on the asphalt mix in service,
- source and type of aggregate (alluvial or quarried), and
- expected future usage.

An Advisory Group consisting of members of the New Zealand Pavement and Bitumen Contractors' Association (BCA) was set up to act as a steering group for this project. Based on the above criteria and in consultation with the BCA Advisory Group, the nine mixes listed in Table 3.1 were selected, from a total of 17 mixes considered.

Table 3.1 Asphalt mixes selected from asphalt plants in New Zealand.

Asphalt Supplier	Nominal Maximum Particle Size (mm)	Plant Type	Aggregate Source	Location
Fulton Hogan	20	Continuous	Quarry	Dunedin
Fulton Hogan	20	Continuous	Quarry	Nelson
Fulton Hogan	20	Continuous	Quarry	Wellington
Fulton Hogan	20	Continuous	Quarry	Auckland
Higgins Contracting	20	Batch	Quarry	Palmerston North
Isaac Contracting	20	Batch	Alluvial	Canterbury
Works Infrastructure	20	Continuous	Quarry	Waikato
Works Infrastructure	15	Continuous	Quarry	Tauranga
Works Infrastructure	14	Continuous	Quarry	Auckland

From each supplier the following information and materials were obtained:

- Geographic location and source of each aggregate,
- Dry aggregates,
- Mix blend % by mass,
- % by mass of 80/100 binder,
- Inclusion / exclusion of Adhesion Agent (none used),

- Ideal dry aggregate mix grading expressed as Sieve size % passing,
- Bulk Specific Gravity of each aggregate.

3.2 Preparation of Asphalt Specimens

As the majority of asphalt mixes currently used in New Zealand are designed using the Marshall-based procedure, and as the intent of this research is to compare the results of the APRG18 performance-related method with the Marshall method, Marshall mix designs were prepared and used as the control specimens for experimental purposes.

For each of the nine mixes, six asphalt specimens were prepared using the Marshall apparatus (at 75 blows), and three asphalt specimens were prepared using the Servopac gyratory compaction (at 120 gyratory cycles). The level of compaction corresponds to the most demanding conditions that the mixes would be subjected to in service.

The volumetric properties, including air voids, voids in the mineral aggregate (VMA), and binder content, of the mix designs and specimens were determined for both Marshall and Servopac specimens as part of the comparison of the two procedures.

Moduli values for three Marshall and three Servopac specimens were measured and recorded, as per APRG18 (AUSTROADS 1998).

In addition, two asphalt specimens were tested to refusal density (350 gyratory cycles) using the Servopac gyratory compactor, and the binder film index was calculated for each mix design.

The bulk specific gravity of all aggregates was established as according to ASTM C127-88 and ASTM C128-97.

40/50 and 180/200 penetration grade bitumens were obtained and their respective penetrations (ASTM D5-97) were established to enable the blended bitumen to be accurately mixed for use in each asphalt batch. In all mixes, 90 penetration grade bitumen was used (TNZ M/1-1995).

Because of the large mass of mix required, two 9 kg blends were batched. The first batch provided the asphalt for the six Marshall specimens and the Maximum Theoretical Specific Gravity (MTSG), and was made to Asphalt Institute MS-2 (1997). The second batch provided the asphalt for the five Servopac specimens and the balance of the MTSG, and was made to AS 2891.2.2-1995.

All target masses and actual figures were recorded with an accuracy of ±0.3 g for dry aggregates larger than 7 mm, and ±0.1 g for the bitumen and the dry aggregates smaller than 7 mm.

3.2.1 Marshall Specimens

The Marshall hammer apparatus was used to form the asphalt test specimens. They were created by the compaction of the blended dry aggregates and bitumen at the prescribed temperature range of 139°C to 145°C.

A mechanically operated sliding hammer was used to compact the loose blended asphalt. Each specimen was subjected to 75 blows on each end of the specimen, which represents heavy traffic loading. The formed specimens were 64 mm high by 101.6 mm diameter.

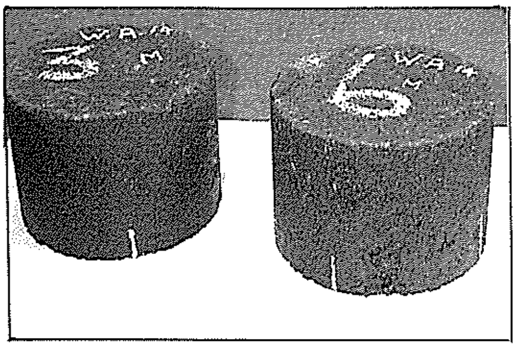
3.2.2 Servopac (Gyratory) Specimens

The IPC Servopac used in this testing meets the APRG18 requirements for a gyratory compactor (AS 2891.2.2-1995).

The loose asphalt was blended and then cured for one hour at 150°C before compaction to form the specimens.

The three specimens for testing in the MATTA were subjected to 120 cycles at 60cycles/min, at a 2° gyratory angle at 150°C. The mass of asphalt used per specimen is regulated to produce a specimen 65 mm thick with 100 mm diameter.

Figure 3.1 shows specimens 3 and 6 of one mix made in the Marshall apparatus with 75 blows per side. Air voids in specimens 3 and 6 are respectively 2.6% and 3.1%. Specimens 7 and 8, of the same mix (Figure 3.2) were made by the Servopac gyratory compactor with 120 cycles. Both specimens 7 and 8 have 1.1% air voids.



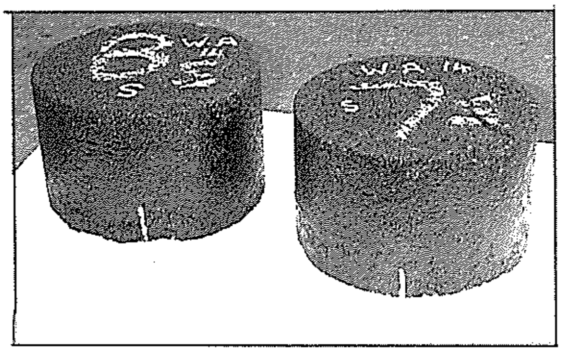


Figure 3.1 (left) Specimens 3 and 6 prepared in the Marshall apparatus.
Figure 3.2 (right) Specimens 8 and 7 prepared in a Servopac gyratory compactor.

Normally, for MATTA testing, specimens are created using a gyratory compactor (Gyropac or Servopac), but for this research, the two compaction procedures, Marshall and Servopac, were used to create specimens. Moduli of both Marshall- and Servopac-compacted specimens were determined.

3.3 Testing the Specimens

3.3.1 Volumetric Properties (Marshall and Servopac Specimens)

The Maximum Theoretical Specific Gravity (MTSG) and Bulk Specific Gravity were established for all eleven specimens from each of the nine sources, from which the following were calculated:

- air voids,
- voids in the mineral aggregate (VMA),
- voids filled with bitumen (VFB),
- film thickness (index),
- absorbed bitumen,
- effective bitumen.

3.3.2 Marshall Compaction (Stability and Flow)

The Marshall Compression test loaded the three specimens from each source to failure. The modified machine uses a calibrated load cell connected to a PC, and with appropriate software captures the resulting data to create a computer-generated Load versus Time chart. The Stiffness (Stability:Flow ratio) is calculated from the Stability and Flow results.

3.3.3 Servopac Refusal Density

The two specimens tested to Refusal Density[3] in the Servopac were subjected to 350 cycles at 60 cycles per minute and 2° gyratory angle at 150°C. To determine Refusal Density 350 gyratory compaction cycles were used because these tests were done before release of the 2002 version of APRG18. In this version the number of gyratory cycles to refusal has been reduced to 250. As the final specimen must comply with the required dimensions of 65 mm in thickness and 100 mm in diameter, additional asphalt (approximately 30 g) is required when compared with the mass used for the '120 cycle' specimen blocks.

3.4 Results

All the results of the laboratory testing are tabulated in Table 3.2. Table 3.3 contains the particle size distribution of the aggregate for all the mixes. Even though not all of the mixes tested were designed to satisfy Transit M/10 (2002) specification for Mix 20 asphalt, the gradation envelope for Mix 20 has been included but only for comparison purposes.

The binder film thickness has been calculated from effective binder content.

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[3] Refusal density – a measure of the maximum degree of packing of the aggregates in the asphalt mix that is possible without degradation of the aggregate (AUSTROADS 2002).

Table 3.2 Laboratory test results for the nine mixes.

Mix Identification No.		**1**	**2**	**3**	**4**
Maximum Particle Size	mm	20	20	20	20
Aggregate Type (A=Alluvial; Q=Quarried)		Q	Q	Q	Q
Mix Plant Type (B=Batch; C=Continuous)		C	C	C	C
Total Bitumen Content	%	5.6	5.1	5.0	5.8
Added Filler	%	6.9	7.1	6.4	9.0
Absorbed Bitumen	%	1.3	0.7	0.9	0.8
Effective Bitumen	%	4.4	4.4	4.1	5.0
Surface Area		6.62	6.72	6.14	8.82
Bitumen Film Thickness	μm	6.8	6.7	6.8	5.9
Marshall Stability	kN	18.20	15.06	16.29	16.71
Marshall Flow	mm	3.50	3.52	3.34	4.21
Maximum Specific Gravity of Mix		2.726	2.415	2.557	2.453
Bulk Specific Gravity of Mix					
Marshall @ 75 blows		2.675	2.312	2.459	2.414
Gyratory @ 120 cycles		2.712	2.364	2.510	2.446
Gyratory @ 350 cycles		2.726	2.398	2.538	2.459
Voids in the Mineral Aggregate (VMA)					
Marshall @ 75 blows	%	13.2	14.1	13.6	13.4
Gyratory @ 120 cycles	%	12.1	12.2	11.8	12.3
Gyratory @ 350 cycles	%	11.5	10.9	10.9	11.8
Air Voids					
Marshall @ 75 blows	%	1.9	4.3	3.8	1.6
Gyratory @ 120 cycles	%	0.5	2.1	1.8	0.3
Gyratory @ 350 cycles	%	0.0	0.7	0.7	0.0
Voids Filled with Bitumen (VFB)					
Marshall @ 75 blows	%	85.8	69.8	71.9	88.2
Gyratory @ 120 cycles	%	95.7	82.7	84.5	97.7
Gyratory @ 350 cycles	%	100.0	93.6	93.2	100.0
Modulus (@ 25°C)					
Marshall @ 75 blows	MPa	2350	2945	3330	2365
Gyratory @ 120 cycles	MPa	1690	2200	2540	1505

Table 3.2 Laboratory test results for the nine mixes *(continued)*

Mix Identification No.		**5**	**6**	**7**	**8**	**9**
Maximum Particle Size	mm	20	20	14	15	20
Aggregate Type (A=Alluvial; Q=Quarried)		Q	A	Q	Q	Q
Mix Plant Type (B=Batch; C=Continuous)		B	B	C	C	C
Total Bitumen Content	%	5.7	6.3	5.5	6.1	6.0
Added Filler	%	7.9	5.9	6.8	5.4	6.6
Absorbed Bitumen	%	0.6	0.7	1.3	1.2	0.8
Effective Bitumen	%	5.1	5.6	4.2	4.9	5.2
Surface Area		7.47	6.68	6.63	5.65	6.50
Bitumen Film Thickness	µm	7.0	8.7	6.5	9.0	8.3
Marshall Stability	kN	16.37	17.75	14.74	11.85	14.76
Marshall Flow	mm	3.02	3.67	2.87	3.16	3.42
Maximum Specific Gravity of Mix		2.425	2.424	2.719	2.400	2.420
Bulk Specific Gravity of Mix						
Marshall @ 75 blows		2.352	2.375	2.643	2.317	2.335
Gyratory @ 120 cycles		2.417	2.407	2.690	2.375	2.376
Gyratory @ 350 cycles		2.415	2.427	2.722	2.392	2.406
Voids in the Mineral Aggregate (VMA)						
Marshall @ 75 blows	%	14.6	14.9	13.6	14.5	15.3
Gyratory @ 120 cycles	%	12.2	13.8	12.1	12.4	13.9
Gyratory @ 350 cycles	%	12.3	13.1	11.0	11.7	12.8
Air Voids						
Marshall @ 75 blows	%	3.0	2.0	2.8	3.5	3.5
Gyratory @ 120 cycles	%	0.3	0.7	1.1	1.0	1.8
Gyratory @ 350 cycles	%	0.4	0.0	0.0	0.3	0.6
Voids Filled with Bitumen (VFB)						
Marshall @ 75 blows	%	79.4	86.5	79.5	76.2	77.1
Gyratory @ 120 cycles	%	97.3	94.9	91.2	91.6	86.9
Gyratory @ 350 cycles	%	96.6	100.0	100.0	97.2	95.5
Modulus (@ 25°C)						
Marshall @ 75 blows	MPa	2470	1850	2585	1770	2085
Gyratory @ 120 cycles	MPa	2310	1440	1850	1375	1790

Table 3.3 Particle size distribution for each mix.

Mix	1	2	3	4	5	6	7	8	9	TNZ M/10: 2002 Mix 20	
										Min	Max
Sieve Size (mm)	Percentage Passing (%)										
19	100.0	100.0	100.0	100.0	100.0	100.0			100.0	100	
13.2	92.8	89.5	80.7	98.6	89.1	98.2	100.0	100.0	94.6	83	95
9.5	78.9	79.4	69.7	86.4	84.9	76.0	89.5	89.0	83.3	70	90
6.7	68.7	70.7	64.3	77.0	69.0		73.8	69.8	72.4	60	79
4.75	57.8	63.0	54.9	70.6	63.0	61.3	63.4	58.6	64.3	52	70
2.36	41.6	50.2	41.2	55.8	47.1	49.1	47.0	39.6	51.7	40	55
1.18	31.3	34.9	29.8	40.1	33.6	35.6	35.1	29.1	36.8	29	43
0.6	22.9	22.4	20.5	28.9	24.6	26.0	24.4	21.2	23.5	20	32
0.3	15.7	14.7	14.0	21.8	17.8	18.1	15.0	13.5	14.0	13	23
0.15	10.1	9.7	9.2	15.1	12.0	10.1	9.4	8.1	9.0	8	16
0.075	6.9	7.1	6.4	9.0	7.9	5.9	6.8	5.4	6.6	4	10

3.5 Re-designing a Mix using APRG18 Procedure

After a preliminary analysis of the laboratory results of the work originally envisaged (i.e. in addition to the research tasks included in the brief for this research), one of the mixes (from the Fulton Hogan Nelson laboratory which did the tests) was selected to be re-designed using APRG18 (AUSTROADS 1998). The requirement set by the researchers was to achieve a grading that had 4% voids in the mix and a refusal air voids greater than 2.5% using gyratory compaction.

A mix was batched, cured for one hour at 150°C and compacted to produce one specimen at 10, 50, 80, 120 and 350 cycles (i.e. 5 specimens plus sample for MTSG). From these specimens volumetric data were calculated and compared to the target. Four combinations of aggregate were trialed at one bitumen content (b) before a potential combination was found. Using the selected combination of aggregate, the procedure was repeated with three different bitumen contents (b –0.5%, b +0.5%, b +1.0%). The data were plotted as Air Voids versus Gyratory cycles, similar to the example shown in Figure 2.7, and a design bitumen content was selected based on a heavy traffic criterion (120 gyratory cycles).

Because the resultant voids in the mineral aggregate (VMA) were considered to be less than desirable, further batches were produced at 120 cycles with different aggregate proportions and bitumen contents to increase the air voids. Nevertheless, the air voids at 120 and 350 (refusal density) Servopac gyratory cycles were still only 3.5%, and 1.4%, respectively.

The results are provided in Table 3.4.

Table 3.4 **Properties of mix designs using Marshall and APRG18 procedures.**

Mix Design Procedure		**Original Marshall**	**APRG18**
Nominal Maximum Particle Size	mm	20	20
Aggregate Type (A=Alluvial; Q=Quarried)		Q	Q
Mix Plant Type (B=Batch; C=Continuous)		C	C
Total Bitumen Content	%	5.0	4.2
Filler	%	6.4	3.65
Absorbed Bitumen	%	0.9	0.6
Effective Bitumen	%	4.1	3.6
Surface Area		6.14	4.43
Marshall Stability	kN	16.29	16.7
Marshall Flow	mm	3.34	3.79
Stability/Flow Ratio		4.9	4.4
Maximum Specific Gravity of Mix		2.556	2.574
Bulk Specific Gravity of Mix			
Marshall @ 75 blows		2.459	2.437
Gyratory @ 120 cycles		2.510	2.485
Gyratory @ 350 cycles		2.538	2.538
Voids in the Mineral Aggregate (VMA)			
Marshall @ 75 blows	%	13.6	13.9
Gyratory @ 120 cycles	%	11.8	12.2
Gyratory @ 350 cycles	%	10.9	10.3
Air Voids			
Marshall @ 75 blows	%	3.8	5.3
Gyratory @ 120 cycles	%	1.8	3.5
Gyratory @ 350 cycles	%	0.7	1.4
Voids Filled with Bitumen (VFB)			
Marshall @ 75 blows	%	71.9	61.6
Gyratory @ 120 cycles	%	84.5	71.6
Gyratory @ 350 cycles	%	93.2	86.4
Filler to Bitumen Ratio		1.6	1.0
Bitumen Film Thickness	μm	6.8	8.3
Modulus (@ 25 °C)			
Marshall @ 75 blows	MPa	3330	3085
Gyratory @ 120 cycles	MPa	2540	3295

The refusal densities (after 350 gyratory compaction cycles) of both the original and re-designed mixes were the same (2.538). This is primarily because the aggregate composition of the mix was not changed, and the aggregate constitutes 95% of the mix by mass. Only the filler and binder content were optimised using the APRG18 procedure.

4. Analysis

The stiffness moduli of specimens in Table 3.1 are within the range of 1375 MPa to 2540 MPa for gyratory-compacted specimens, and 1770 MPa to 3330 MPa for Marshall specimens. All specimens were created using bitumen with a penetration of 90. The presumptive stiffness values of typical Australian dense-graded asphalts containing Class 170 binder (which has approximately a penetration grade of 85/100) determined with laboratory manufactured specimens, using the indirect tensile test at 25°C and 40 milliseconds rise time, are 2000 MPa to 4500 MPa (for mixes with a maximum particle size of 20 mm) (AUSTROADS 2001). Thus, the New Zealand mixes tend to be at the lower end of the Australian range of values, but are nevertheless comparable.

Averaging the moduli results of all nine mixes shows that the moduli of the specimens made using the Marshall procedure are 560 MPa higher than the average moduli of the same mixes compacted to 120 gyratory cycles in the Servopac. The mixes were originally designed using the Marshall procedure so thus achieve a stiffer specimen when compacted by Marshall compaction because the mixes were designed to suit that compaction type and effort. However, based on the results from the specimens compacted in the Servopac, which better replicates field-compacted mixes, the actual stiffness moduli of the field-compacted mixes could be significantly less than would have been predicted if only Marshall-compacted specimens had been tested in the laboratory.

The moduli results of the Marshall and Servopac (at 120 gyratory cycles) specimens were statistically analysed, to confirm that the two compaction methods produce different moduli. The t-test (paired two sample for means) is a paired two-sample Student's t-test to determine whether two sets of the means of a sample are different. This t-test does not assume that the variances of both populations are equal but, because there is a natural pairing of observations in the samples, the paired t-test is applicable.

The data were analysed by comparing the difference in means with a zero mean difference. This analysis gives a t value of 6.764, as shown in Table 4.1, whereas the critical value of t at a 0.1% level of significance is 5.041 for a two-tail test. This means that the two sets of moduli results are significantly different.

The critical t value for the one-tail test is 4.501 at 0.1% level of significance, which confirms that the moduli of the Marshall specimens are statistically significantly greater than those of the Servopac specimens (at 120 cycles).

Table 4.1 t-test results: paired two samples for means of resilient modulus obtained for Marshall and Servopac specimens.

0.1% level of significance	**Resilient Modulus (MPa)**	
	Marshall	**Servopac**
Mean	2416	1855
Variance	250642	168826
Observations	9	9
Hypothesised mean difference	0	
Degrees of freedom	8	
t Calculated	6.764	
t Critical one-tail	4.501	
t Critical two-tail	5.041	

However, this is a relatively small data set to draw any firm conclusions about statistical significance. Nunn (1996) reported that the most appropriate representation of mean stiffness modulus is by its statistical distribution, and suggested that the logarithm of stiffness modulus is normally distributed. He found that the standard deviation of the logarithm of stiffness is independent of the level of stiffness, and is essentially constant at 0.10 (Log_{10} GPa), and the standard deviation varied between 0.07 and 0.21 (Log_{10} GPa).

Converting the data from Table 4.1 into GPa, and calculating the Log_{10} values for the moduli, as in Table 4.2, produces a standard deviation of 0.09 (Log_{10} GPa) for the moduli for both Marshall and Servopac specimens tested in this research.

The potential usefulness of this finding in a practical application should be investigated in future research, because Nunn (1996) concluded that the standard deviation of the Log_{10} (stiffness modulus) is relatively constant at 0.10 for mixes with the same ingredients, and mixed, laid and compacted under the same conditions.

Table 4.2 Stiffness moduli (Log_{10}) for Marshall and Servopac specimens.

Marshall (GPa)	**Servopac (GPa)**	**Marshall Log_{10}**	**Servopac Log_{10}**
2.350	1.690	0.371	0.228
2.945	2.200	0.469	0.342
3.330	2.540	0.522	0.405
2.365	1.505	0.374	0.178
2.470	2.310	0.393	0.364
1.850	1.440	0.267	0.158
2.585	1.850	0.412	0.267
1.770	1.375	0.248	0.138
2.085	1.790	0.319	0.253
Mean (Log_{10})		0.375	0.259
Standard Deviation		0.09	0.09

After one of the mixes was re-designed according to APRG18 (AUSTROADS 1998) procedure, and subjected to the same testing regime as was the original mix design, the moduli of the Marshall specimens reduced slightly from 3330 MPa to 3085 MPa, whereas the moduli of the Servopac-compacted specimens increased by over 700 MPa, from 2540 MPa to 3295 MPa, which is a significant increase. Marshall compaction was substantially less sensitive to the changes in the mix, whereas the gyratory compaction and indirect tensile modulus test were sensitive to changes in the mix. Also the APRG18 mix design procedure created a mix design with a substantially higher modulus.

Other researchers have reported that gyratory-compacted specimens achieve lower moduli (stiffness) values than Marshall specimens, but the former are much closer to field measurements (Oliver 2000c).

As shown in Figure 4.1 and Table 4.3, the densities (as %MTSG) of all mix specimens compacted in the Servopac were greater than densities of the Marshall-compacted specimens, by an average of 1.8%. The results are comparable with those of Brown & Mallick (1998), who found that the densities of specimens created in the Servopac gyratory compactor were greater than the densities of Marshall specimens by approximately 1.5%.

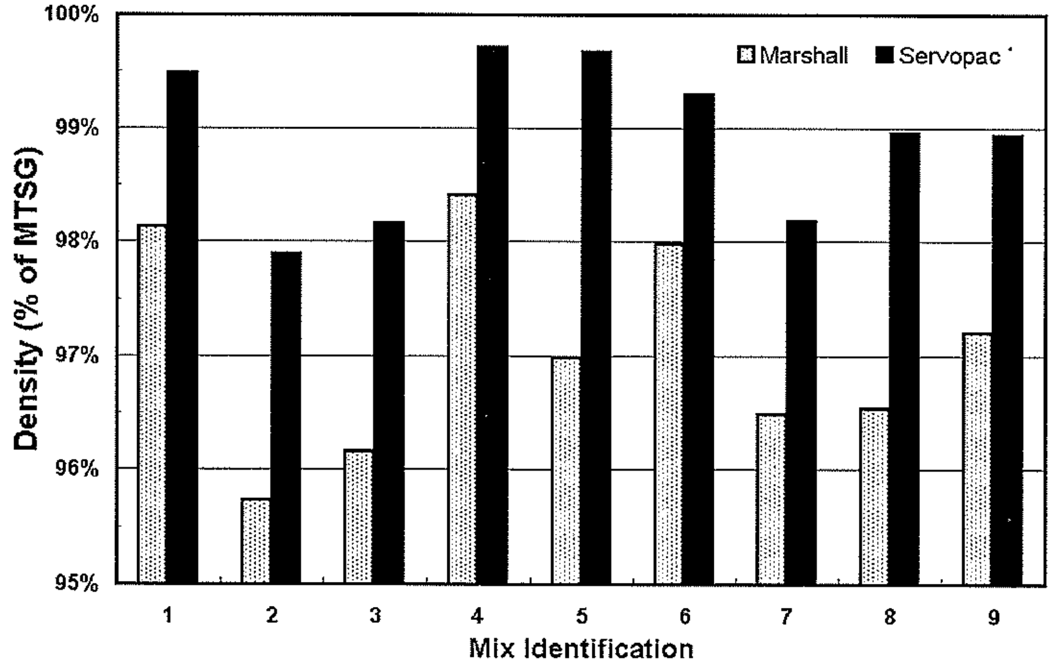

Figure 4.1 Comparison of densities (% MTSG) obtained from Marshall and Gyratory specimens. (MTSG – Maximum Theoretical Specific Gravity)

Table 4.3 **Comparison of densities (% MTSG) of Marshall and Servopac specimens.**

Mix ID No.	1	2	3	4	5	6	7	8	9	Average
Marshall (%)	98.1	95.7	96.2	98.4	97.0	98.0	96.5	96.5	97.2	
Servopac (%)	99.5	97.9	98.2	99.7	99.7	99.3	98.2	99.0	98.9	
Difference(%)	1.4	2.2	2.0	1.3	2.7	1.3	1.7	2.4	1.7	**1.8%**

The correlation (r^2) between six key volumetric parameters plus Marshall stability, and the moduli of the Marshall- and Servopac-compacted specimens are summarised in Table 4.4. The highest correlation was between total bitumen content and modulus for both Marshall and Servopac specimens, which was 0.937 and 0.661 respectively. The correlation between total bitumen content and Marshall specimens was the highest, because the Marshall mix design procedure is focused solely on determining optimal bitumen content.

The correlation between total bitumen content and modulus of Servopac-compacted specimens is lower because the procedure considers other factors, not just bitumen content. Also, the tested mixes were all designed using the Marshall procedure, so it is logical that Marshall specimens had the highest correlation.

Other factors, such as effective bitumen content, voids in the mineral aggregate (VMA), and air voids, had substantially poorer correlation with modulus for both Marshall and Servopac-created specimens. As shown in Figure 4.2, the relationship between air voids and modulus is relatively poor, but both Marshall and Servopac specimens give approximately similar results. Thus air voids alone is not a good indicator of mix modulus.

The most significant observation is that the correlation between Marshall Stability and modulus is so low, and is essentially negligible. It is 0.038 and 0.016 for Marshall and Servopac specimens respectively, regardless of how the specimens were compacted. This confirms that Marshall Stability and modulus of the mix are not related. The stiffness modulus of an asphalt mix is critical in asphalt pavement thickness design and performance prediction models, so designers cannot rely on Marshall test properties as an indicator of asphalt stiffness.

Table 4.4 **Correlation (r^2) of mix properties with moduli obtained for Marshall and Servopac specimens.**

Property	Moduli	
	Marshall	Servopac
Total bitumen content (%)	0.937	0.661
Effective bitumen content (%)	0.585	0.276
VMA (Marshall)	0.270	
VMA (Servopac @ 120 cycles)		0.212
Air voids (Marshall)	0.185	
Air voids (Servopac @ 120 cycles)		0.200
Marshall Stability	0.038	0.016

The refusal density of specimens compacted to 350 gyratory cycles is regarded as a key performance indicator, and all the mixes included in this study had air voids of less than 1%, which is substantially below the minimum of 2.5% recommended in APRG18 (1998). This criterion is too severe for current New Zealand mixes designed using the Marshall procedure and satisfying the Transit NZ M/10 specification. Air voids at refusal density for the re-designed Nelson asphalt mix averaged only 1.4%, which is still lower than 2.5%. Oliver (2002) found that the refusal density requirement of 2.5% voids at 350 gyratory compaction cycles was also not achievable for Victorian (Australia) mixes.

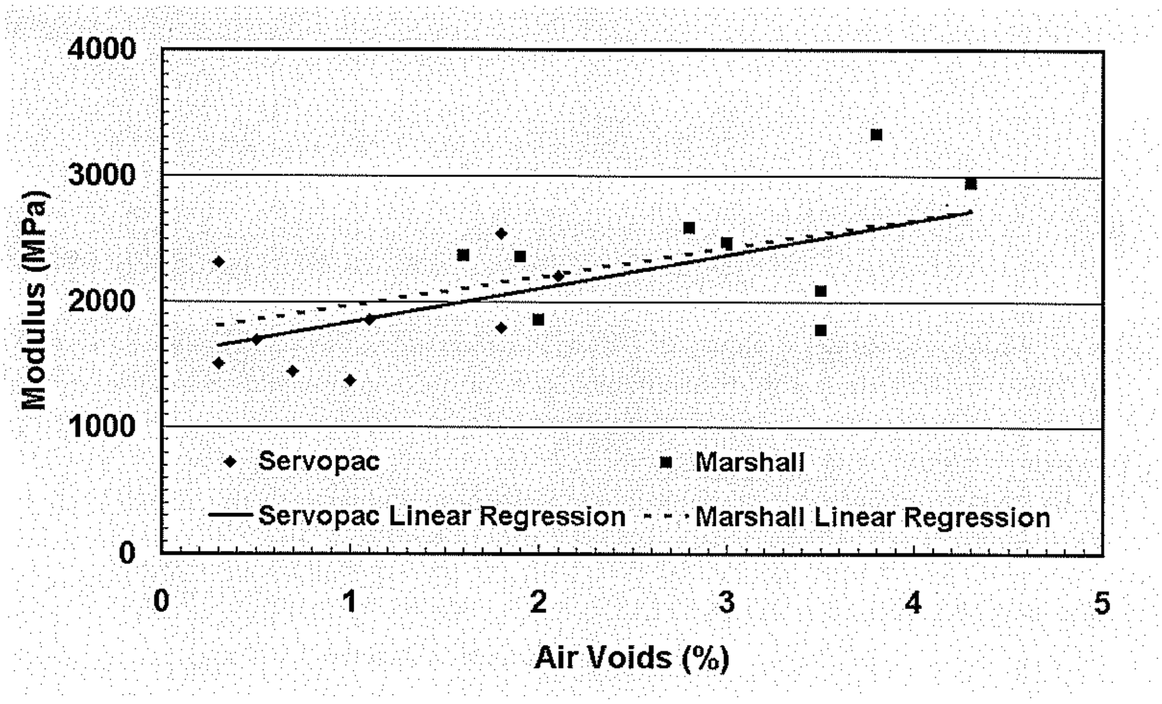

Figure 4.2 **Relationship between air voids (%) and modulus (MPa) for Marshall and Servopac specimens.**

5. Conclusions and Recommendations

The literature review highlighted that orientation of aggregate particles in asphalt mix test specimens created in the laboratory using gyratory compaction provide better replicates of the orientations that are found in the field.

5.1 Conclusions

New Zealand road authorities are progressively adopting performance-related specifications and implementing performance contracts for road maintenance and construction. Adopting a modern performance-related mix design procedure will overcome the deficiencies of the existing empirically based Marshall mix design procedure. As the Marshall compaction and mix design procedure does not create specimens that replicate field compaction, it is not directly related to road conditions and does not reliably predict performance under trafficking. A better understanding of the behaviour of New Zealand asphalt mixes and their integration with future pavement designs and specifications are both necessary, to optimise the use of materials and improve the performance of asphalt pavements.

Adopting a performance-related design procedure based on gyratory compaction will enable a wider range of innovative asphalt mixes to be designed and tested using the same gyratory procedure.

The correlation between six key volumetric parameters plus Marshall stability, and moduli of the specimens were determined. The highest correlation was between total bitumen content and modulus. In contrast, the correlation between Marshall stability and stiffness modulus of the asphalt mix was extremely poor. This shows that the two properties are not related, though the stiffness modulus is the critical property in asphalt pavement thickness design and performance prediction. Also, air voids alone is not a good indicator of a mix's modulus.

The refusal density requirement of 2.5% voids at 350 gyratory compaction cycles is too severe for New Zealand mixes, which also confirms that the findings of Oliver (2002) are applicable to New Zealand. A more realistic refusal voids limit would be 2% after 250 gyratory cycles.

Using asphalt mixes obtained from eight different regions of New Zealand, different aggregate sources, and nine different plants, the tests showed that the range of stiffness moduli (at 25°C) was 1375 MPa to 2540 MPa for gyratory-compacted specimens, and 1770 MPa to 3330 MPa for Marshall-compacted specimens.

The results from this research provide an improved understanding of the behaviour of asphalt (manufactured from materials sourced in New Zealand) using the gyratory compaction and indirect tensile stiffness modulus test method, compared with the current Marshall mix design method.

5.2 Recommendations

Adopting AUSTROADS APRG18 procedure
The Marshall mix design procedure is inadequate for the needs of performance-related specifications, so the AUSTROADS APRG18 asphalt mix design procedure, based on gyratory compaction of test specimens, should be adopted in New Zealand.

New Zealand Supplement to AUSTROADS Pavement Design Guide
As an interim step, the New Zealand Supplement to the AUSTROADS *Guide to the Structural Design of Pavements* should be modified to incorporate the results of this research, namely that the range of stiffness moduli for dense-graded asphalt mixes used on New Zealand roads is 1400 MPa to 3300 MPa. These values would probably have to be changed if the APRG18 asphalt mix design procedure were to be adopted in New Zealand.

The values provided in this report are relevant only to the specific mixes tested for this research. Every asphalt mix should be tested to determine its specific properties.

New Zealand Supplement to APRG18
A New Zealand Supplement to APRG18 should be drafted by a joint industry–Transit working party, to assist with the acceptance and implementation of APRG18. The implementation would have to be in consultation with the industry, to allow the process of upskilling and acquiring the necessary equipment to be completed.

Comparison of Marshall and APRG18 procedures
The performance of asphalt mixes that have been designed using the two procedures (Marshall and APRG18) should be compared using both in-service field trials and test sections at the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF). The latter will yield results relatively quickly (within 6-12 months), whereas field trials require a few years before any definitive conclusions can be made. In both field and CAPTIF testing, cores could be taken from the asphalt, and tested for their stiffness moduli and other properties. Also, deflection bowls should be measured, to allow an estimation of in-situ stiffness moduli of the asphalt.

Acceptance criteria based on statistical analysis
The statistical acceptance criteria for asphalt mixes designed, manufactured and constructed under performance-related specifications must include statistical analysis. The potential application to New Zealand asphalt mixes of using the Log_{10} (GPa) concept as proposed by Nunn (1996) for quantifying the standard deviation of asphalt stiffness moduli should be investigated further.

Safety
One of the major disadvantages of the Marshall compaction hammer is that it is an inherently noisy and unsafe operation, causing numerous injuries to operators, whereas modern gyratory compactors are substantially safer and quieter to operate. This factor must be considered, given the modern pro-active attitude to worker safety.

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