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P11 REVIEW OF UNBOUND PAVEMENT MATERIAL SPECIFICATIONS: WET/DRY STRENGTH VARIATION

SUMMARY

Approximately 70% of the Queensland state-controlled road network is composed of unbound granular layers with a thin bituminous surfacing. Locally available material sources, climate, environment and traffic conditions are highly variable across the state and standard specifications, such as MRTS05 for unbound pavements, have to ensure reliable performance is achieved in a wide range of applications. In-service deterioration of unbound granular material is one of the leading causes of premature failure for these pavement types. In Queensland, resistance to mechanical and weathering-induced degradation is determined by the wet/dry strength variation and degradation factor methods respectively. However, it has been proposed that the current wet/dry strength variation criteria limits may be too restrictive. The objective of this project was to evaluate the appropriateness of the current criteria limits and the wet/dry strength variation testing method for identifying aggregates that may be susceptible to in-service deterioration.

The wet/dry strength criteria in Queensland were found to be the most stringent in Australia, but equivalent to some international agencies, such as in South Africa. It should be noted that inclusion of the wet/dry strength variation method and current criteria limits has significantly reduced the occurrence of durability-related premature failures. While the benefit of including assessment of mechanical degradation potential has been demonstrated, limitations of the wet/dry strength variation method include poor replication of in-service loading conditions and low repeatability and reproducibility.

Alternative mechanical degradation assessment methods including wet/dry strength variation, Los Angeles abrasion and micro-Deval abrasion were examined using basaltic unbound pavement materials representative of the range of products available in Queensland. Based upon the limited testing carried out as part of this investigation, micro-Deval abrasion was observed to provide better simulation of in-service loading conditions, assessment of both fine and coarse aggregates, increased repeatability and reproducibility and significantly improved laboratory efficiency as compared to wet/dry strength variation. However, further testing is required on the range of mineralogy and product standards currently available in Queensland to refine the testing methods (TMR Q229A/B) and establish reliable criteria limits.

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1 INTRODUCTION

Unbound granular pavements comprise a significant proportion, greater than 70%, of the Queensland road transport network. These pavements typically consist of a thin bituminous surfacing applied to the surface of compacted layers of unbound granular material overlying a select fill or native soil foundation. Conventional applications range from heavy traffic volume rural highways to light traffic volume urban roads. Unbound granular pavements require significantly lower initial capital investment when compared to heavily stabilised, thick asphalt or concrete structures. The economy and accessibility of these materials have been instrumental to the establishment and maintenance of the Australian road transport network that connects the vast, but sparsely populated continent. Extensive usage in Queensland, and throughout Australasia, has resulted from the relatively low cost and ready availability of suitable granular materials. However, unbound granular pavements do not provide the same resilience or reliability as compared to structures composed of higher quality stabilised, asphalt or concrete materials.

Predicting the long-term performance of granular materials in pavement applications is difficult, as the materials are heterogeneous and the traffic loading and environmental conditions are variable and complex. Consequently, a comprehensive performance prediction model calibrated for Australian roadbed conditions is not available.

The behaviour of commonly used materials is typically determined by monitoring field trials or conducting full-scale accelerated testing. However, these methods are both time and resource intensive. In practice, confidence in long-term performance is achieved through strict adherence to established material selection and construction techniques validated by historical observations. While effective, this empirically-based approach does not accommodate evolving material sources, the use of non-standard materials nor dramatically different traffic loading and environmental conditions. As a result, frequent review of material specifications, relative to past, current and future conditions, is required to bolster confidence that satisfactory long-term performance will be achieved and to maximise potential sources of suitable material. In addition to the material property limits, the review should also consider the specified characterisation methods to identify those that most accurately and precisely predict in-pavement performance.

Strength and durability are the principal characteristics required for the long-term performance of unbound pavement materials. Sufficient strength is required to resist repeated loading during construction and under traffic. Adequate durability is required to resist particle breakdown or degradation as a result of varying climatic and environmental conditions. Mechanical and weathering degradation cause constituent particles to fracture, abrade, wear and/or deteriorate, decreasing particle interlock and inter-particle friction and increasing the proportion of fine fraction particles. In-service degradation reduces the stiffness, strength and stability of granular layers, which manifests as accelerated permanent deformation at the pavement surface. Degradation of the composing aggregate is the most common cause of unbound granular pavement failure.

The Department of Transport and Main Roads Queensland (TMR) is charged with the establishment and maintenance of the state-controlled road network. The strength and durability of unbound pavement materials in Queensland are determined in accordance with Main Roads Technical Standard (MRTS) 05, *Unbound Pavements* (TMR 2015a), by measuring the wet 10% fines value, wet/dry strength variation, degradation factor and California Bearing Ratio (CBR). This system of characterisation testing measures properties indicative of strength, in addition to particle hardness, toughness and soundness to maximise potential for satisfactory performance.

The wet/dry strength variation test is currently specified to evaluate the potential for TMR Type 1 and Type 2 unbound pavement materials to break down in-service. These materials are primarily used in pavement base layers where the highest quality materials are provisioned to resist concentrated stresses from traffic loading. Wet/dry strength variation is an aggregate toughness measure quantifying the effect of saturated conditions on particle crushing resistance. The test involves applying an increasing vertical load to a confined aggregate sample and measuring the resulting increase in the proportion of fine particles relative to the original mass. The wet/dry strength variation is the ratio of the load required to produce a 10% increase in fines for the oven-dry (OD) to the saturated surface dry (SSD) condition.

The test indicates potential for mechanical degradation and provides an estimate of the minimum bearing capacity and relative clayey material content of igneous and metamorphic rocks. However, the method does not accurately replicate the loading conditions imposed during construction and in-service and anecdotal evidence suggests that the current limits specified in MRTS05 may be overly conservative. As a result, a review of MRTS05 relative to the mechanical degradation potential of unbound pavement material, specifically the wet/dry strength variation test method and limits, was required.

1.1 Objectives

The purpose of this project was to determine the appropriateness of current MRTS05 specification limits for wet/dry strength variation and investigate the availability of alternative testing methods providing improved accuracy and precision. Specific research questions to be examined included:

- Could the wet/dry strength variation limits in MRTS05 be relaxed without negatively impacting long-term pavement performance?
- Did the wet 10% fines value provide an adequate indication of mechanical degradation potential to warrant its use exclusively without referencing the dry 10% fines value?

Were alternative ‘performance-based’ durability test methods available that better simulated in-service conditions and provided greater repeatability and reproducibility?

1.2 Approach

The objectives of the investigation were pursued through:

- reviewing the methodology and development history of the wet/dry strength variation test
- determining the origins of the current MRTS05 specification limits
- defining the range of wet/dry strength variation values for currently available aggregates
- researching alternative durability assessment methods
- examining the accuracy, precision and ‘user friendliness’ of select alternative durability assessment methods.

1.3 Report Outline

A review of unbound granular materials including material properties, selection, production, construction and performance is presented in Section 2. Unbound pavement material durability is introduced in Section 3 with properties of typical Queensland aggregates reported in Section 4. The wet/dry strength variation test, identified alternative durability testing methods and the examination of selected methods are presented in Section 5, Section 6 and Section 7 respectively. Finally, conclusions and recommendations resulting from the above exploratory approach are offered in Section 8.

2 UNBOUND GRANULAR MATERIALS

Unbound granular material is an important naturally occurring pavement construction resource that is comprised of aggregate (Austroads 2008a). Aggregate contains particles of rock that when brought together in either a bound or unbound configuration form part of an engineering structure (Smith & Collis 1993). Examples of bound aggregates include concrete, asphalt and heavily stabilised materials. Unbound aggregates include sand, gravel and crushed rock and represent the dominant proportion of construction materials used in the provision of road pavements. Unbound materials do not provide the same load bearing capacity as bound aggregates in structural pavement layers. However, the comparatively low cost of unbound aggregates has resulted in widespread use in pavement base and subbase layers (Smith & Collis 1993). The primary function of unbound granular base and subbase layers is to distribute concentrated stresses from wheel loads over a wider area to minimise the magnitude of load transferred to, and the resulting deflection of, the underlying foundation (Collis & Fox 1985). The load bearing capacity of unbound granular material develops from the hard constituent grains, particle interlock, inter-particle friction and cementation bonds, where applicable (Austroads 2008b).

The ideal aggregate for use as unbound pavement material is strong and durable, but fragmented or weak enough to breakdown during processing into a wide distribution of particle sizes (Minty & Smith 1980). Road construction materials require sufficient strength to resist repeated loading during construction and under traffic. Durable rock has properties that cause the material to be hard and lasting. Long-term durability is commonly determined through measurement of hardness, toughness and soundness characteristics relative to limits established through historical observation of in-pavement performance. Soft rocks are those that fracture into smaller particles due to weak fabric elements or insufficient cementation bonds and should be avoided in road pavement applications (Minty & Smith 1980).

2.1 Properties

The properties of the composing aggregate significantly influence the engineering characteristics of a pavement layer and subsequently, the long-term performance of the structure. Critical characteristics for consideration in pavement applications include strength and durability. The strength of the pavement layer, as indicated by stiffness and shearing resistance determines the ability to withstand repeated traffic loading. Durability, as indicated by hardness, toughness and soundness properties, defines the resistance to variable climatic and environmental conditions. The strength and durability characteristics of an unbound granular pavement layer are significantly influenced by the mineralogy, physical attributes, fabric and degree of weathering of the composing particles (Austroads 2008b). The suitability of an unbound granular material for a given application is determined by the properties of both the source rock and the delivered end product (Austroads 2008a). Blended source aggregates are often employed to improve the quality of a marginal source and/or to extend the usage of a quality material (Smith 1984). When blended aggregates are utilised, the properties of each constituent material should be determined.

2.1.1 Mineralogy

The mineralogy of aggregate refers to the geological classification of the source rock according to chemical composition, crystalline structure and material properties. The principal source types employed for the construction of road pavements include igneous, metamorphic and sedimentary rocks. Igneous rocks derive from molten material originating deep within the earth's core that solidified at or near the surface (Smith & Collis 1993). Igneous rocks are by far the most abundant source rock and are subdivided according to alkali-silica content into acid, intermediate and basic igneous classifications in order of reduced silica content. Care should be exercised in the use of igneous rocks in pavement applications due to potential alkali-silica reactivity, low abrasion resistance and relative solubility. Metamorphic rock forms from the recrystallisation of igneous and sedimentary rocks subjected to additional heat and pressure (Smith & Collis 1993). The toughness of metamorphic rocks creates challenges when producing a well-graded product composed of angular cubical particles. Other potential limitations in pavement applications include foliation and alkali-silica reactivity. Sedimentary rock is formed from the cementation of loose fragments of other source rocks (Smith & Collis 1993). The attributes of sedimentary rocks stem from the type and degree of cementation of the source particles. Potential issues in pavement applications include alkali-silica reactivity, low abrasion resistance, solubility, slaking and volumetric instability.

2.1.2 Particle Attributes

The shape, size and surface texture of the individual particles composing the unbound granular material significantly influence the in-service behaviour of pavement layers including stiffness, shear strength and workability (Austroads 2008a). Australian standard aggregate particle shapes are presented in Table 2.1. Angular particles with sharp edges are preferred in pavement applications to promote aggregate interlock and the resulting stiffness and shear strength.

Table 2.1: Description of standard aggregate shapes encountered in Australia

Classification	Description
Rounded	Fully water-worn (completely shaped by attrition)
Irregular	Naturally irregular, or partly shaped by attrition and having rounded edges
Angular	Possessing well-defined edges formed at the intersection of roughly planar faces
Flaky	Materials in which the thickness is small relative to the other two dimensions
Elongated	Materials, usually angular, in which the length is considerably larger than the other two dimensions
Flaky and elongated	Materials having the length considerably larger than the width, and the width considerably larger than the thickness

Source: Austroads 2009.

Nominal maximum aggregate size (NMAS) is the largest sieve opening upon which 10% or more of the particles (by mass) of an aggregate are retained (i.e. at least 90% finer than NMAS). Large NMAS (> 25 mm) granular materials provide improved strength and skid resistance. However, larger aggregates also exhibit reduced workability, including increased segregation potential and an irregular surface finish. Excessive, greater than 10% by mass, content of fine particles (< 0.425 mm) should also be avoided due to increased potential for instability and moisture sensitivity. Fines content is a key material quality measure due to the influence on stiffness, shear strength, permeability and workability (Austroads 2008a). Particles with a rough surface texture are preferred due to the influence on inter-particle friction and the resulting shear strength.

2.1.3 Fabric

The material fabric defines the arrangement and orientation of particles in addition to the size, volume and shape of void spaces in a consolidated unbound granular material. Aggregate fabric is dictated by the distribution of particle sizes and the degree of compaction. Particle size distribution or gradation significantly influences the in-service behaviour of unbound granular pavement layers including stiffness, shear strength, permeability and workability (Austroads 2008a). The optimal gradation for conventional pavement applications includes an even distribution of particle sizes that produces the maximum density when compacted (i.e. least voids). The maximum density particle size distribution can be determined using Equation 1 with an adjustment coefficient (n) of between 0.20 and 0.45 for typical Australian road agency crushed rock specifications, including approximately 0.3 for 40 mm NMAS and approximately 0.4 for 20 mm NMAS pavement materials. An adjustment coefficient of 0.5 is representative of the maximum density line (i.e. zero air voids).

$$P = 100\left(\frac{d}{D}\right)^n \qquad 1$$

where

P = percentage (by mass) of particles passing the designated sieve

d = opening size of the designated sieve

D = maximum aggregate size

n = adjustment coefficient

The degree of compaction significantly influences the in-service behaviour of unbound granular pavement layers including stiffness, shear strength and permeability (Austroads 2008a). The degree of compaction is controlled by the compaction apparatus and procedure in addition to the moisture content of the unbound granular material. The degree of compaction is indicated by the unit weight of the material relative to the maximum dry density (MDD). The maximum density that can be reasonably achieved is generally desired to limit void spaces and establish a strong, durable pavement layer.

2.1.4 Weathering

Aggregate that is initially strong can deteriorate over time while in the stockpile or in-service as a result of weathering (Smith & Collis 1993). Some source rocks undergo chemical reactions when exposed to atmospheric conditions. These reactions, broadly categorised as weathering, include both mechanical disintegration and chemical decomposition and occur when source rocks are exposed to oxygen and hydrogen in addition to thermal variations (Smith & Collis 1993). Oxidation produces iron oxide that can discolour an aggregate material. Hydration, typically caused by exposure to water, can cause volumetric expansion of sensitive particles. The evolution of weathering includes limited discolouration, general discolouration, widening discontinuities, weakened structure, altered fabric, change to soil and complete destruction of fabric (Smith & Collis 1993).

Mechanical disintegration occurs primarily in arid and cold climates as a result of differential expansion and contraction that generates or widens existing fractures (Smith & Collis 1993). Disintegration alters the material fabric reducing particle stiffness and strength. Chemical decomposition is accelerated in hot humid climates and results from the transformation of silicate materials into clay particles. Igneous and metamorphic rocks are particularly susceptible (Smith & Collis 1993). Decomposition is accompanied by an increase in porosity and water absorption that typically reduce durability (Smith & Collis 1993). Due to the significant impact on strength and durability, only fresh and faintly weathered rock should be used in pavement applications to minimise the potential for mechanical and chemical breakdown (Smith & Collis 1993).

2.1.5 Characterisation

Evaluation of aggregate properties can be conducted on source rock, supplied end product or the as-constructed pavement layer (Austroads 2008b). Standard practice amongst the Australian states varies with some requiring testing at all levels and others pursuing a full suite of testing on the end product only (Austroads 2008a). Control of the source rock requires a significant commitment to testing, classification and inspection. When consistently applied, this approach allows for very close control of construction materials. Control of the end product requires complex specifications that address uniformity of sources, variation across size fractions, in addition to blended and recycled materials (Austroads 2008b). To ensure material quality, testing of both the source rock and end product is generally required. However, if the source rock is known to possess sufficient quality, assessment of only the end product is required (Austroads 2008a). When blended materials are used, each source rock contribution, in addition to the blended end product, should be subjected to assessment (Austroads 2008b). Only one assessment method should be specified for each characteristic of durability to avoid unnecessary conflict of opinion (Minty & Smith 1980).

2.2 Material Selection

Factors that should be considered when selecting or specifying granular materials include the intended function, required physical properties, production method, in addition to available quality control and assurance techniques (Austroads 2008a). The function of unbound granular material in base layers is to reduce the magnitude of transmitted stresses, maintain shape under repeated traffic loading, provide an adequate surface for construction of a generally bituminous wearing course (asphalt or spray seal) and where required, establish an impermeable or rapid draining moisture barrier. The function of unbound granular material in subbase layers is to further reduce the intensity of transmitted stresses, provide a stiff working platform for construction of overlying layers and prevent moisture infiltration to or facilitate drainage of the subgrade (Austroads 2008a).

The characteristics of the composing unbound granular material have a profound effect on the structural and functional performance of the pavement. Requirements include sufficient strength to withstand traffic and environmental stresses, workability to meet specifications and durability to resist disintegration and decomposition (Austroads 2008a). Not all aggregates make good construction materials. Careful consideration of performance-related attributes is essential. Specification limits are typically established from historical observations of in-service performance. Due to the empirical nature, limits should not be extrapolated outside the range of the data set used in development of the relationship (Austroads 2008b). The applicability of specification limits requires regular review due to changes in material sources, construction equipment and traffic loading. Effective specifications provide guidance on what is required to ensure long-term performance without unnecessary testing (Austroads 2008b).

2.3 Production

Unbound granular materials are principally composed of naturally occurring constituents that are extracted from exposed rock faces, river beds or subsurface mines. These source materials are transformed into engineering-quality products in processing plants. Processing plants employ systems of crushers, screens, conveyors and chutes to produce conforming unbound granular materials. The configuration of these processes regulates the particle size distribution, segregation potential and weathering susceptibility of the end product. Crushers reduce the harvested source rock to a specified range of sizes and include jaw, gyratory, impact and roller types (noting that the type of crusher can sometimes influence the resultant particle shape of the crushed source rock). Screens separate crushed materials into discrete-size fractions and include static and vibrating horizontal, inclined, grizzly, and rotary types. Belt conveyors are utilised to advance the granular materials through the production facility. Chutes and hoppers are used to transfer material between conveyor belts or from conveyors into stockpiles and are specially designed to minimise segregation. Regular quality control testing is required to both monitor and regulate the production processes.

The particle size distribution of the end product is controlled by the crushing plant and screen variables. However, to achieve the specified particle size distribution in the pavement, allowance for particle breakdown during construction also needs to be taken into account (Austroads 2008a). Additional characteristics of the end product, including plasticity, permeability and workability can be modified through the addition of plastic fines or clayey filler. Clayey filler is produced by drying and grinding clay minerals into a fine powder that can be added to a crushed granular material to improve cohesive properties (Austroads 2008a). The nature of the fines significantly influences the in-service behaviour of the unbound granular material. Therefore, careful characterisation of the fines material should be conducted prior to incorporation. Overburden and weathered material should be avoided due to the negative impact on long-term durability.

2.4 Construction

The long-term performance of unbound granular pavements is determined by the properties of the composing aggregate, construction practices, moisture management techniques, in addition to traffic and environmental loading. The principal construction activities for establishment of unbound granular layers include surface preparation, layer formation, compaction, finishing and quality control testing. The principal concerns requiring consideration during construction include segregation minimisation, moisture control, adequate compaction and satisfactory surface finish.

2.4.1 Preparation

Thorough preparation of the underlying layer promotes satisfactory long-term performance. The ideal surface finish for the construction platform is smooth, dense and free of deleterious materials. A poor surface finish accelerates defects in the overlying layers. Additionally, the elevation, slope and crown should be closely monitored to ensure deficiencies are not promulgated through the pavement structure.

2.4.2 Layer Formation

Typical unbound layer thickness ranges from 100 to 200 mm to maximise compactability without increasing delamination potential. The formation of prismatic layers is typically accomplished using mechanical spreaders such as stone boxes and pavers or manually utilising a motor-grader to spread end-dropped aggregate windrows or stockpiles. Base and subbase materials should be placed slightly wet of optimum moisture content (OMC) to allow for loss through evaporation and compaction ‘through optimum’ and with handling minimised to reduce segregation potential.

2.4.3 Compaction

Ensuring adequate compaction is achieved is key to establishing a strong, stable and durable unbound granular pavement layer. The shear strength of granular material is realised through aggregate interlock, which increases with relative compaction. Adequate compaction is also required to minimise void space, reducing permeability and improving durability. Commonly employed compaction equipment for unbound granular layers includes static and vibrating steel wheel and pneumatic tyre rollers. Moisture control is critical, as sufficient quantities are required to lubricate particles for achieving maximum density. However, excessive moisture trapped within the pavement can accelerate structural deterioration.

2.4.4 Surface Finish

Similarly to the prepared construction platform, the ideal surface finish for unbound granular pavement layers is smooth, dense and free of deleterious materials. Trimming of the compacted layer should be minimised, but where required to achieve design elevation, slope and crown, is typically accomplished using a motor-grader. Trimming of unbound granular material should be accomplished immediately following compaction and should be discontinued if tearing or scabbing of the surface occurs. Following formation, compaction and trimming, the surface should be swept to remove dislodged particles and excessive fines prior to adding an overlying granular layer or bituminous sealing.

2.4.5 Quality Control

Regular conformance testing is required to ensure the constructed pavement fulfils the requirements of the design. Construction attributes evaluated as part of typical quality control plans include material properties, layer thickness, moisture content and density, shape, elevation and evenness in addition to ride quality. In addition, structural integrity may be identified through non-destructive testing such as CBR, Clegg impact or deflection under axle load. The type and frequency of testing should be defined in the project specification and are a key to controlling the quality of the final product.

2.5 Performance

As highlighted in Section 2.1, Section 2.3 and Section 2.4, the long-term performance of unbound granular pavement layers is significantly influenced by the intrinsic properties of the composing aggregate, in addition to the imposed boundary conditions determined by the manufacturing and construction practices (Austroads 2008a). Failure mechanisms for granular materials include fracture, abrasion, edge wearing and deterioration of particles. Failure mechanisms for pavements containing a granular basecourse include shear failure (shoving), vertical deformation through particle breakdown (rutting) and asphalt wearing course tensile fatigue where the basecourse does not provide sufficient stiffness

Particle degradation in-service generates localised consolidation and subsequent permanent deformation of the pavement surface (Collis & Fox 1985). The most severe cases of unbound granular failure result from the physical breakdown of particles as a result of weathering (Smith & Collis 1993). Investigation of pavement failures in a number of countries found two common contributing factors were the use of basic igneous rock and high concentrations of secondary minerals. Basaltic aggregates are particularly susceptible to weathering-induced breakdown (Smith & Collis 1993).

Aggregate degradation results from the significant variation in stress, moisture and/or temperature environment within the pavement as compared to the natural state of the parent geological formation (Austroads 2008b). Depending on mineralogy, strong, tough rock may deteriorate significantly when disturbed and exposed to environmental conditions (Austroads 2008b). Unbound granular material must resist fracture, abrasion, wear and degradation when stockpiled, mixed, transported, placed, compacted and subjected to repeated traffic loadings. The same material must also resist disintegration and decomposition due to cyclic environmental conditions such as wetting and drying (Wu et al. 1998). Moisture conditions are particularly significant as saturated conditions negatively impact the strength and durability, as well as accelerate weathering, of all source rock types. A 40% reduction in shear strength can result from the saturation of igneous rocks (Collis & Fox 1985).

3 AGGREGATE DURABILITY

Durability, or resistance to deterioration, is a fundamental aggregate property. Durability defines the resistance of the composing particles to mechanical and weathering-induced degradation that allows the pavement layer to maintain shape and structural properties throughout the service life (Austroads 2008b). Mechanical degradation refers to polishing, wearing down of edges, fracture and/or breakdown of particles due to production, transport, construction and trafficking operations. Mechanical degradation results from aggregate-to-aggregate or aggregate-to-rigid-object contacts. Weathering is defined principally by two mechanisms including disintegration, or the breakdown of rock into smaller particles, and decomposition, or the changing of particles into less desirable compounds. Decomposition occurs primarily in warm, humid climates and disintegration where large thermal variations occur (Austroads 2008b).

Durability is a property inherent to the source rock and can only be improved by selecting rock free of overburden and weathered material and/or concentrating undesirable materials into a single size fraction and then removing that fraction before crushing (Austroads 2008b). Utilisation of durable and sound aggregate is essential to maintaining the integrity of the pavement structure (Wu et al. 1998). Aggregates used in road base construction must exhibit the requisite strength and durability during construction operations through to the end of the service life. As the long-term performance factors vary by location and over time, laboratory index tests for strength, hardness, toughness and soundness are commonly specified to reduce the risk of unsatisfactory performance.

3.1 Physical Properties

Properties required of aggregates for successful long-term performance in pavement applications include strength, hardness, toughness and soundness. Hardness, toughness and soundness are durability measures that can be readily discerned using combinations of assessment methods for mechanical and weathering degradation resistance. The use of durable aggregate with a well-graded distribution of particle sizes compacted to a high density generally ensures adequate strength and durability will be achieved in pavement applications. The properties of strength, hardness, toughness and soundness can and should be directly assessed, particularly in applications where moisture inundation is probable.

3.1.1 Strength

Strength is defined as the ability to withstand repeated load applications (Austroads 2008b) to withstand shear failure, vertical deformation (particle breakdown) and provide adequate stiffness to support overlying asphaltic layers (asphalt fatigue). The strength properties of rock are source dependent, with large variability possible in a given parent material. Aggregate strength is closely related to durability as the effects of weathering can reduce material strength, accelerating deterioration (Austroads 2008b). However, long-term performance predictions should not be based solely on assessments of strength. High dry compressive strength is typically associated with materials with significant clayey material content that tend to be moisture susceptible (Smith 1984).

The strength of unbound granular material is often determined through measurement of the maximum compressive and/or shear strength. Commonly utilised methods for measuring the strength of unbound granular materials include CBR, Texas triaxial (unsoaked and soaked test conditions) and dry compressive strength. CBR testing measures the resistance of a confined unbound granular material to penetration by a cylindrical punch. CBR testing is commonly undertaken on saturated specimens and is indicative of shear strength capacity. The Texas triaxial test can be used to evaluate the shear strength of compacted unbound granular materials. An increasing vertical load is applied to a cylindrical specimen with variable confining pressure. The dry unconfined compressive strength test evaluates the bearing capacity of cubical specimens subjected to an increasing vertical load and is also indicative of shear strength capacity.

3.1.2 Hardness

Hardness is defined as the ability to resist abrasion by other materials (Austroads 2008b). Abrasion resistance is critical to maintaining the mechanical properties of the unbound granular material. The smoothing or breaking of particles reduces aggregate interlock, increases permeability and alters the fabric of the material, accelerating deterioration of the pavement layer. Aggregate hardness is most commonly determined by Los Angeles (LA) abrasion testing where a loose specimen is tumbled with steel spheres inside a sealed chamber.

3.1.3 Toughness

Toughness is defined as the ability to withstand impact loading (Austroads 2008b). Adequate toughness is required to withstand construction operations, but aggregates that are too tough do not generate the required distribution of particle sizes during production. Reduction in toughness, such as that resulting from weathering, can accelerate deterioration (Austroads 2008b). The toughness of granular material is commonly determined by measuring the aggregate crushing value (ACV) or dry/wet 10% fines value. Measurements of ACV and 10% fines value provide an indication of aggregate resistance to crushing. Both methodologies involve the application of a vertical load to a confined aggregate specimen.

3.1.4 Soundness

Soundness describes the resistance of an aggregate to breakdown from weathering. Measurements of soundness are indicative of the physical and chemical stability of rock when subjected to extreme temperature and moisture environments. Variations in moisture content can result in the development of internal stresses that can fracture or produce slaking of the aggregate particles. Soft, expansive and chemically reactive materials deteriorate rapidly when exposed to extreme environments (temperature/moisture). Rocks with significant montmorillonite or illite clay content are particularly susceptible (Smith & Collis 1993). Aggregates with insufficient soundness are subject to disintegration and decomposition processes that accelerate deterioration of the pavement layer. The soundness of unbound pavement material is commonly determined by measuring the degradation factor or accelerated soundness index. The degradation factor method gauges the propensity of aggregate to self-abrade in the presence of water. The accelerated soundness index test assesses the disintegration potential of aggregates subjected to repeated cycles of wetting and drying.

3.2 Characterisation

Laboratory testing is required to describe the physical, mechanical and chemical properties of aggregate for prediction of in-service performance, comparison of alternative materials, ensuring specification compliance and to provide control of material quality (Collis & Fox 1985). Selection of the most appropriate durability test should be accomplished in consideration of the type and magnitude of applied stress (Minty & Smith 1980). Currently available durability testing methods are empirically based and were developed to address specific issues and/or environments that may or may not be applicable to the conditions of a particular project (Austroads 2008b). The performance requirements for aggregates vary by location and application and therefore, a wide range of tests are commonly specified to predict in-service behaviour (Smith & Collis 1993).

No single test measure can guarantee long-term durability (Smith & Collis 1993). A reliable estimate of performance requires a minimum of two tests, including one to assess mechanical degradation resistance and another to evaluate weathering potential (Austroads 2008b). In Australia, mechanical degradation is typically assessed through measurement of wet/dry strength variation, LA abrasion or ball mill value. The assessment of disintegration and/or decomposition potential as a result of weathering commonly includes measurement of the degradation factor or accelerated soundness index. Where long-term durability issues are suspected, petrological examination and absorption tests should be combined with standard durability methods (Smith &

Collis 1993). The induced distress mechanisms vary between the durability testing methods. However, none of the currently available tests exactly reproduce field conditions and empirical relationships are required to correlate with in-pavement performance (Austroads 2008b).

Durability measures are only as accurate and representative as the selection of test specimen (Austroads 2008b). Testing should be conducted on materials similar to those used in construction, prepared to like conditions. Additionally, the reliability of the testing results should be determined relative to repeatability and reproducibility. Repeatability is a measure of random error between successive results, all other variables including material, operator, equipment and environment held constant. Reproducibility is an expression of random error between different operators in different laboratories using identical equipment and environmental conditions (Collis & Fox 1985).

3.3 Specification Limits

Granular material specifications should be practical and clearly address the interests of all stakeholders including making certain the final product performs as designed, provides value for money, achieves the desired in-pavement characteristics and is produced in a cost-effective, reliable manner (Austroads 2008a). Durability specifications can address source rock properties with visual inspection of the end product or directly address the properties of the end product (Austroads 2008b). Divergence in specification requirements between Australian states is typically related to durability limits and results from differing prevalent source aggregates and historical practices adopted to address performance issues (Austroads 2008a). The durability measures and associated limits specified by the different Australian states and territories are presented in Table 3.1.

Table 3.1: Durability testing methods and limits of Australian road agencies

Authority	Standard specification	Durability test limits				
		Maximum wet/dry strength variation (%)	Maximum ball mill value	Minimum degradation factor	Minimum accelerated soundness index (%)	Maximum secondary minerals content (%)
QLD	MRTS05[a]	30 - 45	-	30 - 50	-	-
NSW	3051[b]	35 - 40	-	-	-	-
VIC	Section 812[c]	-	30 - 45	40 - 50	94	25
SA	Part 215[d]	-	30 - 45	40 - 50	94	25
WA	501[e]	35	-	-	94	25
TAS	R40[f]	35 - 45	-	-	-	-
NT	Road Maintenance[g]	-	-	-	-	-
ACT	R44[h]	35 - 40	-	-	-	-

[a] Department of Transport and Main Roads Queensland (2015a).

[b] Roads and Maritime Services New South Wales (2013b).

[c] VicRoads (2011).

[d] Department of Planning, Transport and Infrastructure South Australia (2014).

[e] Main Roads Western Australia (2012).

[f] Department of Infrastructure, Energy and Resources Tasmania (2013).

Authority	Standard specification	Durability test limits				
		Maximum wet/dry strength variation (%)	Maximum ball mill value	Minimum degradation factor	Minimum accelerated soundness index (%)	Maximum secondary minerals content (%)

[g] Department of Construction and Infrastructure Northern Territory (2012).

[h] Roads and Maritime Services New South Wales (2013a).

The purpose of establishing durability index limits is to reduce the risk of particle deterioration in-service that may alter the particle interlock, inter-particle friction and fines content with detrimental effects on shear strength, stiffness and resistance to permanent deformation (Austroads 2008a). Aggregates that do not meet the strength and durability standards can still be successfully employed in less severe environments and traffic loading conditions (Austroads 2008b). Where the use of unsound materials cannot be avoided, strong, dense and impermeable surfacings are required to minimise traffic stresses and prevent moisture infiltration (Collis & Fox 1985). The addition of 2% lime (by mass) to crushed aggregate has also been employed to decrease susceptibility to weathering-induced degradation. The effects of pre-treatment techniques are rock-type dependent, and generally, hard aggregates are less susceptible as compared to softer aggregates (Smith 1984).

3.3.1 Specification Criteria in Queensland

The durability properties of unbound pavement materials in Queensland are determined in accordance with MRTS05 (TMR 2015a). Basford (1993) summarises the supporting research and documents the approach for selecting the durability testing methods and criteria limits for MRTS05. The current durability criteria limits are the same as established in 1993. The basis for reviewing and updating the unbound pavement material specification was the durability-related premature failure of a number of pavements serving heavy traffic volumes in wet environments. However, the previous specification criteria did not include provisions to detect these types of performance issues.

Strength and durability were established as the critical properties for satisfactory long-term in-service performance. The wet 10% fines value, degradation factor and wet/dry strength variation methods were selected as the optimal measures of toughness, weathering degradation potential and mechanical degradation potential respectively. As basic igneous rocks are prevalent throughout Queensland and also most susceptible to in-service degradation, a sliding scale approach was adopted for the establishment of criteria limits. Based on extensive research and reference to historical performance (Basford 1993), criteria limits of 150 kN, 50 and 30% were adopted respectively for wet 10% fines value, degradation factor and wet/dry strength variation for Type 1.1 basic igneous products. The criteria limits were subjectively lessened for decreasing product standards and alternative source material groups.

4 PROPERTIES OF QUEENSLAND AGGREGATES

The strength and durability properties of granular materials are most accurately determined in the laboratory under conditions similar to those expected in-service. Unbound granular material used in Queensland road pavements must resist a wide range of climatic, environmental and traffic loading conditions. Operating environments include both very wet and very dry conditions in temperate to hot climates for a service period typically ranging from 10 to 40 years. Coastal regions, particularly in northern Queensland, are very wet due to prolonged rainfall events of regular frequency. Inland areas are very dry, but can experience high intensity precipitation resulting from isolated storms. Natural foundation materials are highly variable and include a number of poor quality materials providing low bearing capacity and high potential for moisture induced differential volumetric change.

Unbound granular materials are utilised in an extensive array of road classes along the state-controlled network serving traffic volumes ranging from 10^4 to 10^7 equivalent standard axle (ESA) loads. Additionally, the more frequent occurrence of extreme weather and flooding events in addition to sea level rise as a result of changing climate patterns will increase the required level of resilience.

4.1 Basic Igneous Rocks

Basic igneous rock, and in particular basalt, is readily available throughout Queensland and is the most commonly used material in base and subbase layers of unbound granular pavements. Igneous rocks are formed by the cooling and solidification of molten rock material near the earth's surface. The suitability of igneous rock for engineering applications depends on the mineral composition, crystalline fabric, texture and degree of chemical alteration or weathering (Smith & Collis 1993). The properties of the source rock are determined by the chemical composition of the molten material and the prevalent conditions during formation (Austroads 2008b). Igneous rocks are composed of eight primary elements - oxygen, silicon, aluminium, iron, calcium, sodium, potassium and magnesium (Smith & Collis 1993). Classification is according to silica and free quartz content, with acid igneous having greater than 66%, intermediate igneous having between 66 and 52% and basic igneous having less than 52% silica and rarely any free quartz (Austroads 2008b).

Unweathered igneous rocks are hard, strong, quality construction materials (Smith & Collis 1993). The strength of igneous rocks results from the hard constituent particles and interlock between numerous small, angular crystals. However, even slight decomposition of the crystals, resulting from exposure to air and water, can severely weaken the rock (Austroads 2008b). Basic igneous rocks including altered or weathered materials are subject to disintegration and decomposition causing the material to become unsound. Basalt is an abundant basic igneous rock available throughout Queensland that is tough, but also subject to secondary mineralisation in the presence of moisture. Some basalt sources have been found to be susceptible to rapid degradation due to secondary mineralisation. Aggregate containing secondary minerals can abrade during production, construction and in-service to form plastic fines. These fines can migrate to the surface of the pavement layer, reducing structural stability and precipitating rapid failure. Secondary minerals are the primary cause of distress and premature failure in unbound granular pavements (Smith & Collis 1993).

4.2 Product Assessment Scheme

Unbound pavement materials must retain sufficient strength and durability during construction through to the end of the service life. The performance of aggregates in pavement applications is significantly influenced by the properties of the source rock in addition to the processing and construction practice. The influencing properties of the source rock include mineralogy, particle characteristics, fabric and degree of weathering. Variability in composition and condition of aggregate products from certain sources can result in unsatisfactory performance (Basford 1993). Weathering can rapidly alter the characteristics of some rock types, deteriorating the strength and durability properties. The method of extraction, crushing, screening, stockpiling, processing and transporting aggregate can accelerate weathering processes prior to delivery of the product. As a result, assessment of both the source rock and supplied end product is commonly undertaken.

The strength and durability assessment of unbound pavement materials in Queensland is accomplished at two stages including examination of the properties of the source rock at the quarry and the end product delivered to the project. The assessment of source rock is conducted in accordance with the TMR Quarry Registration System (QRS) as outlined in QRS1 (TMR 2015b). The QRS is managed by TMR and includes reviewing a quarry assessment report (QAR), consulting the appropriate TMR Region, inspecting the quarry site, issuing a quarry registration certificate (QRC), regular product monitoring and random surveillance/auditing. The QAR is supplied by the material producer and includes the quarry details, regional geology, site development history, production methods and procedures, source rock testing results including petrographic analysis, wet 10% fines value, wet/dry strength variation and degradation factor, quality management plan and nominated testing frequency. Consulting the presiding TMR Region regarding historical performance and conducting a visual site inspection are also performed to complement the QAR review. Applications satisfying the requirements of the QRS are issued a QRC valid for two years. During the period of validity source rock testing results are submitted in accordance with the QRC and the site is subject to random auditing by TMR (TMR 2015b).

The strength and durability of unbound pavement materials delivered to state road projects in Queensland are determined in accordance with MRTS05 (TMR 2015a). Although the testing methods and limits are similar, certification according to the QRS does not guarantee product conformance with MRTS05 due to variability in the source rock in addition to project-specific processing and construction practices (TMR 2015b). Conformance with MRTS05 requires submission of a construction plan, source material properties report including petrographic analysis, wet 10% fines value, wet/dry strength variation and degradation factor and the design mix grading envelope to the TMR Project Administrator for approval before initiating construction activities. Additionally, material compliance testing is conducted on each lot supplied to the project before incorporation into the works and includes wet 10% fines value, wet/dry strength variation and CBR in addition to standard material characterisation methods (TMR 2015a).

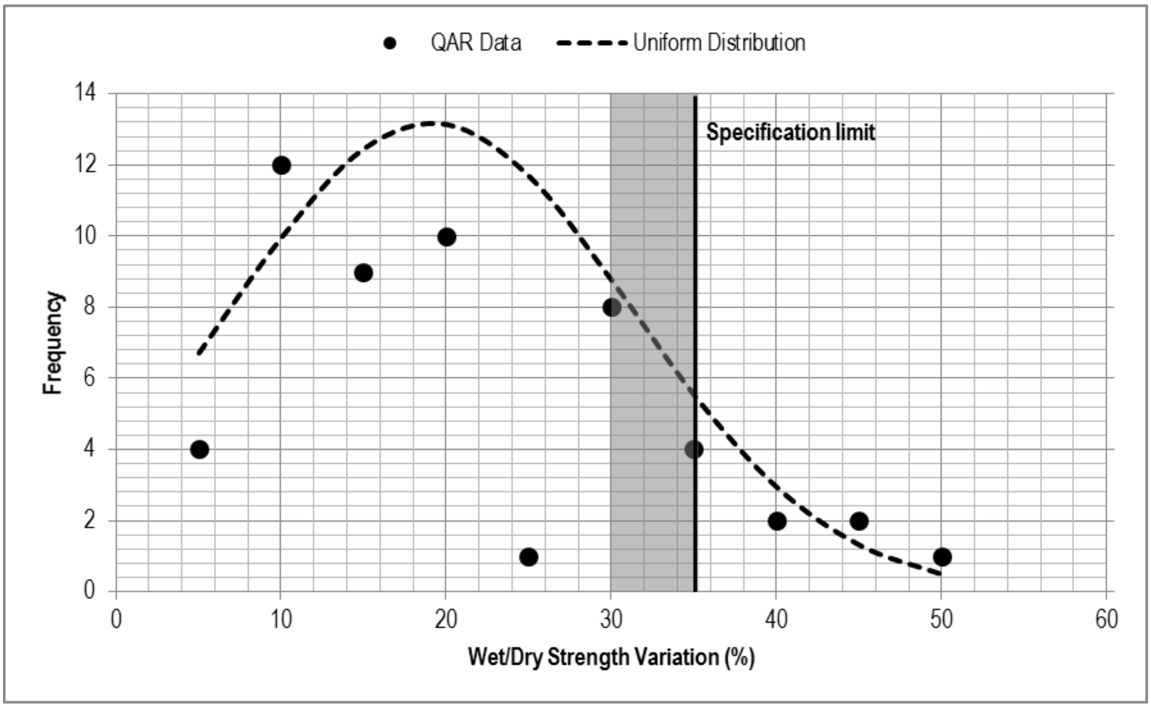
4.3 Properties of Basalt Products

Basic igneous rocks consist of hard constituent particles, can be processed without difficulty and are widely available throughout Queensland. However, some basic igneous unbound pavement materials, mainly basalt products, also have the greatest propensity to degrade rapidly in-service. The principal aggregate properties influencing performance in engineering applications are strength and durability. Durability correlates well with rock type, but strength can vary widely including between locations of the same source (Basford 1993). Construction aggregates in Queensland are extracted from a wide range of sources developed in a variety of rock types. Significant differences in source rock and aggregate product properties have been observed across the state (Basford 1993). The variation is typically the result of the inclusion of weathered rock and natural fines during the extraction and production processes. Deep and variable weathering in addition to difficulty excluding overburden and seam/joint infillings plague many production sources (Basford 1993).

The durability properties of basalt products currently available in Queensland were determined by evaluating the wet 10% fines value and wet/dry strength variation testing results provided as part of the certification of products according to the QRS (TMR 2015b). Aggregate products provided for utilisation in TMR construction projects must conform with established quality criteria as outlined in Section 4.2. The quality testing results submitted with the QAR for 34 quarries across Queensland were provided to the ARRB Group by the TMR Engineering and Technology Branch. Prior to delivery, proprietary information such as the name of the quarry and the production processes was removed. Data provided included regional location, source rock type, dry 10% fines value, wet 10% fines value, wet/dry strength variation, NMAS, degradation factor, flakiness, year of testing and certified TMR product type.

The 10% fines value and wet/dry strength variation results for 10 basalt quarries across Queensland were analysed to establish the general distribution of toughness and soundness properties of currently available products. The included QAR testing results were relative to a range of basalt products including unbound pavement material, surfacing stone and railway ballast. A histogram of wet/dry strength variation frequency was developed and characterised according to a uniform distribution as shown in Figure 4.1.

Figure 4.1: Distribution of wet/dry strength variation testing results

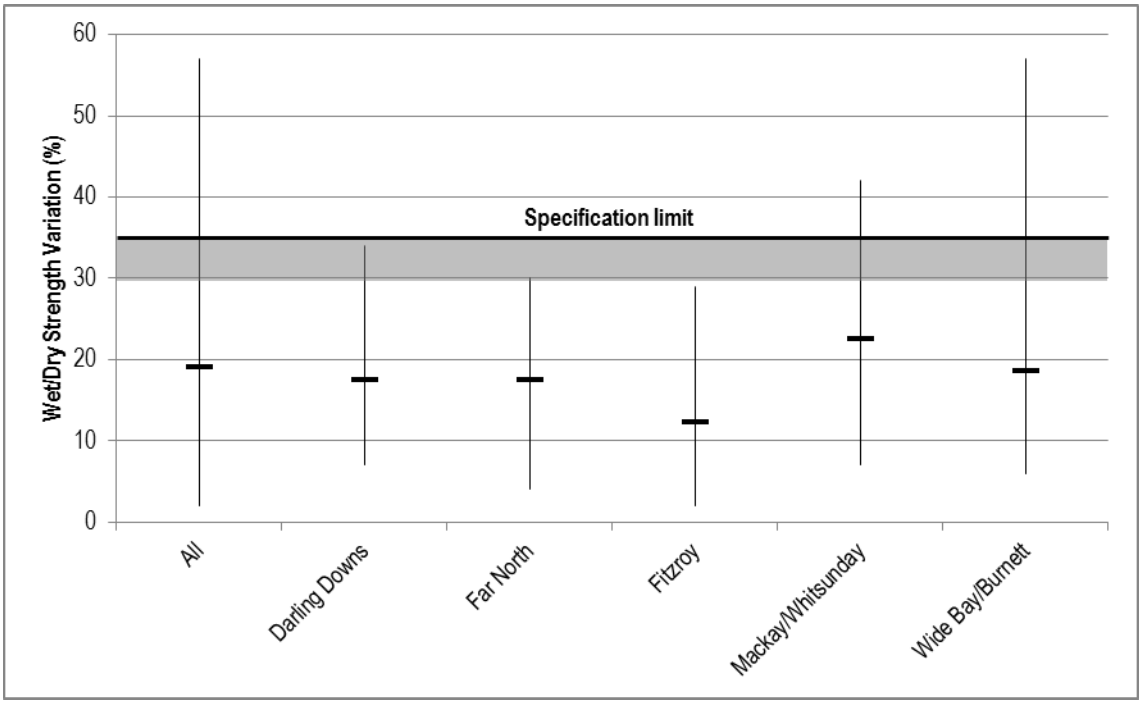


As can be observed from Figure 4.1, the wet/dry testing results are well characterised by a uniform distribution. The wet/dry strength variation results range from 5% to 50%, with half of products providing values ranging from 10% to 30%.

The conformance of Type 1 and Type 2 aggregate according to MRTS05 is indicated by the grey specification limit area that ranges from 30% to 35%, depending on material subtype. Type 1 and Type 2 aggregates are high quality unbound granular materials primarily used in the provision of base and subbase pavement layers. Allowing that the distribution of wet/dry strength variation properties for basalt rocks follows a uniform distribution, Figure 4.1 indicates that approximately 10 to 20% of Queensland basaltic source rocks exceed the limits provided in MRTS05 and should not be included in base and subbase pavement layers.

In addition to examining the range of basalt rock soundness properties across Queensland, the regional variation was also investigated. The maximum, minimum and average wet/dry strength variation values for unbound pavement, surface stone and railway ballast aggregates in the Darling Downs, Far North, Fitzroy, Mackay/Whitsunday and Wide Bay/Burnett regions are presented in Figure 4.2. The maximum and minimum values are connected by the vertical line and the mean value is indicated by the horizontal line.

Figure 4.2: Regional variation in wet/dry strength variation testing results



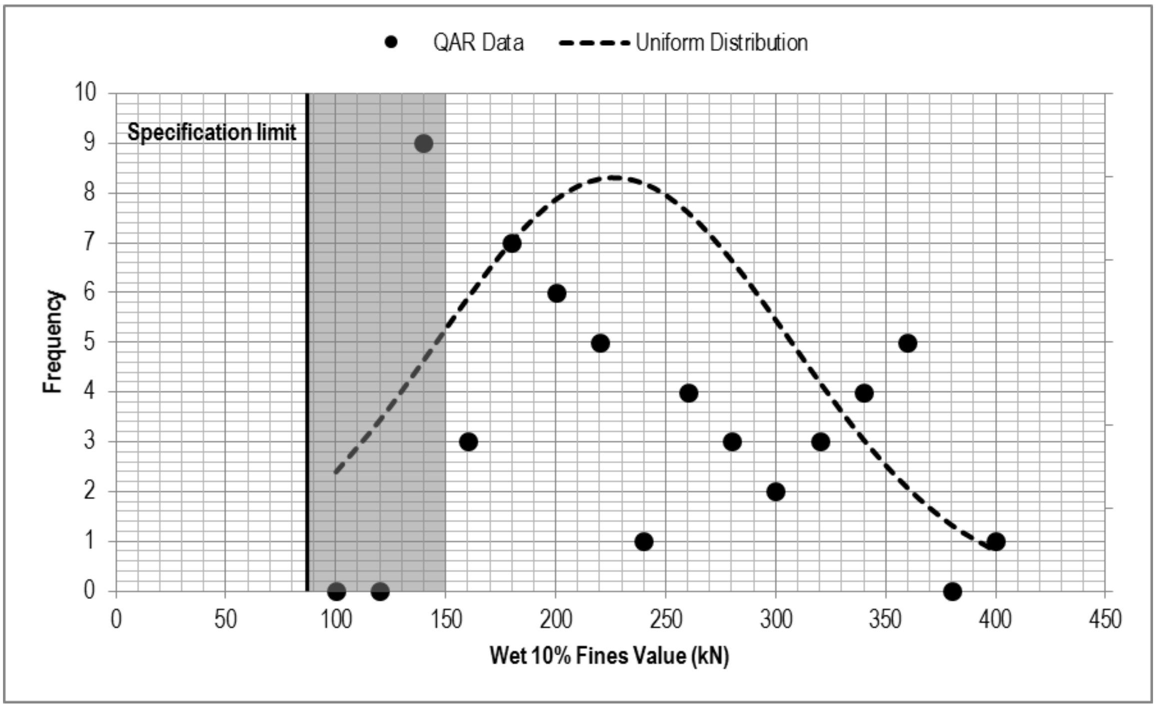
The average wet/dry strength variation for basaltic rock sources across the state is approximately 19%. This value is well below the Type 1 and Type 2 unbound pavement material maximum limit of 30% to 35%, indicating that the majority of sources should be capable of providing products that conform to MRTS05. However, Figure 4.2 indicates a significant difference in the variability of values, with similar levels in the northern and southern regions but substantial variability in the central regions.

The grey specification limit area for Type 1 and Type 2 aggregates in accordance with MRTS05 is also included in Figure 4.2. Evaluation of material properties relative to the specification limit area would indicate that the majority of products available in the northern and southern regions conform fully with the criteria limits of MRTS05. However, some sources in the Mackay/Whitsunday and Wide Bay/Burnett regions have properties well in excess of the acceptable limits.

The wet/dry strength variation limits in MRTS05 were established to minimise the potential for unbound granular material to break down in-service under heavy traffic load and extreme environmental conditions. Current criteria were established in consideration of national and international practice, research findings, pavement performance history and product manufacturing efficiency (Basford 1993). The practice review, research and history of performance indicated that a wet/dry strength variation limit of 25% should be adopted for Type 1.1 basic igneous products, but a more lenient limit of 30% was adopted to minimise the impact on the aggregate production industry (Basford 1993). In consideration of the history of development and the moderation of the current criteria, the further relaxation of specification limits requires careful consideration of the source rock properties and typical processing methods, material and construction characteristics and in-pavement performance history of currently available basalt and alternative commonly available source rock products. The impromptu relaxation of specification limits without undertaking a thorough review, as previously executed by TMR and documented by Basford (1993), may lead to the reoccurrence of widespread durability-related premature pavement failures.

In addition to investigating the current wet/dry strength variation limits in MRTS05, the reliability of the wet 10% fines value as an indicator of aggregate soundness was also examined as part of the project. The wet 10% fines value is commonly accepted as an indicator of aggregate toughness and is widely used (as either 10% fines or ACV) throughout Australasia, Europe and Africa. Ten per cent fines value testing results submitted as part of the QAR for 16 basalt quarries across Queensland were used to develop a histogram for unbound granular, surfacing stone and railway ballast products available in Queensland as shown in Figure 4.3. Similar to wet/dry strength variation, a uniform distribution was applied to characterise the relative frequency of results.

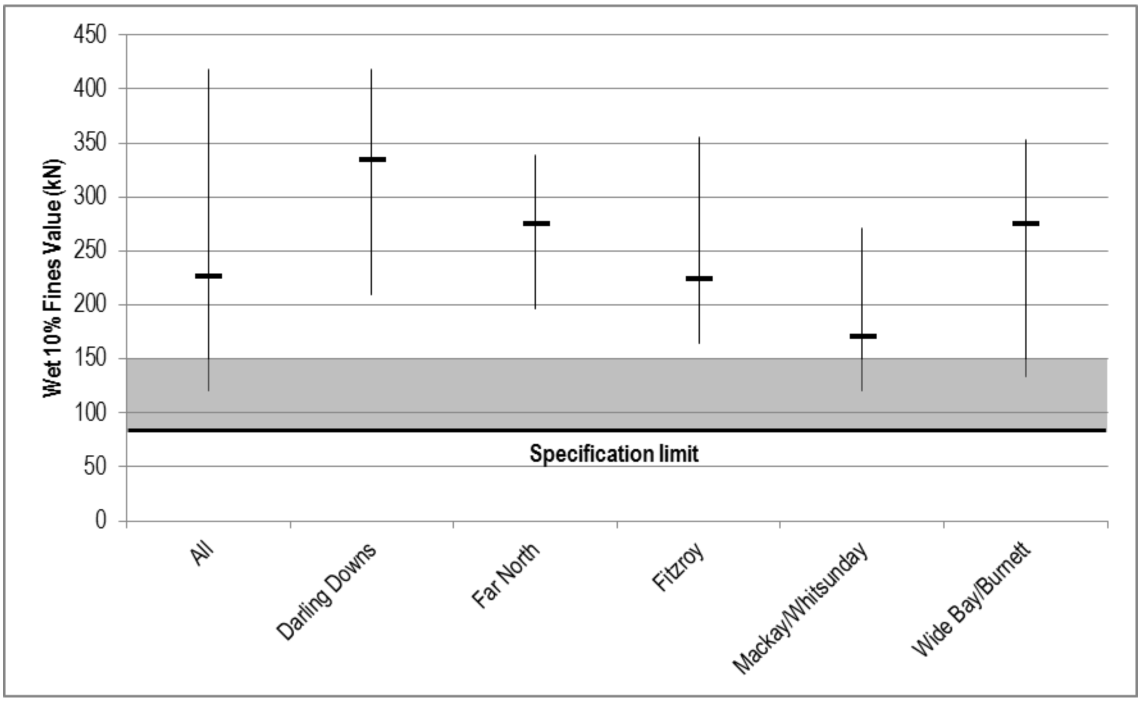
Figure 4.3: Distribution of wet 10% fines value testing results



As can be observed from Figure 4.3, the submitted QAR testing results are not well characterised by a uniform distribution and do not seem to follow an established trend. Wet 10% fines values for basalt source rocks across Queensland range from 100 kN to 400 kN, with the majority of products ranging from 140 kN to 370 kN. The grey specification limit area ranges from 85 kN to 150 kN, depending on material subtype, for Type 1 and Type 2 unbound pavement materials in accordance with MRTS05. Although the wet 10% fines values results do not follow a uniform distribution, if one is applied only to characterise the relative distribution of values, between 83% and 100% of basalt source rocks conform to the specification limits provided in MRTS05. Compared to the wet/dry variation testing results, where approximately 15% of sources would potentially be rejected for non-conformance with MRTS05, approximately half as many (some 8.5%) would potentially be rejected when referencing wet 10% fines values exclusively.

The consistent mean but variable range of values observed in the wet/dry strength variation QAR testing results for basalt unbound pavement, surfacing stone and railway ballast products was not observed in the wet 10% fines value testing results. Conversely, the range of values when examined by regional location is relatively consistent, approximately ± 60 kN, but the mean values vary as shown in Figure 4.4. Similarly to wet/dry strength variation, the products in the northern and southern regions are almost fully conforming and a number of products from the Mackay/Whitsunday and Wide Bay/Burnett regions are potentially nonconforming with MRTS05.

Figure 4.4: Regional variation in wet 10% fines value testing results



Aggregate durability, as indicated by the wet/dry strength variation and wet 10% fines value methods are determined by the properties of the source rock. Toughness, or resistance to fracture, is an important property for aggregate in pavement applications as it determines the capacity of the material to withstand construction operations and, for basecourse materials, impact loading without breaking down. Alternatively, soundness defines the resistance to disintegration and decomposition.

As described in Section 2.1.4, weathering changes the physical and chemical properties of the aggregate, impacting both the structural and volumetric stability of the pavement. Both wet/dry strength variation and 10% fines value methods assess aggregate toughness. However, the wet/dry strength variation method also provides an indication of soundness, as indicated by the relative difference in dry and wet 10% fines values. Materials containing a high proportion of deleterious secondary minerals may provide acceptable wet 10% fines values, but typically also provide considerable dry 10% fines values due to the cohesion and adhesion properties of the clayey inclusions.

While the wet/dry strength variation method provides an indication of both toughness and soundness, the wet 10% fines value does not allow for consideration of the soundness of coarse aggregates. As demonstrated by the increased number of conforming source materials based on QAR testing results, durability assessment based solely on wet 10% fines value may lead to the acceptance of aggregate products that are highly susceptible to weathering.

5 WET/DRY STRENGTH VARIATION

All granular materials lose strength, of varying degree, with increasing moisture content (Austroads 2008a). Wet/dry strength variation is a quantitative measure of the reduction in aggregate toughness due to saturation and is also used as an indicator of mechanical degradation potential. The method compares the relative crushing force required to generate 10% (by mass) fines in a confined coarse aggregate specimen under both SSD and OD conditions. Wet/dry strength variation is calculated using measurements of dry and wet 10% fines value. The dry 10% fines value is a measure of maximum toughness; the wet 10% fines value indicates minimum toughness; and wet/dry strength variation is a soundness assessment method that indicates the concentration of clayey materials in the specimen that have potential to breakdown under weathering (Smith 1984).

The presence of clayey materials increases dry crushing resistance and has a variable impact, determined by the type of clay, on the wet crushing resistance. However, low wet/dry strength variation indicates a volumetrically stable material with reduced concentrations of clayey material formed by alteration or weathering of the source rock. Adoption of wet/dry strength variation in New South Wales (NSW) in 1968 led to a considerable reduction in testing requirements without impacting overall quality (Minty & Smith 1980). The test was introduced to identify altered and weathered aggregates susceptible to disintegration. Wet/dry variation testing was originally developed for igneous and high-grade metamorphic rock, but is now widely applied to include sedimentary and all metamorphic source rock types (Austroads 2008b). Specification limits originally established in NSW resulted from laboratory testing and observation of test track performance for a range of materials (Minty & Smith 1980). Historical testing values less than 35% designated acceptable aggregate, while values between 35% and 60% indicated additional treatment was required (Smith 1984). Wet/dry strength variation provides an indication of coarse aggregate quality and additional tests are required to evaluate the quality of the fine proportion (Smith 1984).

The wet/dry strength variation test has been used to evaluate the toughness and soundness of coarse aggregates in Australasia since 1968 (Minty & Smith 1980). The loading configuration induces both indirect tensile and crushing failure modes analogous to shear and point loading respectively. The dynamic loading conditions make the test ideal for the examination of granular material performance in pavement applications (Austroads 2008b). Wet/dry strength variation can be determined in accordance with TMR test method Q205C, *Wet/dry Strength Variation* (TMR 2013e) or Australian Standard (AS) 1141.22, *Methods for Sampling and Testing Aggregates: Wet/dry Strength Variation* (AS 1141.22-2008). Despite the general acceptance and long history of use, the principal limitation of the wet/dry strength variation method is poor reliability as demonstrated by low repeatability and reproducibility.

5.1 Methodology

5.1.1 Apparatus

Equipment required to execute wet/dry strength variation testing includes:

- rigid cylinder: 75 mm by 75 mm or 150 by 135 mm (diameter by height)
- rigid plunger: 74 or 148 mm diameter
- baseplate: 7.5 mm thick by 115 or 220 mm diameter
- compression machine: Grade A; 1.0 MPa minimum capacity
- balance: ± 5 g (mass > 2 kg) ; ± 0.5 g (mass < 2 kg)
- desiccator
- oven: 105 to 110 °C

- sieves: 26.5, 19.0, 13.2, 9.5, 6.7, 4.75, 3.35, 2.36, 1.7, 1.18, 0.85 and 0.60 mm.

5.1.2 Sample Preparation

The wet/dry strength variation test is typically performed on the portion of coarse aggregate passing the 13.2 and retained on the 9.5 mm sieves (TMR 2013e). The preparation of aggregate samples for wet/dry variation testing includes:

1. Separate sufficient aggregate between the sieve pairs.
2. Wash and oven dry the specimen.
3. Shake over the retaining sieve.
4. Compact the aggregate in the rigid cylinder using three lifts.
5. Determine the mass of cylinder.
6. Prepare five additional specimens of equivalent mass.

Samples prepared for wet 10% fines value testing are soaked for 24 to 72 hours prior to testing. Aggregate is patted dry to achieve SSD condition and then prepared in accordance with Steps 4 and 5 above.

5.1.3 Procedure

The wet/dry strength variation testing procedure includes:

1. Place the rigid cylinder on the baseplate and insert the plunger into the test cylinder.
2. Insert the plunger, rigid cylinder and baseplate assembly into the compression testing machine.
3. Apply the vertical load at a uniform rate for approximately 10 minutes.
4. Record the maximum force.
5. Remove the specimen from the rigid cylinder.
6. Measure the proportion of fines passing the separating sieve (4.75 to 0.60 mm).

The percentage of fines should fall between 7.5 and 12.5%. The testing load should be established so that one value is between 7.5 and 10% and another between 10 and 12.5%.

5.1.4 Results

Two tests are required, one above and one below 10% fines, within the range of 7.5 and 12.5% fines generation. The percentage of fines generated is determined as the mass of material passing the separating sieve divided by the total specimen mass multiplied by 100. Both the wet and dry 10% fines value to the nearest kN is determined from interpolation of the results from two test specimens (TMR 2013e). The wet/dry strength variation is calculated as the per cent difference between dry and wet 10% fines values relative to the dry value as shown in Equation 2.

$$WDV = \frac{(D - W)}{D} * 100 \qquad 2$$

where

WDV = wet/dry strength variation

D = dry 10% fines value

W = wet 10% fines value

5.2 Typical Values

The resistance to crushing of unbound granular material is dependent upon the rock type, particle characteristics, void distribution and degree of weathering. Typical dry and wet 10% fines values for Australian and Queensland-specific aggregates are presented in Table 5.1. The dry and wet 10% fines values for Australian aggregates were obtained from Table 2 of AS 1141.22 (AS 1141.22-2008). The typical values for Queensland aggregates are as presented in Table 4 of TMR test method Q205A, *Ten Per Cent Fines Value (Dry)* (2013c) and Table 4 of test method Q205B, *Ten Per Cent Fines Value (Wet)* (2013d) for dry and wet 10% fines values respectively. The representative wet/dry strength variation values were calculated using the typical dry and wet 10% fines values according to Equation 2.

Table 5.1: Comparison of typical properties for Queensland and Australian aggregates

Aggregate class	Typical dry 10% fines value (kN)		Typical wet 10% fines value (kN)		Representative wet/dry strength variation (%)	
	Queensland	Australian	Queensland	Australian	Queensland	Australian
Acid igneous	150 - 300	299 - 300	130 - 260	220 - 244	9 - 15	18 - 27
Basic igneous	180 - 290	233 - 340	160 - 250	145 - 280	11 - 20	18 - 38
Intermediate igneous	190 - 260	255 - 255	140 - 230	225 - 225	12 - 26	12 - 12
Metamorphic	190 - 330	170 - 177	110 - 240	112 - 125	21 - 50	29 - 34
Sedimentary	180 - 200	145 - 150	160 - 160	45 - 97	11 - 20	33 - 70

The wet/dry strength variation testing equipment, methodology and approach are comparable between TMR Q205C and AS 1141.22. The primary difference in the TMR method (Q205C) and the Australian Standard (AS 1141.22) is the duration of the soaking period for the SSD specimens. TMR uses an overnight soaking period not to exceed 24 hours and Standards Australia recommends a minimum of 24 and maximum of 72 hours. Additional variations include the minimum water cover and specimen size for 6.7 mm NMAS aggregates. The TMR method requires a minimum 15 mm of water cover during soaking whereas the Australian Standard requires 50 mm. TMR method Q205C calls for a 60 mm measure and 75 mm specimen for 6.7 mm NMAS aggregate whereas Standards Australia calls for a 115 mm measure and 150 mm specimen.

5.3 Discussion

The dry crushing resistance of Queensland aggregates is generally lower for igneous and higher for metamorphic and sedimentary rock types as compared to the rest of Australia. Similarly, the crushing resistance of saturated aggregates is lower for igneous and higher for metamorphic and sedimentary rock types.

The typical wet/dry strength variation values follow a similar trend with acid and basic igneous in addition to sedimentary rock types lower, intermediate igneous types equivalent and metamorphic rocks higher than the general values for Australian aggregates. These findings suggest that aggregate products currently produced in Queensland may be altered or weathered to a lesser degree as compared to the rest of Australia. However, the increased soaking period, water cover and specimen size of the Standards Australia method may contribute to the increased wet/dry strength variation of general Australian aggregates as compared to Queensland source materials.

6 ALTERNATIVE DURABILITY TESTING METHODS

The suitability of source rock for utilisation in unbound pavement applications is determined by the physical strength and the hardness, toughness and soundness durability properties. As described in Section 3.1, aggregate hardness defines the abrasion resistance, toughness defines the crushing resistance and soundness defines the resistance to decomposition and disintegration. Hardness, toughness and soundness are closely related and are often used interchangeably with each other and also with the broader term durability. The key distinction is that hardness and toughness refer to resistance to mechanical degradation whereas soundness refers to resistance to degradation resulting from weathering (Wu et al. 1998).

Laboratory characterisation testing of unbound granular materials is generally undertaken to ensure compliance with engineering standards and to control aggregate product quality. Two types of laboratory methods are currently available for assessing the durability properties of aggregate including mechanical and weathering degradation methods. Mechanical degradation methods measure resistance to fracture, abrasion or wear and include wet/dry strength variation, ball mill value, LA abrasion, Deval attrition and micro-Deval abrasion.

Weathering degradation methods in the laboratory include methods to simulate accelerated deterioration and include degradation factor, accelerated soundness index, sodium/magnesium sulphate soundness, and aggregate durability index. Tertiary testing methods such as secondary minerals content and absorption do not provide a direct assessment of durability, but contribute significant value when employed complementary to any of the above testing methods. Due to the variability inherent in natural construction materials such as aggregate, there will always be degrees of uncertainty with respect to the long-term performance of crushed stone products (Basford 1993).

A number of different methods are specified to assess the durability of aggregates used in pavement applications. The mechanical and weathering degradation of aggregate undermines structural stability through reduced particle interlock and inter-particle friction (Collis & Fox 1985). Selection of the most effective method requires consideration of the prevalent source material, available production and construction methods, in addition to the local climate and environment. The durability assessment methods specified by different national and international road agencies are presented in Table 6.1. A detailed description of the alternative durability testing methods to include the required apparatus, specimen preparation techniques, testing procedures and calculation of results is presented in Appendix A.

Table 6.1: Summary of durability testing methods specified by different road agencies

Test method	Road agency							
	TMR[a]	VicRoads[b]	RMS[c]	MRWA[d]	TNZ[e]	COLTO[f]	FHWA[g]	UKHA[h]
Mechanical degradation								
Wet/dry strength variation	x		x	x		x		
Ball mill value		x				x		
LA abrasion value				x			x	x
Deval attrition value								x
Micro-Deval loss							x	
Weathering degradation								
Degradation factor	x							
Accelerated soundness index		x		x				

Test method	Road agency							
	TMR[a]	VicRoads[b]	RMS[c]	MRWA[d]	TNZ[e]	COLTO[f]	FHWA[g]	UKHA[h]
Weathering quality index					x			
NaS_2/MgS_2 soundness loss							x	x
Durability index							x	
Supplementary methods								
Secondary minerals content		x		x				
Absorption								x

[a] Department of Transport and Main Roads Queensland (2015a).

[b] VicRoads (2011).

[c] Roads and Maritime Services New South Wales (2013b).

[d] Main Roads Western Australia (2012).

[e] Transit New Zealand (2006).

[f] Committee of Land Transport Officials (1998).

[g] Federal Highway Administration (2003).

[h] British Standards Institution (2013).

The Australian states vary in the methods utilised, but most evaluate both mechanical and weathering degradation resistance. Internationally, the requirements also vary widely. New Zealand (Transit New Zealand 2006) evaluates only weathering degradation, South Africa (Committee of Land Transport Officials 1998) only assesses mechanical degradation, and both the USA (Federal Highway Administration 2003) and UK (British Standards Institution 2013) evaluate both forms of degradation similarly to the Australian states. Additionally, Victoria (VicRoads 2011), Western Australia (Main Roads Western Australia 2012) and the UK (British Standards Institution 2013) mandate supplementary durability measures such as secondary minerals content and/or absorption.

6.1 Mechanical Degradation Methods

Durability testing methods assessing mechanical degradation potential induce particle fracture, abrasion or wear by simulating the forces imparted during stockpiling, mixing, transport, layer formation, compaction and repeated traffic loading. The commonly utilised mechanical degradation assessment methods identified during this investigation included wet/dry strength variation, ball mill value, LA abrasion, Deval attrition and micro-Deval abrasion. These mechanical degradation methods measure the hardness and/or toughness properties of unbound granular material by evaluating the ability to withstand particle-to-particle and/or particle-to-rigid-object contact stresses.

The wet/dry strength variation, ball mill value, Deval attrition and micro-Deval abrasion methods also provide an indication of soundness by examining the mechanical degradation behaviour in the presence of moisture. Aggregate mineralogy, particulate properties and fabric (wet/dry strength variation only) significantly influence the results of mechanical degradation tests. A summary comparison of the highlighted mechanical degradation testing methods is presented in Table 6.2.

Table 6.2: Summary comparison of mechanical degradation methods

Test method	Applicable rock types	Degradation mechanism	Aggregate size (mm)	Sample required (kg)	Definition of fines (mm)	Measured parameter
Wet/dry strength variation	Igneous, metamorphic & sedimentary	Confined uniaxial crushing	26.5 - 2.36	30.0	4.750 - 0.600	Change in load resistance

Test method	Applicable rock types	Degradation mechanism	Aggregate size (mm)	Sample required (kg)	Definition of fines (mm)	Measured parameter
Ball mill value	Igneous, metamorphic & sedimentary	Dynamic impact & abrasion	50 - 0.425	3.5	0.425	Increase in fines
LA abrasion	Igneous, metamorphic & sedimentary	Dynamic impact & abrasion	53 - 4.75	5.0	1.700	Increase in fines
Deval attrition	Igneous, metamorphic & sedimentary	Dynamic abrasion	37.5 - 2.36	30.0	2.360	Increase in fines
Micro-Deval abrasion	Igneous, metamorphic & sedimentary	Dynamic impact & abrasion	19 - 0.075	5.0	1.18/0.075	Increase in fines

Wet/dry strength variation differs greatly from the other mechanical degradation assessment methods. The dry and wet 10% fines value tests evaluate aggregate resistance to crushing (toughness) when a uniaxial load is applied to a confined specimen. In comparison to the other mechanical degradation methods, this is the least representative of loading conditions applied during handling, construction and in-service for unbound granular pavement materials.

Ball mill value, LA abrasion, Deval attrition and micro-Deval abrasion are comparable methodologies imparting similar stress conditions. In these methods the coarse aggregate fraction is confined in a chamber and subjected to tumbling for a fixed number of cycles (hardness). Variations between the methods include the use, size and number of steel spheres, number of testing cycles, and inclusion of moisture and separation of aggregate into discrete test size fractions.

The alternative methods more accurately simulate the forces imparted during stockpiling, mixing, transport, and compaction of unbound pavement material. The ball mill and micro-Deval abrasion methods apply the most severe loading conditions employing both saturated aggregates and steel spheres. LA abrasion also employs steel spheres but assesses aggregate only in the dry condition. Deval attrition allows for testing of both SSD and OD aggregate, but does not employ steel spheres. Correlations between wet/dry strength variation and the other mechanical degradation assessment tests have been developed. However, it should be noted that the methods measure different properties of the material (toughness vs. hardness) (Smith 1984). In an evaluation of currently available durability testing methods for asphalt aggregates, Wu et al. (1998) found micro-Deval abrasion to be the most reliable mechanical degradation method for separating good and fair-performing aggregates from the poor performers.

In addition to the fundamental differences between the durability testing methodologies, the advantages and disadvantages from a practical standpoint vary. The wet/dry strength variation method has a long history of use in Australasia and provides an assessment of both toughness and soundness. The principal limitations of the wet/dry strength variation method are the poor simulation of in-service loading conditions, large sample requirements and low repeatability and reproducibility. The ball mill value, LA abrasion, Deval attrition and micro-Deval abrasion methods all provided better simulation of in-service loading conditions. However, each of the methods has distinct advantages and disadvantages as outlined in Table 6.3.

Table 6.3: Practical considerations for alternative mechanical degradation methods

Test method	Standard	Test fraction	Sample size (kg)	Measured parameter	Pros	Cons
Wet/dry strength variation	Q205C	13.2 - 9.5 mm	15.0	Change in particle strength	10% fines test specified to assess particle toughness; loading configuration induces both shear & point loading; testing apparatus is readily available; long history of use	Poorly replicates in-service conditions; low repeatability & reproducibility; expensive testing apparatus; only gravel size fraction is assessed; large sample size required
Ball mill value	AS 1141.28	26.5 - 0.425 mm	3.5	Increase in fines (< 0.425 mm)	Simulates handling during production & construction; assessment of both gravel & sand size fractions; short testing duration; history of use nationally	Specialty testing apparatus without additional applications; severe testing conditions (steel charge)
LA abrasion	AS 1141.23	19.0 - 9.5 mm	5.0	Increase in fines (< 1.7 mm)	Simulates handling during production & construction; short testing duration; testing apparatus is readily available; long history of use	Specialty testing apparatus without additional applications; only gravel size fraction is assessed; only oven-dry condition assessed; severe testing conditions (steel charge)
Deval attrition	AS 1141.27	53.0 - 37.5 mm	30.0	Increase in fines (< 2.56 mm)	Simulates handling during production & construction; assessment of both OD & SSD conditions	Specialty testing apparatus without additional applications; only gravel size fraction is assessed; large sample size required; long testing duration
Micro-Deval abrasion	Q229A Q229B	19.0 - 0.075 mm	1.5	Increase in fines (< 0.075 mm or < 1.18 mm)	Simulates handling during production & construction; assessment of wide range of particle sizes; international correlations with in situ performance	Specialty testing apparatus without additional applications; long testing duration

In addition to better simulating in-service loading conditions, the alternative mechanical degradation assessment methods provide significant benefits as compared to wet/dry strength variation including the assessment of both coarse and fine aggregate (ball mill and micro-Deval), shorter testing durations (ball mill and LA abrasion) and availability of established laboratory-to-field-performance relationships (micro-Deval). The principal limitation of the alternative mechanical degradation assessment methods is the requirement for specialised testing apparatus. Unlike wet/dry strength variation where the loading frame is also used for CBR, unconfined compressive strength (UCS) and indirect tensile testing, the apparatus for ball mill value, LA abrasion, Deval attrition and micro-Deval abrasion are only used to conduct the respective testing methods.

6.2 Weathering Degradation Methods

Degradation due to weathering results from cyclic environmental extremes such as wetting and drying or freezing and thawing. Durability testing methods can be utilised to indicate the resistance of aggregates to disintegration and decomposition resulting from weathering. Testing methods commonly utilised to identify resistance to weathering-induced degradation include degradation factor, accelerated soundness index, sodium/magnesium sulphate soundness and durability index.

The weathering degradation testing methods provide an indication of the soundness of aggregates by characterising either the nature of fines generated through self-abrasion or resistance to accelerated simulated weathering. The mineralogy, particle properties and degree of weathering significantly influence the results of weathering degradation tests. A summary comparison of the highlighted weathering degradation testing methods is presented in Table 6.4.

Table 6.4: Summary comparison of weathering degradation methods

Test method	Applicable rock types	Degradation mechanism	Aggregate size (mm)	Sample required (kg)	Definition of fines (mm)	Measured parameter
Degradation factor	Igneous & metamorphic	Dynamic abrasion	13.2 - 4.75	5.0	0.075	Nature of fines
Accelerated soundness	Igneous (basalt)	Chemical decomposition	13.2 - 11.2	2.0	6.700	Increase in fines
NaS_2/MgS_2 soundness	Igneous, metamorphic & sedimentary	Internal crystalline expansion	75 - 0.30	30.0	4.75	Increase in fines
Durability index	Igneous & metamorphic	Dynamic abrasion	19 - 4.75	30.0	0.075	Nature of fines

The degradation factor and durability index testing methods are very similar and essentially only vary in the separation of the coarse aggregate into discrete-size fractions. The tests measure the settling rate of fine particles generated through self-abrasion of the aggregate in the presence of moisture. Due to the low repeatability and reproducibility, these tests should be used as supplementary diagnostic measures, with the rejection of aggregate based on the results of other methods (AS 1141.25.2-2003).

The distress mechanism of accelerated soundness testing is fracture due to volumetric change and thermal variation stresses (Austroads 2008b). Boiling in ethylene glycol is a severe environment allowing for accelerated assessment of weathering resistance of primarily basalt rock types. Due to the limited applicability of this testing measure, routine utilisation in the evaluation of aggregate is not recommended (AS 1141.29-1999).

The sodium and magnesium sulphate soundness testing methods simulate freeze-thaw in cold regions and wetting-drying conditions in marine environments. The performance prediction capability of the sulphate soundness method was considered only fair in an evaluation of durability testing methods, despite widespread utilisation (Wu et al. 1998). The method has been found to be insensitive to aggregate attributes and exhibits low reproducibility (Collis & Fox 1985). Due to the low repeatability and reproducibility, sulphate soundness testing is not suitable for the outright rejection of aggregates without confirmation from other tests more closely related to the specific intended use (AS 1141.24-2013).

Due to the inherent limitations of the accelerated soundness (severe conditions) and sodium and magnesium soundness (low sensitivity) methods, weathering degradation potential is ideally assessed using the degradation factor/durability index methods. Degradation factor is more commonly used in Australasia and can be determined in accordance with TMR (Q208B) or Standards Australia (AS 1141.25.2/3) methods. The degradation factor method has a number of practical advantages and limitations as outlined in Table 6.5.

Table 6.5: Practical considerations for alternative weathering degradation methods

Test method	Standard	Test fraction	Sample size (kg)	Measured parameter	Pros	Cons
Degradation factor	Q208B AS 1141.25.2	13.2 - 2.0 mm	1.0	Settling rate of fines (< 0.075 mm)	Long history of use; specified regularly both nationally & internationally; assessment of both gravel & sand size fractions	No correlation to engineering property; low repeatability & reproducibility; O, H & S concerns (stock solution); long testing duration
	AS 1141.25.3	4.75 - 0.425 mm	0.2			

6.3 Supplementary Methods

The secondary minerals content test is a visual method for identifying late-stage crystallisation, alteration and weathering products in aggregate specimens. The method is only applicable to igneous rocks without identifiable metamorphic texture or mineral assemblage (AS 1141.26-2008). Secondary minerals content cannot be used alone to provide a measure of quality, as secondary minerals are not necessarily deleterious. Limitations of the method include the requirement for specialised optical equipment and personnel qualified by education and experience in petrological work. The method provides valuable insight to the nature of the aggregate, but the accuracy of the assessment is limited by the accuracy of the petrographer. The practical benefits and limitations of the secondary minerals content method are presented in Table 6.6.

Aggregates with a high capacity to absorb moisture are typically more sensitive to moisture-induced strength and volumetric change in addition to decomposition and disintegration. Absorption values for high-quality pavement construction materials typically range from 1% to 3% (Smith & Collis 1993). In general, source rocks with absorption values less than 2% produce good-quality aggregate and those with values in excess of 4% generally do not (Collis & Fox 1985). The absorption capacity of aggregate is rapidly and easily determined and can provide a clear separating characteristic in the selection of preferred aggregate sources. The practical benefits and limitations of the absorption testing method are presented in Table 6.6.

Table 6.6: Practical considerations for supplementary durability methods

Test method	Standard	Test fraction	Sample size (kg)	Measured parameter	Pros	Cons
Secondary minerals content	AS 1141.26	All	1.0	Proportion of secondary minerals	Accurate geological classification of material; quantitative assessment of secondary minerals	No distinction between deleterious & non-deleterious materials; specialty testing apparatus required; highly skilled operator required; low repeatability & reproducibility
Absorption	Q214B	> 4.75 mm	10.0	Moisture affinity	Specified regularly both nationally & internationally; assessment of wide range of particle sizes; quick, cheap & easy test procedure	Poor indicator of fines activity; large sample required
	Q214A	< 4.75 mm	2.0			

6.4 Applicability to Queensland

The source mineralogy for aggregate used in Queensland is predominantly basic igneous (basalt), but significant sources of metamorphic and sedimentary materials are also available. The decomposition and disintegration of basaltic rock types is the principal, durability-related, failure mode for unbound granular pavements in Queensland. Commonly employed methods for assessing resistance to mechanical degradation include wet/dry strength variation, ball mill, LA abrasion, Deval attrition and micro-Deval abrasion. Wet/dry strength variation is the method utilised in Queensland (TMR 2015a). Dry aggregate materials containing significant proportions of clayey materials provide high crushing resistance. However, when saturated, the toughness of these materials degrades rapidly.

Wet/dry strength variation provides an indication of the robustness of the composing particles (dry/wet 10% fines value) and the relative clayey materials content (wet/dry strength variation). However, not all clayey materials are deleterious and secondary assessment methods are required to characterise the nature of the fines. Material sources known to possess highly reactive fines, high concentrations of clayey particles or high secondary minerals content should be subjected to rigorous soundness assessment. Commonly utilised methods for assessing resistance to weathering-induced degradation include degradation factor, accelerated soundness, sodium/magnesium sulphate soundness and durability index. Determination of the degradation factor is the current method employed in Queensland (TMR 2015a).

Alternative mechanical degradation assessment methods such as ball mill, LA abrasion, Deval attrition and micro-Deval abrasion are fundamentally different from wet/dry strength variation. The methods subject aggregate specimens to dynamic aggregate-to-rigid-object and/or aggregate-to-aggregate impacts representative of stresses imparted during processing and construction activities. The methods measure the increase in fines resulting from repeated tumbling that is indicative of abrasion and wear propensity in addition to the relative degree of weathering. The ball mill, LA abrasion and micro-Deval abrasion methods incorporate steel spheres during the tumbling that provide greater impact loads for the additional assessment of aggregate toughness. The ball mill and micro-Deval abrasion tests are conducted in the presence of moisture, LA abrasion is conducted on OD aggregate and Deval attrition is accomplished under both OD and SSD conditions. The prevalence of saturated conditions in the Queensland roadbed environment warrants durability assessment under saturated conditions.

Degradation factor and durability index are similar testing methodologies and vary principally in the discrete-size fractions utilised for testing. The test methods subject aggregates to tumbling in the presence of moisture, similar to Deval attrition, and measure the settling rate of the generated fines. The rate at which the fine particles settle indicates the nature and potential reactivity of the materials. The accelerated soundness test subjects aggregates to cyclic boiling and soaking in ethylene glycol. The process provides a rapid simulation of the effects of weathering on basaltic rock types. The proportion of coarse particles remaining is indicative of resistance to weathering-induced degradation. The severity of the imposed conditions and applicability only to basalts limits the effectiveness for routine implementation. Sodium/magnesium sulphate soundness induces expansive pressure within aggregates subjected to repeated soaking and drying. The method simulates the forces endured by aggregates during freeze-thaw in cold climates and wetting-drying in marine climates. The generally warm climate of Queensland limits the feasibility of the method for routine application. However, the method may be more appropriate in coastal areas where materials are subject to regular saltwater inundation.

7 ASSESSMENT OF ALTERNATIVE METHODS

The in-service breakdown of unbound granular material diminishes the strength properties, reduces the stability and increases the permeability of pavement layers with significant negative impacts on long-term structural performance. Reliable characterisation of the long-term durability of unbound pavement materials requires consideration of hardness, toughness and soundness properties. Hardness, or resistance to abrasion, can be determined using the ball mill, LA abrasion, Deval attrition or micro-Deval abrasion testing methods. Toughness, or resistance to impact loads, can be determined through measurement of ACV, 10% fines value, ball mill value, LA abrasion value, or micro-Deval abrasion loss.

Soundness, or resistance to weathering, can be directly assessed using measures such as degradation factor, durability index, accelerated soundness or sodium/magnesium sulphate soundness or inferred by considering the difference in performance of wet and saturated specimens in the wet/dry strength variation and ball mill mechanical degradation tests. Other supplementary testing methods such as secondary minerals content and absorption can be utilised to increase the reliability of the durability assessment. The optimal system of durability assessment allows for accurate, highly repeatable and reproducible determination of hardness, toughness and soundness properties using the minimal number of independent tests.

In addition to investigating the wet/dry strength variation criteria limits and the impact of referencing the wet 10% fines value exclusively, an objective of this study was to determine if alternative durability testing methods better simulating in-service conditions could provide improved repeatability and reproducibility as compared to wet/dry strength variation. The effectiveness and efficiency of selected durability testing methods was investigated by examining sensitivity to durability-related material properties and material ranking relative to historical performance observations.

Four representative basaltic pavement materials conforming to MRTS05 Type 2.1 or Type 2.2 (TMR 2015a) and covering the range of durability properties (10% fines value, degradation factor and wet/dry strength variation) currently encountered in Queensland were selected for assessment. The laboratory testing protocol included basic material characterisation in addition to strength (soaked CBR) and durability (wet/dry strength variation, LA abrasion value, micro-Deval loss and degradation factor) assessments. The laboratory testing reported in this section was conducted at the TMR Materials Laboratory in Herston during the period of July to September 2015.

7.1 Representative Materials

As basic igneous (basalt) pavement materials are widely available throughout Queensland and also have the greatest propensity to deteriorate in-service, the assessment of alternative durability testing methods was conducted using products derived from basalt source rocks. The identification of candidate materials was accomplished by referencing the QAR testing results submitted as part of the TMR QRS (outlined in Section 4.2) and consulting materials experts in the TMR Engineering and Technology Branch. Ideal aggregates for the investigation were TMR Type 2.1 or Type 2.2 pavement materials with an established history of utilisation in unbound granular applications, relatively consistent QAR testing results and durability properties representative of the wide range of basalt products currently available in Queensland.

Four material sources, identified herein as Quarry 1, Quarry 2, Quarry 3 and Quarry 4, were selected from the Far North, Wide Bay/Burnett and South West regions of the state. A description of each material source and the typical properties for pavement products determined from the available QAR testing results are presented in Table 7.1.

Table 7.1: Material property summary for selected quarry products

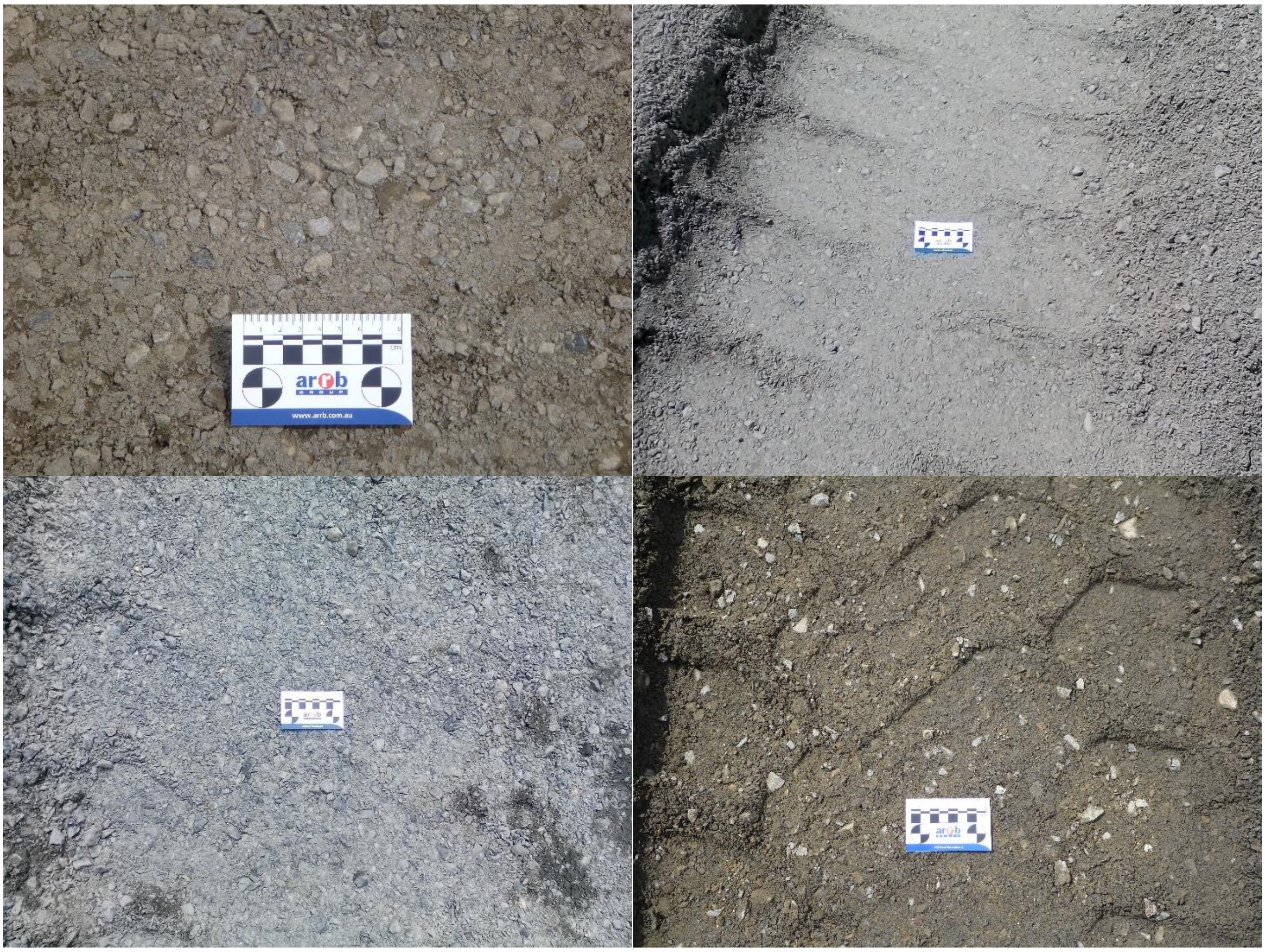
Site ID	Quarry 1		Quarry 2		Quarry 3		Quarry 4		
Description	Partly glassy basalt		Olivine basalt		-		Basalt (various)		
Region	South West		Far North Qld		Far North Qld		Wide Bay/Burnett		
Product	2.1	2.2	2.1	2.3	2.1	2.3	2.1	2.3	2.4
Wet 10% fines (kN)	168	202	-	183	-	212	-	-	-
Dry 10% fines (kN)	206	230	-	272	-	252	-	-	-
Wet/dry strength variation (%)	18	12	-	33	-	16	-	-	-
Degradation factor	76	63	61	59	57	50	83	78	-
Liquid limit (%)	28	31	22	23	23	26	24	26	30
Plastic limit (%)	24	28	19	19	19	20	21	23	25
Plasticity index	4	4	3	4	4	5	3	4	5
Linear shrinkage (%)	1.4	2.4	1.3	2.1	2.3	3.8	1.2	1.7	3.8
Flakiness index	-	14	12	11	33	-	-	-	-

All of the selected representative sources produce TMR Type 2.1 or Type 2.2 unbound granular material that is regularly used in the provision of base and subbase pavement layers. The sources are widely distributed (north-south) across Queensland within 500 km of the eastern coastline. The QAR testing results provided by the TMR Engineering and Technology Branch included initial registration, re-registration and monitoring data in accordance with the QRS (TMR 2015b) submitted from 2009 to 2014.

Quarry 1 and Quarry 3 were selected as being representative of the typical standard basalt pavement material currently available. The wet/dry strength variation values for Quarry 1 and Quarry 3 materials approach the state-wide mean value of 19% determined in this study (Section 4.3). It should be noted that the liquid limit results for TMR Type 2.1 and Type 2.2 material from Quarry 1 (highlighted red) are in excess of the MRTS05 criteria limit of 25.

Quarry 2 and Quarry 4 were selected as being representative of the low and high ends of the currently available product standards respectively. Ten per cent fines value and wet/dry strength variation QAR testing results were not available for Quarry 4. However, personnel from the TMR Engineering and Technology Branch attested to the quality and consistency of the source. Images of basic igneous products 1 through 4 obtained from quarries 1 through 4 respectively after compaction on the quarry floor using a 10-tonne front-end loader are presented in Figure 7.1.

Figure 7.1: Basic igneous product 1 (top left), 2 (top right), 3 (bottom left) and 4 (bottom right)



7.2 Laboratory Testing

The objective of the laboratory testing protocol was to verify the physical properties of the selected representative materials and evaluate alternative mechanical degradation testing methods relative to: 1) sensitivity to durability properties, 2) repeatability and 3) ranking of materials relative to historical performance observations. Material characterisation included determination of the distribution of particle sizes, Atterberg limits, apparent particle density, moisture/density relationship, flakiness, crushed particles and soaked CBR. The testing methods, reference standards and test size fractions utilised for characterisation of the representative basalt materials are presented in Table 7.2.

Table 7.2: Laboratory testing protocol

Test method	Reference standard	Test fraction
Material characterisation		
Particle size distribution	Q103A	26.5 - 0.075 mm
Liquid limit	Q104A	< 0.425 mm
Plasticity index	Q105	< 0.425 mm
Linear shrinkage	Q106	< 0.425 mm
Apparent particle density	Q109A	< 2.36 mm
Apparent particle density	Q109B	> 2.36 mm
Soaked CBR	Q113A	< 19.0 mm

Test method	Reference standard	Test fraction
Dry density/moisture relationship	Q142A	< 19.0 mm
Flakiness index	Q201	37.5 - 4.75 mm
Crushed particles	Q215	37.5 - 4.75 mm
Durability assessment		
Degradation factor	Q208B	13.2 - 2.36 mm
Degradation factor	AS 1141.25.3	4.75 - 0.425 mm
Absorption	Q214B	> 4.75 mm
Absorption	Q214A	< 4.75 mm
Secondary minerals content	AS 1141.26	> 0.425 mm
Secondary minerals content	AS 1141.26	< 0.425 mm
Wet/dry strength variation	Q205C	13.2 - 9.5 mm
LA abrasion	AS 1141.23	19.0 - 9.5 mm
Micro-Deval abrasion	Q229A	4.75 - 0.075 mm
Micro-Deval abrasion	Q229B	19.0 - 9.5 mm

In addition to the material characterisation testing, weathering degradation potential and supplementary durability measures were also assessed. As outlined in Section 6.2 and Section 6.4, the alternative weathering degradation assessment methods including accelerated soundness and sodium/magnesium sulphate soundness are inappropriate for characterisation of weathering in the prevalent Queensland roadbed environment. As such, degradation factor was the sole weathering-degradation assessment method investigated and was undertaken on both the coarse and fine fractions of the representative basalt materials.

Supplementary durability measures of absorption and secondary minerals content were also undertaken on both the coarse and fine fractions of the representative materials to validate the relative ranking of materials accomplished using the mechanical degradation assessment methods. The testing methods, reference standards and applicable test fractions utilised for the weathering degradation and supplementary durability assessments are presented above in Table 7.2.

The ball mill, LA abrasion, Deval attrition and micro-Deval abrasion methods were identified as commonly utilised (either nationally or internationally) alternatives to the wet/dry strength variation method for assessment of the mechanical degradation potential of unbound pavement materials. The LA abrasion test is commonly utilised locally, nationally and internationally and was selected for further investigation due to the long history of use and ready availability of the required testing apparatus.

The micro-Deval abrasion method was also selected for further investigation as it evaluates both hardness and toughness properties in the presence of moisture, is becoming widely accepted as the preferred aggregated durability assessment method internationally and relationships between laboratory testing values and in situ performance have been previously developed.

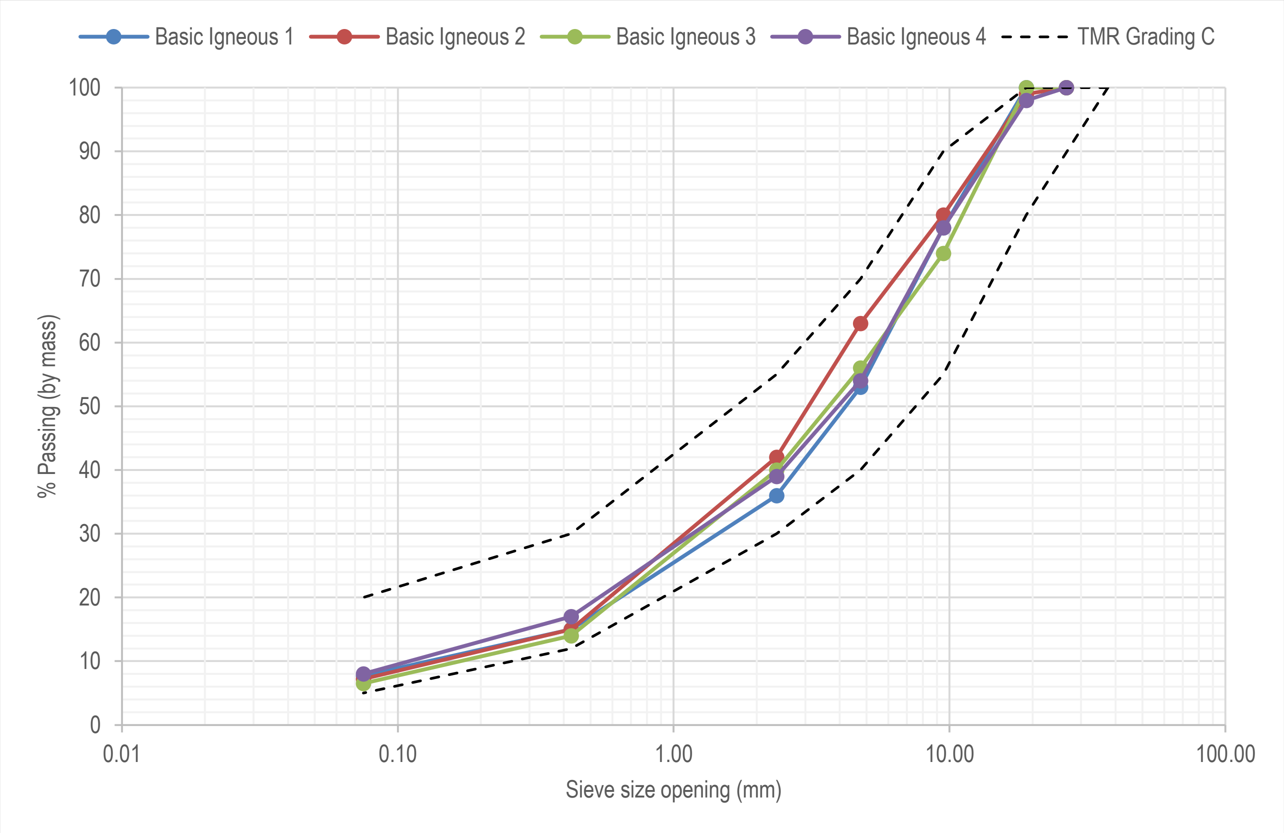
The ball mill method is commonly utilised in Victoria and South Africa, but was not selected for further investigation as the fundamental methodology is similar to the micro-Deval abrasion method, but is not as widely utilised internationally. The Deval attrition method is primarily utilised in the UK and was not selected for further investigation as the loading configuration (self-abrasion due to tumbling in the presence of moisture) is similar to the degradation factor method, but does not provide a direct assessment of material soundness. The testing methods, reference standards and test fraction sizes utilised as part of the assessment of alternative mechanical degradation methods are presented above in Table 7.2.

7.3 Results

7.3.1 Material Characterisation

Material characterisation testing was undertaken to validate the physical properties of the representative basalt pavement materials prior to assessment using the alternative mechanical degradation, weathering degradation and supplementary durability methods. The material characterisation included determination of the particle size distribution, Atterberg limits, apparent particle density, moisture/density relationship, flakiness index, percentage of crushed particles and soaked CBR. The particle size distribution of the four basic igneous products are presented in Figure 7.2.

Figure 7.2: Particle size distribution of sampled products



As can be observed in Figure 7.2, the particle size distribution of basic igneous products 1 through 4 are very similar and fall within the pilot grading boundaries for a Type 2 C-grading material in accordance with MRTS05 (TMR 2015a). The relative particle size proportions are almost identical for sizes greater than 10 mm and smaller than 1 mm. Slight differences can be observed for the intermediate particle sizes (coarse sand and fine gravel) probably due to differences in the source rock fabric in addition to extraction and processing techniques. A geological description of basic igneous products 1 thru 4 and associated material properties are presented in Table 7.3.

Table 7.3: Material properties of sampled products

Material ID	Basic Igneous 1	Basic Igneous 2	Basic Igneous 3	Basic Igneous 4
Description	Partly glassy basalt	Olivine basalt	Olivine basalt	Olivine basalt
Region	South West	Far North Qld	Far North Qld	Wide Bay/Burnett
Product (grading)	2.2 (mod. C)	2.1 (C)	2.1 (C)	2.1 (C)
Wet 10% fines (kN)	157	141	249	185
Wet/dry strength variation (%)	25	41	20	14
Degradation factor	54	43	49	72
Flakiness index (%)	14	10	25	35
Liquid limit (%)	30	26	21	25
Plasticity index	4	3	3	3
Weighted plasticity index	59	49	40	52
Fines ratio	0.50	0.47	0.45	0.46
Soaked CBR (%)	125	112	102	114
Maximum dry density (t/m^3)	2.07	2.21	2.20	2.08
Optimum moisture content (%)	13	11	10	12

Basic igneous products 2, 3, and 4 are olivine basalt conforming to a TMR Type 2.1 C-grading in accordance with MRTS05. Basic igneous product 1 is a partly-glassy basalt conforming to a TMR Type 2.2 modified (mod.) C-grading.

As can be observed in Table 7.3, the selected representative basalt materials cover a wide range of properties, with the exception of plasticity index where the values range from 3 to 4. It should be noted that some nonconforming (highlighted red) testing results were obtained for wet/dry strength variation (basic igneous 2), degradation factor (basic igneous 2 and 3) and liquid limit (basic igneous 1 and 2). Referencing the mean QAR testing results for liquid limit also indicated that Quarry 1 (basic igneous1) produced aggregates with potentially nonconforming liquid limit properties. Basic igneous 4 was the only representative material evaluated as part of this study found to be in full conformance with the material property requirements of MRTS05 (TMR 2015a).

7.3.2 Durability Assessment

The assessment of durability properties for the representative basalt products included evaluation of the coarse and fine fractions independently (where possible). The coarse fraction was subjected to the entire durability assessment protocol including wet/dry strength variation, LA abrasion and micro-Deval abrasion in addition to degradation factor, secondary minerals content and absorption. The fine fraction was subjected to the same durability assessment protocol with the exception of wet/dry strength variation and LA abrasion, as these methods are not appropriate for fine graded materials. In addition to the separate assessment of the coarse and fine fractions, the mechanical degradation methods were conducted in duplicate to assess the repeatability of the respective methods. The results obtained from the durability assessment of the coarse fraction are presented in Table 7.4.

Table 7.4: Durability properties for coarse fraction of sampled products

Material ID	Basic Igneous 1		Basic Igneous 2		Basic Igneous 3		Basic Igneous 4	
Description	Partly glassy basalt		Olivine basalt		Olivine basalt		Olivine basalt	
Region	South West		Far North Qld		Far North Qld		Wide Bay/Burnett	
Product (grading)	2.2 (mod. C)		2.1 (C)		2.1 (C)		2.1 (C)	
Wet/dry strength variation (%)	27.0	22.0	38.0	43.0	22.0	18.0	12.0	15.0
LA abrasion (%)	20.0	19.0	17.0	17.0	12.0	12.0	17.0	18.0
Micro-Deval abrasion (%)	13.5	13.4	15.5	14.6	12.7	12.9	13.6	14.7
Degradation factor	54.0	-	43.0	-	49.0	-	72.0	-
Secondary minerals content (%)	5.0	-	14.8	-	17.1	-	9.8	-
Absorption (%)	4.8	-	2.8	-	1.7	-	2.6	-

The measured wet/dry strength variation values ranged from 12% to 43% with nonconforming (highlighted red) measurements obtained for basic igneous product 2. The mean variability between measurements was approximately ± 4.25%. It should be noted that nonconforming (highlighted red) wet/dry strength variation values were obtained for both tests on basic igneous product 2 and nonconforming degradation factor values were obtained for basic igneous products 2 and 3.

The measured LA abrasion values ranged from 12% to 20% with a mean variation between measurements of ± 0.5%. The measured micro-Deval abrasion values ranged from 12.7% to 15.5% with a mean variation between measurements of ± 0.575%. The measured degradation factor, secondary minerals and absorption values ranged from 43% to 72%, 5.0% to 17.1% and 1.7% to 4.8% respectively. The durability assessment results obtained from the fine fraction evaluation are presented in Table 7.5.

Table 7.5: Durability properties for fine fraction of sampled products

Material ID	Basic Igneous 1		Basic Igneous 2		Basic Igneous 3		Basic Igneous 4	
Description	Partly glassy basalt		Olivine basalt		Olivine basalt		Olivine basalt	
Region	South West		Far North Qld		Far North Qld		Wide Bay/Burnett	
Product (grading)	2.2 (mod. C)		2.1 (C)		2.1 (C)		2.1 (C)	
Wet/dry strength variation (%)	-	-	-	-	-	-	-	-
LA abrasion (%)	-	-	-	-	-	-	-	-
Micro-Deval abrasion (%)	16.7	19.5	21.7	22.5	16.2	16.3	15.1	15.2
Degradation factor	66.0	-	50.0	-	65.0	-	83.0	-
Secondary minerals content (%)	8.5	-	15.4	-	14.2	-	7.9	-
Absorption (%)	6.0	-	3.3	-	3.1	-	3.2	-

The measured micro-Deval abrasion values for the fine fraction ranged from 15.1% to 22.5% with a mean variability between measurements of ± 0.7%. The range of values and mean variation for the fine fraction was greater than observed for the coarse fraction. It is worth noting that in their evaluation of alternative durability assessment methods Wu et al. (1998) determined that a micro-Deval abrasion value of 18% separated the good (< 18%) and poor (> 18%) performing materials. In accordance with the findings of Wu et al. (1998), basic igneous product 2 would be considered a potentially poor performing material. The measured degradation factor, secondary minerals and absorption values ranged from 50% to 83%, 7.9% to 15.4% and 3.1% to 6.0% respectively.

7.4 Comparison of Alternative Methods

7.4.1 Method Efficiency

In addition to differences in loading conditions, test fraction size and repeatability, the relative efficiency with which the alternative methods can be executed varies. The laboratory testing results presented in Section 7.3 was provided by the TMR Materials Laboratory in Herston. Table 7.6 presents a comparison of significant factors contributing to the overall efficiency of the wet/dry strength variation, LA abrasion, micro-Deval abrasion and degradation factor methods including specimen preparation, required apparatus, procedure complexity and resource (time and budget) requirements. The comparison presented in Table 7.6 is a summary of a practical assessment of the alternative durability testing methods provided by Jason Maudsley, Senior Materials Officer, TMR.

Table 7.6: Practical considerations for alternative durability assessment methods

Testing considerations	Testing method			
	Wet/dry strength variation (Q205C)	LA abrasion (AS 1141.23)	Micro-Deval abrasion (Q229A/B)	Degradation factor (Q208B & AS 1141.25.3)
Bulk sample size & preparation time	High	High	Moderate	Low
Specialised apparatus required	No	Yes	Yes	Yes
Specialised material handling required (storage facilities, MSDS, etc.)	No	No	No	Yes
Method complexity	Moderate	Low	Low	Moderate
Approximate test execution time (days)	3+	3	3	2
Approximate test cost (per sample)	$600-$800	$300-$500	$600-$800	$350-$550

As can be observed in Table 7.6, sample size requirements and preparation time are greatest for wet/dry strength variation and LA abrasion, followed by micro-Deval abrasion and with degradation factor requiring the smallest samples with least amount of pre-processing. The preparation of samples for wet/dry strength variation and LA abrasion was observed to be labour-intensive and time-consuming by Maudsley. As presented in Section 6.1, the LA abrasion, micro-Deval and degradation factor methods all require specialised testing equipment and due to the use of a stock solution containing formaldehyde, specialised material handling procedures are also required for the degradation factor method. Maudsley found all of the methods to be relatively easy to understand and execute. However, selecting the appropriate load to achieve a 7.5% to 12.5% increase in fines in the wet/dry strength variation method and the transition between testing phases in the degradation factor method are non-trivial and increase the complexity as compared to the LA abrasion and micro-Deval abrasion methods. Total testing time from sample preparation to the calculation of results is shortest for degradation factor followed by LA abrasion and micro-Deval abrasion. Wet/dry strength variation requires the longest testing time, which is primarily the result of extensive specimen processing requirements. From a cost perspective, LA abrasion and degradation factor provide similar value where wet/dry strength variation and micro-Deval abrasion are considerably more costly.

7.4.2 Method Effectiveness

Sensitivity to Material Properties

The effective assessment of long-term unbound pavement material durability requires the specified characterisation measures be able to measure and distinguish between the engineering properties most significantly contributing to mechanical and weathering-induced degradation. The selected representative basaltic pavement materials include a wide-range of material properties and are representative of the range in material quality standard currently available in Queensland. As such, a wide distribution in durability properties should be indicated by the investigated assessment methods. This is the case for all of the mechanical and weathering-induced degradation potential assessment methods investigated in this study. A wide range in results can be observed between materials for the coarse and fine proportion assessments. This finding indicates that the methods investigated are sensitive, to varying degrees, to the engineering properties influencing long-term durability and can successfully be used as performance indicators when correlations between laboratory testing results and in-pavement performance are available.

Repeatability

The alternative mechanical degradation methods were conducted in duplicate to allow for comparison (non-statistically significant) of the relative repeatability of each method. Repeatability is a measure of random error between successive results, all other variables including material, operator, equipment and environment held constant. The quantitative assignment of method repeatability requires the assessment of several replicates of multiple materials in a number of different laboratories. Determining the explicit repeatability of the investigated methods was outside the scope of the project.

Wet/dry strength variation, LA abrasion and micro-Deval abrasion methods were conducted in duplicate and the standard deviation (σ) between results calculated to assess the relative repeatability of the alternative methods. The mean and σ for the mechanical degradation assessment results for the coarse proportion of the representative materials are presented in Table 7.7.

The average standard deviation for the results of the wet/dry strength variation, LA abrasion and micro-Deval abrasion testing on the coarse fraction of the representative materials were 2.975, 0.35 and 0.4 respectively. Only the micro-Deval method includes provisions for the assessment of the fine fraction and the mean σ was consistent with the coarse fraction assessment at 0.7 as presented in Table 7.8. Based on the limited results of this study, the LA abrasion and micro-Deval abrasion testing methods provide significantly improved repeatability as compared to wet/dry strength variation. Reduced measurement error is an inherent benefit of the micro-Deval abrasion method as the testing is conducted in duplicate and the results averaged.

Table 7.7: Comparison of durability assessments for coarse fraction of sampled products

Material ID	Basic Igneous 1		Basic Igneous 2		Basic Igneous 3		Basic Igneous 4	
Description	Partly glassy basalt		Olivine basalt		Olivine basalt		Olivine basalt	
Region	South West		Far North Qld		Far North Qld		Wide Bay/Burnett	
Product (grading)	2.2 (mod. C)		2.1 (C)		2.1 (C)		2.1 (C)	
	Average	σ	Average	σ	Average	σ	Average	σ
Wet/dry strength variation (%)	24.5	3.5	40.5	3.5	20.0	2.8	13.5	2.1
LA abrasion (%)	19.5	0.7	17.0	0.0	12.0	0.0	17.5	0.7
Micro-Deval abrasion (%)	13.5	0.1	15.1	0.6	12.8	0.1	14.2	0.8
Degradation factor	54.0	-	43.0	-	49.0	-	72.0	-
Secondary minerals content (%)	5.0	-	14.8	-	17.1	-	9.8	-
Absorption (%)	4.8	-	2.8	-	1.7	-	2.6	-

Table 7.8: Comparison of durability assessments for fine fraction of sampled products

Material ID	Basic Igneous 1		Basic Igneous 2		Basic Igneous 3		Basic Igneous 4	
Description	Partly glassy basalt		Olivine basalt		Olivine basalt		Olivine basalt	
Region	South West		Far North Qld		Far North Qld		Wide Bay/Burnett	
Product (grading)	2.2 (mod. C)		2.1 (C)		2.1 (C)		2.1 (C)	
	Average	σ	Average	σ	Average	σ	Average	σ
Wet/dry strength variation (%)	-	-	-	-	-	-	-	-
LA abrasion (%)	-	-	-	-	-	-	-	-
Micro-Deval abrasion (%)	18.1	2.0	22.1	0.6	16.3	0.1	15.2	0.1
Degradation factor	66.0	-	50.0	-	65.0	-	83.0	-
Secondary minerals content (%)	8.5	-	15.4	-	14.2	-	7.9	-
Absorption (%)	6.0	-	3.3	-	3.1	-	3.2	-

Relative Ranking of Materials

The mean (mechanical degradation) and absolute (weathering degradation and supplementary methods) durability assessment testing results for each of the basaltic pavement materials were compared to allow for ranking of the respective materials according to each of the durability assessment methods. Table 7.7 and Table 7.8 present the relative ranking of the coarse and fine proportions of the representative materials respectively were green shading indicates the most preferred material, amber shading indicates the next preferred material and orange shading indicates the least preferred material. Red shading is also used to indicate nonconforming values according to MRTS05 (TMR 2015a).

When evaluating the relative ranking according to the coarse fraction testing, significant variability can be observed between the alternative mechanical degradation methods. Each of the materials is considered either most preferred or least preferred according to one method or the other. The only relative ranking agreement for the coarse fraction assessment methods is between the LA abrasion and absorption measures. However, when evaluating the relative ranking according to the fine fraction testing, the methods are more-or-less in agreement with basic igneous material 4 most preferred, basic igneous materials 1 and 3 next preferred and basic igneous material 2 least preferred. It is interesting to note that the relative ranking according to the fine fraction assessment is in agreement with the general quality standard assessment conducted during selection of the representative basic igneous sources (Section 7.1) based upon the QAR testing results and qualitative performance assessments according to historical performance observations.

Coarse vs. Fine Fraction Assessment

The long-term durability of unbound pavement materials is determined by the degree of weathering and alteration in addition to the nature of the fines component. In consideration of this, assessment of the fines fraction and/or the fines generated through abrasion of the coarse fraction (degradation factor) may be the most appropriate approach for assessing aggregate potential for mechanical and weathering-induced degradation.

Referencing the mechanical degradation assessment obtained through micro-Deval abrasion of the fine fraction in addition to weathering degradation assessment obtained through degradation factor testing of both the coarse and fine component and the supplementary durability assessment of the fines component shows good agreement between the methods where the preferability of the materials would be ranked basic igneous 4, basic igneous 1, basic igneous 3, basic igneous 2 from most to least preferred. It is interesting to note that this ranking is in agreement with the relative quality standard assessment presented in Section 7.1. It is also interesting to note that the current material assessment scheme including wet/dry strength variation and degradation factor assessment of the coarse fraction does not produce the same relative material ranking.

8 CONCLUSIONS AND RECOMMENDATIONS

The use of unbound granular materials in the upper layers of flexible pavements is reaching the performance limits of the application (Basford 1993). A review of the wet/dry strength variation testing method and the criteria limits specified in MRTS05 (TMR 2015a) was undertaken to confirm the appropriateness and effectiveness of current durability assessment methods. Wet/dry strength variation is utilised by a number of road agencies to identify aggregates composed of potentially deleterious materials. In Queensland, wet/dry strength variation and degradation factor testing are referenced as indicators of mechanical and weathering-induced degradation potential respectively. Anecdotally, current specification limits are too restrictive and relaxation of the criteria or adoption of alternative testing methods will expand potential sources of unbound pavement material, potentially reducing the cost of establishing and rehabilitating road pavement infrastructure.

The in-service deterioration of unbound granular material is one of the leading causes of premature failure for these pavement types. Historical performance issues with basic igneous materials were the primary driver of the current MRTS05 durability testing regimen and specification limits. National and international criteria limits for wet/dry strength variation were reviewed in addition to typical values for Queensland aggregates. MRTS05 criteria for basic igneous rocks are the most stringent in Australia and exclude some 10% to 20% of basalt sources. However, inclusion of the wet/dry strength variation method and current criteria limits has significantly reduced the occurrence of durability-related premature failures. While the benefits of assessing mechanical degradation potential have been demonstrated, limitations of the wet/dry strength variation method, including poor replication of in-service loading conditions and low repeatability and reproducibility, inhibited a reliable assessment of criteria limit appropriateness.

Alternative mechanical degradation assessment methods including wet/dry strength variation, LA abrasion and micro-Deval abrasion were also examined using basaltic unbound pavement materials representative of the range of products currently available in Queensland. Based upon the limited testing carried out as part of this investigation, micro-Deval abrasion was observed to provide better simulation of in-service loading conditions, assessment of both fine and coarse aggregates, increased repeatability and reproducibility and significantly improved laboratory efficiency as compared to wet/dry strength variation. However, further testing is required on the range of mineralogy and product standards currently available in Queensland to refine the standard testing methods (TMR Q229A/B) and establish reliable criteria limits for micro-Deval abrasion.

Recommendations resulting from this investigation include:

- The wet/dry strength variation testing method and current criteria limits in MRTS05 should continue to be specified in the immediate future, as the value of the method in reducing the occurrence of durability-related premature pavement failure has been demonstrated.
- The degradation factor testing method should continue to be specified .for assessment of susceptibility to weathering-induced degradation in conjunction with a mechanical degradation assessment method such as wet/dry strength variation or micro-Deval abrasion. Alternative methods are available, but are inappropriate for characterisation of Queensland roadbed conditions.
- A transition to the micro-Deval abrasion testing method should be systemically undertaken following validation of the sensitivity of the method to variances in Queensland aggregate properties and establishment of reliable performance criteria.

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APPENDIX A ALTERNATIVE DURABILITY TESTING METHODS

A.1 Ball Mill

The ball mill value test provides an indication of the ability of coarse aggregates to resist degradation when exposed to moisture. Testing includes the tumbling of an aggregate specimen, six 48 mm steel spheres and measured amounts of water for 600 revolutions and measuring the mass of fine particles (< 0.425 mm) generated as a result of aggregate-to-aggregate and aggregate-to-rigid-object contact. The method was developed to assess the resistance to mechanical degradation of sedimentary materials but can also be applied to other rock types. The ball mill value can be determined in accordance with Australian Standard (AS) 1141.28, *Methods for Sampling and Testing Aggregates: Ball Mill Value* (AS 1141.28-1999).

A.1.1 Apparatus

Equipment required for determination of the ball mill value of coarse aggregate includes:

- ball mill: 259 mm diameter and 273 mm height including an internal 83 mm by 8 mm shelf; minimum 60 revolutions per minute rotation capability
- measuring cylinder: 2.0 L capacity, graduated at 50 mL intervals
- oven: thermostatically controlled; 50 to 60 °C
- sieves: 53, 26.5, 9.5, 4.75, and 0.425 mm
- steel spheres: six of 417.5 g mass and 48 mm diameter.

A.1.2 Specimen Preparation

The preparation of coarse aggregate samples for the ball mill test includes:

1. Obtain sufficient size aggregate sample.
2. Crush the sample as required to ensure all particles pass the 53 mm sieve opening.
3. Dry the sample to constant mass at 50 to 60 °C.
4. Assemble test fractions of 53 to 26.5 mm, 26.5 to 9.5 mm, 9.5 to 4.75 mm and 4.75 to 0.425 mm.

A.1.3 Procedure

The procedures for execution of the ball mill test include:

1. Determine the mass of the test sample.
2. Immerse the specimen in water and soak for 1 hour.
3. Place the aggregate test fraction, water and steel spheres into ball mill chamber.
4. Operate the ball mill continuously for 600 revolutions.
5. Remove all contents of the ball mill chamber.
6. Wash the sample over a 0.425 mm sieve.
7. Oven dry the material retained on the 0.425 mm sieve to a constant mass at 50 to 60 °C.
8. Sieve the sample and record the mass of material retained on the 0.425 mm or larger sieves.

A.1.4 Results

The ball mill value is the percentage of fines (< 0.425 mm) relative to the total sample mass generated due to abrasion in the ball mill as shown in Equation 3.

$$BM = \frac{M_t - M_r}{M_t} \times 100 \qquad 3$$

where

BM = ball mill value

M_t = pre-test specimen mass

M_r = post-test mass of specimen retained on 0.425 mm sieve

A.2 Los Angeles Abrasion

The resistance of unbound granular material to mechanical degradation can also be determined using the LA abrasion test. The testing method includes tumbling of aggregate particles with seven to 12 steel spheres (depending on particle size distribution) in the LA abrasion testing machine for 500 revolutions. The method determines the amount of fine particles (< 1.7 mm) generated as a result of aggregate-to-aggregate and aggregate-to-rigid-object contact. The LA value can be determined in accordance with AS 1141.23, *Methods for Sampling and Testing Aggregates: Los Angeles Value* (AS 1141.23-2009).

A.2.1 Apparatus

Equipment required for determination of the LA value of coarse aggregate includes:

- LA abrasion machine
- oven: thermostatically controlled; operating at 105 to 110 °C
- sample dividers (riffle boxes)
- sieves: 53, 37.5, 26.5, 19, 13.2, 9.5, 6.7, 4.75 and 1.7 mm
- slotted sieves
- thickness gauge
- steel spheres: twelve of 417.5 g mass and 48 mm diameter.

A.2.2 Specimen Preparation

The preparation of coarse aggregate samples for the LA abrasion test includes:

1. Separate the aggregate into test fractions in accordance with Tables 1 to 3 of AS 1141.23 (AS1141.23-2009).
2. Wash each aggregate sample fraction.
3. Oven dry each fraction at 105 to 110 °C for a period of 15-16 hours.

A.2.3 Procedure

The procedures for execution of the LA abrasion test include:

1. Record the mass of the test fraction.
2. Assemble the required steel spheres as per Tables 1 to 3 of AS 1141.23 (AS 1141.23-2009).

3. Place the test fraction and steel spheres in the LA abrasion machine.
4. Operate the LA abrasion machine continuously for 500 revolutions.
5. Remove the test fraction and steel spheres from the LA abrasion machine.
6. Separate the test fraction using a 1.7 mm sieve.
7. Wash and oven dry the material retained on the 1.7 mm sieve at 105 to 110 °C for at least 16 hours.
8. Measure the mass of retained material.

A.2.4 Results

The LA value is the percentage of fine material (< 1.7 mm) relative to the total test fraction mass generated by abrasion in the LA abrasion machine. The LA value can be calculated as shown in Equation 4.

$$LA = \frac{m_t - m_w}{m_t} \times 100 \qquad 4$$

where

LA	=	LA abrasion value
m_t	=	pre-test specimen mass
m_w	=	post-test mass of the test specimen retained on the 1.7 mm sieve

A.3 Deval Attrition

The resistance of aggregate to mechanical degradation in both saturated and OD conditions can be assessed using the Deval attrition test. The test methodology includes tumbling of an OD aggregate specimen with or without an equivalent mass of water for 10000 cycles and measuring the mass of fine particles (< 2.36 mm) generated as a result of aggregate-to-aggregate contact. Abrasion resistance using the Deval attrition machine can be determined in accordance with AS 1141.27, *Methods for Sampling and Testing Aggregates: Resistance to Wear by Attrition* (AS 1141.27-1995).

A.3.1 Apparatus

Equipment required for determination of the Deval attrition value of coarse aggregates includes:

- Deval attrition machine: 200 mm diameter by 340 mm height steel cylinder(s); 30 to 33 revolutions per minute
- oven: thermostatically controlled, operating at 105 to 110 °C
- sieves: 53, 37.5 and 2.36 mm.

A.3.2 Specimen Preparation

The preparation of coarse aggregate samples for the Deval attrition test includes:

1. Screen material using 53 and 37.5 mm sieves and discard retained material.
2. Divide the material passing the 37.5 mm sieve into four test portions of approximately 5.0 kg.
3. Wash and oven dry the sample to a constant mass at 105 to 110 °C.

A.3.3 Procedure

The procedures for execution of the Deval attrition test include:

1. Determine the mass of the test fraction.
2. Place the test fraction in the cylinder of the Deval attrition machine.
3. Operate the Deval attrition machine continuously for 10 000 cycles.
4. Remove the contents of the cylinder.
5. Separate the test fraction using a 2.36 mm sieve.
6. Wash and oven dry the test fraction retained on the 2.36 mm sieve.
7. Measure the mass of the retained material.

For saturated conditions, an equivalent mass of water is added to the cylinder of the Deval attrition machine with the aggregate test fraction. Testing then proceeds in accordance with Steps 3 to 7 above.

A.3.4 Results

The Deval attrition value is the percentage of fine particles (< 2.36 mm) relative to the total test fraction mass generated by abrasion in the Deval attrition machine. The Deval attrition value under both saturated and OD conditions is calculated as shown in Equation 5.

$$DA = \frac{m_t - m_r}{m_t} \times 100 \qquad 5$$

where

DA = Deval attrition value

m_t = pre-test mass of the test fraction

m_r = post-test mass of the test fraction retained on the 2.36 mm sieve

A.4 Micro-Deval Abrasion

The resistance of both coarse and fine aggregate to abrasion can be determined using the micro-Deval abrasion machine. The method determines mass loss of a specimen subjected to aggregate-to-aggregate and aggregate-to-rigid-object contacts in the presence of moisture. The method includes tumbling of either coarse or fine aggregate with 9.5 mm steel spheres and water for 12 000/1500 cycles. The mass of fine particles (< 1.18/0.075 mm) is measured to provide an indication of the toughness of the aggregate. Abrasion resistance of coarse aggregate using the micro-Deval apparatus can be determined in accordance with ASTM International test method D6928, *Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* (ASTM International 2010). The abrasion resistance of fine aggregate can be determined in accordance with D7428, *Standard Test Method for Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus* (ASTM International 2008).

A.4.1 Apparatus

Equipment required for determination of the micro-Deval loss of both coarse and fine aggregates includes:

- micro-Deval abrasion machine: 200 mm diameter by 175 mm height stainless steel jar(s); 100 revolutions per minute

- oven: thermostatically controlled, operating at 105 to 115 °C
- sieves: 19, 126, 12.5, 9.5, 6.7, 6.3, 4.75, 2.36, 1.18, 0.6, 0.3, 0.15, and 0.075 mm
- steel spheres: 9.5 mm diameter; 5000 g total mass.

A.4.2 Specimen Preparation

The preparation of samples for the micro-Deval abrasion test includes:

1. Wash and oven dry the material sample to a constant mass at 105 to 115 °C.
2. Separate the sample into discrete-size fractions in accordance with Section 8.2 of D7428 (ASTM International 2008).
3. Recombine the size fraction to produce material conforming to Section 8.2 of D7428 (ASTM International 2008).

A.4.3 Procedure

The procedures for execution of the micro-Deval abrasion test include:

1. Determine the mass of the test sample.
2. Immerse the sample in 2.0/0.75 L of water and soak for 1.0 hour at 20 °C (coarse/fine).
3. Add the sample, water and steel spheres to the stainless steel jar.
4. Operate the micro-Deval abrasion machine continuously for 12 000/1500 cycles.
5. Collect the contents of the stainless steel jar.
6. Wash and oven dry the sample to a constant mass at 105 to 115 °C.
7. Screen the sample over a 1.18/0.075 mm sieve (coarse/fine).
8. Measure the mass of the retained material.

A.4.4 Results

The micro-Deval loss is the percentage of fine particles (< 1.18/0.075 mm) relative to the total test fraction mass generated by abrasion in the micro-Deval abrasion machine. The micro-Deval loss is calculated as shown in Equation 6.

$$MDL = \frac{(A - B)}{A} \times 100 \qquad 6$$

where

MDL	=	micro-Deval loss
A	=	pre-test mass of the test sample
B	=	post-test mass of the fraction retained on the 1.18/0.075 mm sieve

A.5 Degradation Factor

The degradation factor provides an indication of the degree of weathering of aggregate products. The test can be used to assess both abrasion resistance in the presence of water and the nature of the generated fines. The quality of the fines generated by aggregate-to-aggregate contact are categorised according to the level of decomposition. The testing protocol includes the agitation of an aggregate specimen and measured amounts of water for 20 minutes, followed by measuring the settling rate of the generated fine particles (< 0.075 mm). Degradation factor testing is primarily utilised for assessment of basic igneous sources, but is also applicable for other igneous and metamorphic rock types. Determination of degradation factor can be accomplished in accordance with TMR test method Q208B, *Degradation Factor (Coarse Aggregate)* (TMR 2010) or AS 1141.25.2, *Methods for Sampling and Testing Aggregates – Degradation Factor – Coarse Aggregate* (AS 1141.25.2-2003).

A.5.1 Apparatus

Equipment required for determination of the degradation factor of coarse aggregate includes:

- basket(s): 1.0 to 2.0 mm opening size
- plastic canister: 190 mm diameter by 150 mm height
- measuring cylinders: (2) 500 mL, 100 mL gradation intervals and (2) 10 mL, 1.0 mL graduation
- test cylinder: 40 mm outside diameter, 32 mm inside diameter and 430 mm height, 5 mm markings
- oven: thermostatically controlled, operating at 105 to 110 °C
- modified Tyler shaker: 22 mm eccentricity, 44 mm throw, minimum 300 cycles per minute
- sieves: 19, 13.2, 9.5, 6.7, 4.75, 2.0 and 0.075 mm.

A.5.2 Specimen Preparation

The preparation of coarse aggregate samples for the degradation factor test includes:

1. Prepare 1.0 L of stock solution containing:
   (a) 219 g of crystallised calcium chloride hexahydrate, AR grade
   (b) 480 g of glycerine of 99% glycerol, BP grade
   (c) 12 g of 40% formaldehyde solution, BP grade
   (d) distilled water.
2. Obtain an adequate sample to produce 500 g of 13.2 to 9.5 mm, 9.5 to 6.7 mm and 6.7 to 4.75 mm test fractions.
3. Wash and oven dry to a constant mass at 105 to 110 °C.
4. Obtain approximately 300 g of each size fraction.
5. Crush the remaining material until a 300 g sample of material passing through the 4.75 mm and retained on the 2.0 mm sieve is obtained.
6. Wash and oven dry each fraction to constant mass at 105 to 110 °C.
7. Obtain 250 g samples of each (4) test fraction.

A.5.3 Procedure

The procedures for execution of the degradation factor test include:

1. Place the sample in the plastic canister and add 200 mL of potable water.
2. Place the sample and canister assembly in the Tyler shaker and operate for 20 minutes.
3. Empty the contents into nested 2.0 and 0.075 mm sieves above a 500 mL cylinder (measure).

4. Measure out 7 mL of stock solution into an empty 500 mL cylinder (test).
5. Shake the (measure) cylinder and fill the (test) cylinder with the contents to 380 mm height.
6. Seal the (test) cylinder and shake for 35 seconds.
7. Allow the (test) cylinder to stand for 20 minutes.
8. Record the height of the flocculent column.

A.5.4 Results

The height of the flocculent column composed of fine material (< 0.075 mm) after settling for 20 minutes is used to calculate the degradation factor as shown in Equation 7.

$$D_c = \frac{380 - H}{380 + 1.75H} \times 100 \qquad (7)$$

where

D_c = degradation factor for each size fraction

H = height of the fines flocculent column

A.6 Accelerated Soundness

The accelerated soundness test measures the disintegration of aggregate particles subjected to simulated weathering. Testing includes cyclic boiling and soaking of coarse aggregate submerged in ethylene glycol. The mass of fine particles (< 6.7 mm) generated by five cycles of eight hour boiling and 16 hour soaking is indicative of physical degradation resulting from advanced weathering. The accelerated soundness test is primarily utilised to identify basalt rocks containing significant smectite or chlorite clay content. The accelerated soundness index can be determined in accordance with AS 1141.29, *Methods for Sampling and Testing Aggregates: Accelerated Soundness Index by Reflux* (AS 1141.29-1999).

A.6.1 Apparatus

Equipment required for determination of the accelerated soundness index of coarse aggregate includes:

- electric hotplate: thermostatically controlled, 450 °C maximum temperature
- oven: thermostatically controlled
- fume cabinet
- refluxing apparatus: 500 mL wide-neck and flat-bottom boiling flask, reflux condenser, rubber tubing and adaptor
- sieves: 13.2, 11.2 and 6.70 mm
- slotted sieve: 9.66 mm.

A.6.2 Specimen Preparation

The preparation of coarse aggregate samples for the accelerated soundness test includes:

1. Separate the material using nested 13.2 and 11.2 mm sieves.
2. Sieve the retained material through a 9.66 mm slotted sieve.
3. Wash and surface dry the retained material at 50 °C maximum temperature.

A.6.3 Procedure

The procedures for execution of the accelerated soundness test include:

1. Place the sample in a boiling flask and cover with ethylene glycol.
2. Assemble the refluxing apparatus.
3. Place the refluxing apparatus with the sample over a hotplate in the fume cabinet.
4. Execute five cycles of 8 hour boiling followed by 16 hour soaking.
5. Decant the ethylene glycol.
6. Wash and dry the sample over a hotplate at 250 °C.
7. Break up all the friable particles.
8. Separate the sample using a 6.7 mm sieve.
9. Determine the mass of both the retained and the passing fractions.

A.6.4 Results

The accelerated soundness index is the percentage of coarse particles (> 6.7 mm) relative to the total sample mass retained after accelerated simulated weathering. The accelerated soundness index is calculated as shown in Equation 8.

$$ASI = \frac{m_r}{m_r + m_p} \times 100 \qquad 8$$

where

ASI	=	accelerated soundness index
m_r	=	sample mass retained on the 6.7 mm sieve
m_p	=	sample mass passing the 6.7 mm sieve

A.7 Sodium Sulphate Soundness

The sodium sulphate soundness test provides an indication of the ability of unbound granular material to resist degradation due to weathering. The method promotes the development of internal expansive forces, simulating freezing conditions in cold climates and cyclic wetting and drying in marine environments. The testing protocol includes the cyclic soaking and drying of discrete size fractions in saturated sodium sulphate solution at room temperature. The mass loss for each fraction is indicative of susceptibility to cyclic freeze-thaw and wetting-drying. The sodium sulphate soundness can be determined in accordance with AS 1141.24, *Methods for Sampling and Testing Aggregates: Aggregate Soundness: Evaluation by Exposure to Sodium Sulphate Solution* (AS 1141.24-2013).

A.7.1 Apparatus

Equipment required for determination of the sodium sulphate soundness of unbound granular material includes:

- bath: constant temperature 23 ± 1 °C, corrosion resistant
- hydrometer(s): range of 1.155 to 1.170 g/mL, accuracy of ± 0.001 g/mL
- oven: thermostatically controlled, operating at 105 to 110 °C

- sieves: 75, 53, 37.5, 26.5, 19, 16, 13.2, 9.5, 8.0, 6.7, 4.75, 3.35, 2.36, 1.7, 1.18, 0.85, 0.60, 0.425, 0.30 and 0.212 mm
- thermometer: range of 20 °C to 30 °C, graduated to 1 °C or less.

A.7.2 Specimen Preparation

The preparation of coarse aggregate samples for the sodium sulphate soundness test includes:

1. Prepare the saturated sodium sulphate solution.
2. Sieve the sample to prepare discrete-size fractions in accordance with Tables 1 and 2 of AS 1141.24 (AS 1141.24-2013).
3. Remove fractions representing less than 5% total mass.
4. Wash each test fraction over the smallest retained sieve (coarse 4.75 mm, fine 0.30 mm).
5. Oven dry to a constant mass at 105 to 110 °C.
6. Place five 1.0 L glass beakers on each shelf of the oven filled with 500 g of water.

A.7.3 Procedure

The procedures for execution of the sodium sulphate soundness test include:

1. Submerge the aggregate test fractions to a depth of 15 mm in sodium sulphate solution.
2. Allow the samples to soak undisturbed for 16 to 18 hours.
3. Drain the sodium sulphate solution.
4. Oven dry test the fractions to constant mass at 105 to 110 °C.
5. Repeat soaking, draining and drying for five cycles.
6. Wash and oven dry the test fractions to constant mass at 105 to 110 °C.
7. Separate each test fraction over the designated separating sieve in accordance with Tables 3 and 4 of AS 1141.24 (AS 1141.24-2013).
8. Determine the mass retained on each separating sieve.

A.7.4 Results

The sodium sulphate soundness loss value is the percentage of degraded particles relative to the total test fraction mass resulting from cyclic wetting and drying in a saturated sodium sulphate solution. The sodium sulphate soundness loss value for each test fraction is calculated as shown in Equation 9.

$$C_n = \frac{A_n - B_n}{A_n} \times 100 \qquad 9$$

where

C_n = test fraction per cent loss

A_n = test fraction mass prior to testing

B_n = test fraction mass after testing

A.8 Durability Index

The durability index is indicative of the resistance of unbound granular material to the production of deleterious clay-like materials as a result of self-abrasion. The durability index methodology, equipment and procedures are similar to degradation factor testing. The method includes agitation of an aggregate specimen and measured amounts of water for 20 minutes and measuring the settling rate of the generated fine particles (< 0.075 mm). The durability index can be determined in accordance with ASTM International standard test method D3744, *Standard Test Method for Aggregate Durability Index* (ASTM International 2011).

A.8.1 Apparatus

Equipment required for determination of the durability index of unbound granular material includes:

- mechanical washing vessel: 7.0 L volume, 200 mm diameter
- collection pan: 230 mm diameter, 100 mm height
- agitator: 45 ± 6.0 mm throw, 285 ± 10 cycles per minute
- sieves
- oven: thermostatically controlled, 110 ± 5 °C
- graduated cylinder: 1000 mL.

A.8.2 Sample Preparation

The preparation of coarse aggregate samples for the durability index test includes:

1. Combine the test sample and 1000 mL of water in the mechanical washing vessel.
2. Insert the assembly into the agitator and operate for two minutes.
3. Separate the sample using a 4.75 mm sieve.
4. Wash and oven dry the retained material to a constant temperature at 110 °C.
5. Sieve the retained material and prepare 2500 g test fractions of 19 to 12.5 mm, 12.5 to 9.5 mm and 9.5 to 4.75mm.

A.8.3 Procedure

The procedures for execution of the durability index test include:

1. Measure 7.0 mL of the stock calcium chloride solution into the graduated cylinder.
2. Place the nested 4.75 and 0.075 mm sieves over the collection pan.
3. Insert the prepared test fraction and 1000 mL of water into the mechanical washing vessel.
4. Insert the assembly into the agitator and operate continuously for 600 seconds.
5. Remove the mechanical washing vessel from the agitator.
6. Vigorously shake mechanical the washing vessel and empty the contents into nested sieves.
7. Transfer the contents of the collection pan into the graduated cylinder.
8. Add additional water as required to achieve 1000 mL volume.
9. Cap the graduated cylinder and shake vigorously.
10. Allow the graduated cylinder to stand undisturbed for 1200 seconds.
11. Record the height of the clay suspension.

A.8.4 Results

The durability index is determined from the height of the clay suspension after settling for 20 minutes. The durability index is calculated as shown in Equation 10.

$$D_c = 30.0 + 20.8 \cot\ (0.29 + 0.15H) \qquad 10$$

where

D_c = durability index

H = height of the clay suspension (in.)

A.9 Secondary Minerals Content

Determination of the secondary minerals content provides a quantitative measure of the potentially deleterious material content of coarse aggregates. A petrographic examination is undertaken to describe and classify the constituents of the sample, assess the physical and chemical character and determine the relative amount of secondary or deuteric constituents (Collis & Fox 1985). The method is relevant for the supplementary durability assessment of igneous rocks. The testing protocol includes counting the primary minerals, secondary minerals and voids apparent under microscopic examination of a representative thin slice of aggregate. The secondary minerals content can be determined in accordance with AS 1141.26, *Methods for Sampling and Testing Aggregates: Secondary Minerals Content in Igneous Rocks* (AS 1141.26-2008).

A.9.1 Apparatus

Equipment required for determination of the secondary minerals content of igneous aggregates includes a petrological (polarising) microscope and an optional point counter.

A.9.2 Specimen Preparation

The preparation of coarse aggregate samples for the secondary minerals content test includes preparation of three representative thin (0.03 mm) sections of each identifiable material type in the aggregate sample.

A.9.3 Procedure

The procedures for execution of the secondary minerals content test include:

1. Examine each section under the microscope.
2. Ensure a mineral count of at least 600 points is obtained along a series of traverses of equal length.
3. Identify primary minerals, secondary minerals, veinlets and microcracks in addition to secondary minerals as linings or infillings within vesicles or primary pores.

A.9.4 Results

The secondary minerals content is the percentage of secondary minerals relative to the total mineral count. The secondary minerals content is calculated as shown in Equation 11.

$$SMC = \frac{S}{M} \times 100 \qquad 11$$

where

SMC = secondary minerals content

S = number of secondary mineral points counted

P = number of primary mineral points counted

M = total minerals counted (P + S)

A.10 Absorption

The absorptivity of aggregate does not directly influence durability, but aggregates with high absorption exhibit greater vulnerability to variations in climate and environment. The absorption test measures the difference between OD and SSD mass after soaking in water for 24 hours. The absorption of fine (< 4.75 mm) aggregate can be determined in accordance with Q214A, *Particle Density and Water Absorption of Aggregate (Fine Fraction)* (TMR 2013a) or AS 1141.5, *Methods for Sampling and Testing Aggregates: Particle Density and Water Absorption of Fine Aggregate* (AS 1141.5-2000). The absorption of coarse (> 4.75 mm) aggregate can be determined in accordance with Q214B, *Particle Density and Water Absorption of Aggregate (Coarse Fraction*) (TMR 2013b) or AS 1141.6.1, *Methods for Sampling and Testing Aggregates: Particle Density and Water Absorption of Coarse Aggregate – Weighing-in-water Method* (AS 1141.6.1-2000).

APPENDIX B LABORATORY TESTING RESULTS

B.1 Basic Igneous 1

Product	Type 2.2/3.2 (mod C)
Lot #	RB2-295
Sample ID	HER15W-0070-S01
Date sampled	18/06/2015
Identification	Partly glassy basalt

As-received moisture content (%)	6.4	**Sieve opening (mm)**	**% passing**
Maximum dry density (t/m^3)	2.068	26.500	100
Optimum moisture content (%)	13.2	19.000	100
Compactive effort	Standard	9.500	78
Total apparent particle density (t/m^3)	2.917	4.750	53
Fine apparent particle density (t/m^3)	2.945	2.360	36
Fine absorption (%)	5.95	0.425	15
Coarse apparent particle density (t/m^3)	2.934	0.075	7.7
Coarse absorption (%)	4.79		
Linear shrinkage (%)	2.2	**Fines ratio**	0.5
Liquid limit (%)	30.4	**C_u**	33
Plastic limit (%)	26.6	**C_c**	3
Plasticity index	3.8		
WPI	59	**Secondary minerals coarse**	5.00%
WLS	34	**Secondary minerals fine**	8.50%
Flakiness index (%)	14		
Crushed particles (%)	100		

Pre-test moisture content (%)	Dry density (t/m^3)	CBR 2.5 mm (%)	CBR 5.0 mm (%)	Swell (%)	Post-test moisture content (%)

Product		Type 2.2/3.2 (mod C)				
	12.9	2.105	79	125	0	12.4
	11.6	2.078	106	149	0	11.5
	15.4	2.052	51	83	-0.1	13.7
	14.1	2.086	55	92	-0.1	13

CBR MDD (t/m³)	2.11
CBR OMC (%)	13
Preparation	Soaked
CBR 2.5 mm (%)	80
CBR 5.0 mm (%)	125
Material CBR (%)	125
Compactive effort	Standard

Degradation factor coarse	54			
Degradation factor fine	66			**Standard deviation**
LA value (%)	20	**LA value (%)**	19	0.7
Wet strength (kN)	157	**Wet strength (kN)**	156	0.7
Dry strength (kN)	216	**Dry strength (kN)**	199	12.0
Wet/dry strength variation (%)	27	**Wet/dry strength variation (%)**	22	3.5
Micro-Deval coarse (%)	13.5	**Micro-Deval coarse (%)**	13.4	0.1
Micro-Deval fine (%)	16.7	**Micro-Deval fine (%)**	19.5	2.0

Primary components coarse		**Secondary minerals coarse**		**Porosity coarse**	**Description**
clinopyroxene	33%	yellowish smectite clay	6%	2%	finely crystalline
plagioclase feldspar	37%	calcite	<1%		glassy to partly glassy
mesostasis of brown/black glass with microlites of pyroxene and opaque oxide	6%				unweathered
late yellow glass	13%				lightly altered
black basaltic glass	1%				hard

Product	Type 2.2/3.2 (mod C)				
opaque oxide (magnetite and/or ilmenite) as discrete grains	2%				strong durable
Primary components fine		**Secondary minerals fine**		**Free silica content**	**Description**
clinopyroxene	31%	yellowish smectite clay	8%	<12%	subangular
plagioclase feldspar	37%	calcite	<1%		hard
mesostasis of brown/black glass with microlites of pyroxene and opaque oxide	8%	iddingsite	1%		strong
late yellow glass	12%				durable
black basaltic glass	2%				
opaque oxide (magnetite and/or ilmenite) as discrete grains	1%				

B.2 Basic Igneous 2

Product	Type 2.1 (C)
Lot #	50119
Sample ID	HER15W-0070-S02
Date sampled	28/06/2015
Identification	Olivine basalt

As-received moisture content (%)	4.3
Maximum dry density (t/m^3)	2.208
Optimum moisture content (%)	10.5
Compactive effort	Standard
Total apparent particle density (t/m^3)	2.961
Fine apparent particle density (t/m^3)	2.99
Fine absorption (%)	3.32
Coarse apparent particle density (t/m^3)	2.973
Coarse absorption (%)	2.77
Linear shrinkage (%)	3.8
Liquid limit (%)	25.6
Plastic limit (%)	22.4
Plasticity index	3.2
WPI	49
WLS	58
Flakiness index (%)	10
Crushed particles (%)	100

Sieve opening (mm)	% passing
26.500	100
19.000	99
9.500	80
4.750	63
2.360	42
0.425	15
0.075	7.2

Fines ratio	0.47
C_u	22
C_c	3

Secondary minerals coarse	14.80%
Secondary minerals fine	15.40%

Pre-test moisture content (%)	Dry density (t/m^3)	CBR 2.5 mm (%)	CBR 5.0 mm (%)	Swell (%)	Post-test moisture content (%)
8.7	2.193	117	137	-0.1	9.4
9.7	2.206	91	118	0	9.7
10.9	2.206	75	105	0	10.8
12.5	2.178	35	63	0.5	11.2

Product	Type 2.1 (C)			
CBR MDD (t/m³)	2.21			
CBR OMC (%)	10.2			
Preparation	Soaked			
CBR 2.5 mm (%)	82			
CBR 5.0 mm (%)	112			
Material CBR (%)	112			
Compactive effort	Standard			
Degradation factor coarse	43			
Degradation factor fine	50			**Standard deviation**
LA value (%)	17	**LA value (%)**	17	0.0
Wet strength (kN)	145	**Wet strength (kN)**	136	6.4
Dry strength (kN)	235	**Dry strength (kN)**	237	1.4
Wet/dry strength variation (%)	38	**Wet/dry strength variation (%)**	43	3.5
Micro-Deval coarse (%)	15.5	**Micro-Deval coarse (%)**	14.6	0.6
Micro-Deval fine (%)	21.7	**Micro-Deval fine (%)**	22.5	0.6

Primary components coarse		**Secondary minerals coarse**		**Porosity coarse**	**Description**
clinopyroxene	55%	iddingsite	8%	<1%	finely crystalline
remnant olivine	7%	smectite clay	4%		partly glassy
feldspar and feldspathoids	8%	zeolite	2%		sparsely vesicular
opaque oxides (magnetite &/or ilmenite)	6%	calcite	trace		unweathered
brown glass	10%				lightly-moderately altered
apatite	<1%				finely veined by iddingsite, smectite & zeolite
					hard

Primary components fine		**Secondary minerals fine**		**Free silica content**	**Description**
clinopyroxene	55%	iddingsite	10%	2%	finely crystalline

Product	Type 2.1 (C)			
remnant olivine	6%	smectite clay	6%	partly glassy
feldspar and feldspathoids	5%	zeolite	1%	sparsely vesicular
opaque oxides (magnetite &/or ilmenite)	5%	calcite	trace	unweathered
brown glass	10%			lightly-moderately altered
apatite	<1%			finely veined by iddingsite, smectite & zeolite
quartz	2%			hard
				strong
				durable

B.3 Basic Igneous 3

Product	Type 2.1 (C)
Lot #	155
Sample ID	HER 15W-0070-S03
Date sampled	14/04/2015
Identification	Olivine basalt

As-received moisture content (%)	2.9
Maximum dry density (t/m³)	2.197
Optimum moisture content (%)	9.8
Compactive effort	Standard
Total apparent particle density (t/m³)	2.873
Fine apparent particle density (t/m³)	2.87
Fine absorption (%)	3.12
Coarse apparent particle density (t/m³)	2.947
Coarse absorption (%)	1.69
Linear shrinkage (%)	2.6
Liquid limit (%)	21.2
Plastic limit (%)	18.4
Plasticity index	2.8
WPI	40
WLS	37
Flakiness index (%)	25
Crushed particles (%)	100

Sieve opening (mm)	% passing
26.500	100
19.000	100
9.500	74
4.750	56
2.360	40
0.425	14
0.075	6.5

Fines ratio	0.45
C_u	24
C_c	2

Secondary minerals coarse	17.10%
Secondary minerals fine	14.20%

Pre-test moisture content (%)	Dry density (t/m³)	CBR 2.5 mm (%)	CBR 5.0 mm (%)	Swell (%)	Post-test moisture content (%)
13.4	2.15	63	91	0	9.7
10.2	2.2	67	92	0	9.6
8.5	2.184	85	113	0	8.8
7.7	2.124	91	110	0	7.5

Product	Type 2.1 (C)			
CBR MDD (t/m³)	2.21			
CBR OMC (%)	9.6			
Preparation	Soaked			
CBR 2.5 mm (%)	74			
CBR 5.0 mm (%)	102			
Material CBR (%)	102			
Compactive effort	Standard			
Degradation factor coarse	49			
Degradation factor fine	65			**Standard deviation**
LA value (%)	12	**LA value (%)**	12	0.0
Wet strength (kN)	238	**Wet strength (kN)**	260	15.6
Dry strength (kN)	304	**Dry strength (kN)**	318	9.9
Wet/dry strength variation (%)	22	**Wet/dry strength variation (%)**	18	2.8
Micro-Deval coarse (%)	12.7	**Micro-Deval coarse (%)**	12.9	0.1
Micro-Deval fine (%)	16.2	**Micro-Deval fine (%)**	16.3	0.1

Primary components coarse		**Secondary minerals coarse**		**Porosity coarse**	**Description**
plagioclase feldspar	37%	iddingsite	8%		Holocrystalline
clinopyroxene	25%	various coloured clay of smectite style	10%		variably glassy
opaque oxides	6%				unweathered-slightly weathered
olivine	7%				moderately altered
mesostasis of black glass and mafic microlites	4%				porphyritic
incipiently altered late glass	3%				hard
apatite and perovskite	<1%				strong
					durable
Primary components fine		**Secondary minerals fine**		**Free silica content**	**Description**

Product	Type 2.1 (C)				
plagioclase feldspar	32%	iddingsite	2%	15%	olivine basalt & 20-30% metagreywacke/meta-argillite
clinopyroxene	19%	various coloured clay of smectite style	10%		angular
opaque oxides	2%				hard
olivine	4%				strong
mesostasis of black glass and mafic microlites	2%				durable
apatite and perovskite	<1%				

B.4 Basic Igneous 4

Product	Type 2.1 (C)
Lot #	BB1
Sample ID	HER 15W-0070-S04
Date sampled	18/06/2015
Identification	Olivine basalt

As-received moisture content (%)	3.7
Maximum dry density (t/m^3)	2.08
Optimum moisture content (%)	11.5
Compactive effort	Standard
Total apparent particle density (t/m^3)	2.866
Fine apparent particle density (t/m^3)	2.877
Fine absorption (%)	3.24
Coarse apparent particle density (t/m^3)	2.859
Coarse absorption (%)	2.57
Linear shrinkage (%)	2
Liquid limit (%)	25
Plastic limit (%)	22
Plasticity index	3
WPI	52
WLS	34
Flakiness index (%)	35
Crushed particles (%)	100

Sieve opening (mm)	**% passing**
26.500	100
19.000	98
9.500	78
4.750	54
2.360	39
0.425	17
0.075	8

Fines ratio	0.46
C_u	39
C_c	3
Secondary minerals coarse	9.80%
Secondary minerals fine	7.90%

Pre-test moisture content (%)	**Dry density (t/m^3)**	**CBR 2.5 mm (%)**	**CBR 5.0 mm (%)**	**Swell (%)**	**Post-test moisture content (%)**
8.8	2.03	103	130	0	8.7
9.3	2.087	72	116	0	9.7
12.6	2.106	67	110	0	11
14.5	2.083	44	81	0	11.1

CBR MDD (t/m³)	2.15
CBR OMC (%)	10.8
Preparation	Soaked
CBR 2.5 mm (%)	70
CBR 5.0 mm (%)	114
Material CBR (%)	114
Compactive effort	Standard

Degradation factor coarse	72			
Degradation factor fine	83			**Standard deviation**
LA value (%)	17	**LA value (%)**	18	0.7
Wet strength (kN)	189	**Wet strength (kN)**	180	6.4
Dry strength (kN)	214	**Dry strength (kN)**	212	1.4
Wet/dry strength variation (%)	12	**Wet/dry strength variation (%)**	15	2.1
Micro-Deval coarse (%)	13.6	**Micro-Deval coarse (%)**	14.7	0.8
Micro-Deval fine (%)	15.1	**Micro-Deval fine (%)**	15.2	0.1

Primary components coarse		**Secondary minerals coarse**		**Porosity coarse**	**Description**
plagioclase feldspar	46%	brown to yellow clay of smectite style (slightly oxidized nontronite)	11%	<1%	crystalline
pyroxene	19%	calcite	<1%		variably glassy
olivine	5%				unweathered-slightly weathered
mesostasis of black glass darkened by microlites of pyroxene and opaque oxide	14%				lightly altered
opaque oxide	3%				hard
inferred late green (now yellowish) glass	2%				strong
					durable

Primary components fine		**Secondary minerals fine**		**Free silica content**	**Description**
clinopyroxene	20%	yellowish smectite clay	9%	<12%	angular
plagioclase feldspar	57%	calcite	<1%		hard

mesostasis of brown/black glass with microlites of pyroxene and opaque oxide	2%	iddingsite	1%	strong
late yellow glass	5%			durable
black basaltic glass	<1%			
opaque oxide (magnetite and/or ilmenite) as discrete grains	4%			
olivine	2%			