

Optimizing the durability of the coarse fraction of porous asphalt RAP for effective recycling

Irina Holleran¹, Douglas J Wilson¹, Philippa Black¹, Glynn Holleran¹ and Lubinda F Walubita²

¹The University of Auckland, 20 Symonds Street, Auckland, 1010, New Zealand

²Texas A&M Transportation Institute, College Station, Texas, 77843, USA

E-mail: imot002@aucklanduni.ac.nz

Abstract. Porous asphalt (PA) durability depends not only on the binder used to manufacture the mix, but also on the aggregates chosen, particularly the coarse fraction component. Aggregates for PA should be of the highest quality and highly durable to withstand the effects of weather and traffic. To recycle PA into a new PA mix, without compromising the long-term performance, the durability of the recovered aggregates from PA-derived reclaimed asphalt pavement (RAP) should be assessed alongside the aged binder properties. In this study, the Micro-Deval (MD) Abrasion test, combined with water absorption, was found to be a good predictor of asphalt mix performance for PA. Minerology of the aggregates is an important factor when setting limits for MD loss. New Zealand (NZ) aggregates are significantly younger in geological terms, and chemically and physically less stable compared to the aggregates used in many other countries. This is especially true for greywacke, the most used aggregate in NZ for road construction. If the MD limits reported in some literature are applied to NZ PA-derived RAP aggregates, poor performing material can be erroneously incorporated in asphalt mixes. Findings from this study contributes in understanding how PA-derived RAP can be recycled into new value PA mixes.

1. Introduction

Porous asphalt (PA) is a stone-on-stone mix designed to drain water from road surfacing and attenuate noise. It provides significant safety and environmental benefits; and, is primarily utilized in warmer climates especially where frequent heavy rainfalls are present. In New Zealand (NZ), the Auckland motorway network is the greatest user of PA mixes. The PA life span is reported to be 10 years compared to 7 years nationwide for conventional asphalt mixes [1]. All PA mixes used on this network are polymer-modified. However, unmodified PA mixes are still sometimes used outside the Auckland region in NZ.

Currently, in accordance with NZ specifications, no reclaimed asphalt pavement (RAP) of any type can be utilized in PA mixes. In contrast, 30% of RAP in dense-graded (DG) pavement surfacing mixes and up to 50% in pavement base mixes are routinely used. It is logical to utilize PA-derived RAP in high value mixes such as PA because the aggregates required for PA manufacture have significantly more stringent control compared to aggregates used for conventional DG mixes. Furthermore, PA-derived RAP millings can contain valuable aggregate resources, such as melter slag (a byproduct from steel making), that has historically performed well in relation to skid resistance. Demand for this aggregate outstrips the supply to the extent that New Zealand Transport Agency (NZTA) has recently



decided to take control of the supply chain to ensure greater optimal use of this material in critical areas to maximize network safety outcomes.

To be able to recycle PA-derived aggregates into new PA mixes, RAP aggregate durability needs to be understood and measured, especially for the coarse fraction component. Resistance of PA to withstand traffic forces relies on the aggregate interlock structure provided by the coarse aggregates. Airey et al. [2] found that gap-graded mixes develop aggregate contact stresses in the coarse fraction at the time of mix compaction, which can result in fracture planes in coarse aggregate stones and aggregate degradation compared to DG mixes, where stresses are more evenly spread through the interaction of the coarse and fine aggregate structure. In PA surfacing, the durability of coarse aggregates is likely to be affected by wet and dry cycles. The PA mix and layer structure will operate in higher moisture environments due to the higher relative air voids in comparison to DG mixes. It is likely that the moisture level increases within the PA mat once the PA mix starts to trap finer particle size material fractions (both detritus and abraded materials) that over time reduces the capacity of the PA to drain water efficiently from its surface. This is especially the case in countries like NZ, where the PA is not cleaned (vacuumed), and frequent and heavy rainfall events are relatively common.

It has been reported in the literature that the Micro-Deval (MD) abrasion loss is currently the best indicator for predicting the PA aggregate performance, and if combined with other tests such as absorption, will increase the chance of better enabling aggregate performance prediction and therefore selection of appropriate aggregates. A considerable amount of research work has been carried out in various countries on setting the MD limits to separate good and fair performing materials from poor performers. Maximum MD limits vary from country to country, ranging from about 5% to 30%. The original work on MD was performed using virgin materials, not recycled aggregates. This paper looks at MD and abrasion testing as indicative tests for PA-derived RAP assessment for the suitability of this PA-derived RAP to be incorporated into new PA mixes containing RAP.

2. Background and literature review

MD is a wet abrasion test, which better reflects the real field conditions compared to the commonly used Los Angeles (LA) Abrasion test performed in the dry aggregate state. Under field conditions, especially in PA surfacing in countries where rainfall is frequent, the PA mat rarely remains dry by design. Some aggregates can have reduction in strength or slake when subjected to wet environments [3]. Bartley et al. [4] suggested that the durability of NZ aggregates should always be performed under wet conditions due to the unique mineralogy of these aggregates, which potentially contain highly absorbing clay minerals and zeolites that results in high water absorption and swelling.

Despite the majority of research work showing that LA Abrasion is not a good test for predicting field performance, many countries continue to use this test since ASTM adopted it in 1937 [5]. This is still the case for NZ, where LA Abrasion is required by NZTA specifications for the screening and selection of aggregates for PA manufacture; although it is reported only as an item with no limits currently set. MD testing is not required for any aggregates, virgin, or RAP. Very limited data on MD testing on NZ virgin aggregates is available from aggregate suppliers, and currently no MD limits, even tentative, have been proposed. There is no published data on MD testing of RAP aggregates from NZ. Using the MD limits from other countries may be an issue as they significantly vary based upon aggregate geological source properties, and these limits were mostly established based on research on virgin aggregates.

It is reported that the 18% limit in MD loss is suitable to differentiate good and fair virgin aggregates from poor field performers [6, 7]. Williamson [7] reported that even though the 18% MD limit is a good indicator of aggregate performance, it is possibly too stringent for Wisconsin aggregates; a maximum of 25-30% MD loss limit was suggested instead. The limit of 15% in MD loss together with a maximum of 2.2% water absorption were investigated as the indicators to predict virgin aggregate performance in PA mixes [5]. The Missouri Department of Transportation requires MD testing to be done on RAP aggregates; RAP materials with a loss of above 20% are prohibited for use in asphalt mixes [8]. The Ontario Ministry of Transportation specification presented by Lane et al.

[9] takes into account the mineralogy of the aggregate, as well as traffic loading and type of asphalt course. For the more heavily trafficked motorway asphalt surfacing mixes, the MD abrasion loss limit is reported to be 5% for igneous and metamorphic gravels; 10% for traprock, diabase, and andesite; and 15% for dolomitic sandstone, granitic meta-arkose, and gneiss. This is a more tailored specification, which is designed to accommodate real field conditions and parent rock mineralogy, compared to a generalized MD abrasion loss limit. Canada also has a long history of using MD testing compared to most countries, and their specification is most likely a reflection of the substantial database collected on MD, mineralogy of the parent aggregate, and field performance.

The combination of MD with other tests can increase the accuracy of field performance prediction [10]. For instance, aggregate absorption combined with MD gave a 93% success prediction rate compared to 82% with MD alone for PA performance [5]. If field observation data is collected for each PA site and linked to the actual aggregate MD loss and absorption, and the aggregate mineralogy is considered, this information can be used as a baseline to set the MD and absorption limits for NZ aggregates.

3. Research motivation and objectives

Due to the projected maintenance work on Auckland motorways in the next 6 years, more PA-derived millings will be available, and thus, more PA mix will be paved. If these millings can be recycled back to new quality PA mixes, it will optimize the re-use of valuable resources, aggregate and binder, in this high value application. Currently, these millings are primarily used in low level applications such as filling trenches, drainage layers, or as dust mitigation layers on unsealed roads, or places in landfills. The objective of this research paper was to assess the suitability of MD and Abrasion tests to predict the performance of coarse aggregate fraction from PA-derived RAP in PA surfacing.

4. Materials used in the study

Seventeen samples (minimum 150 kg each) of PA-derived millings were collected over a period of 13 months from various AMA sites ranging in age from 4 to 12 years. Information for each site is shown in Table 1.

Table 1. Site information used for sampling of RAP.

Site ID	Age (years)	Type of milling	PA mat condition
PAV108	8	Full mill at 25mm	Ravelling, highly aged and “hungry” surface
PAV112	7	Full mill at 25mm	No site visit
PAV117	8	Key millings	No site visit
PAV118	7	Full mill at 25mm	Cracking and ravelling. Base failure
PAV119	12	Key millings	Highly aged and ravelled
PAV123	7	Full mill at 25mm	Aggregate disintegration and ravelling
PAV125	5	Full mill at 35mm	Cracking with no ravelling. Base failure
PAV128	8	Key millings	Cracking and ravelling. Base failure
PAV129	6	Full mill at 35mm	Cracking with no ravelling. Base failure
PAV131	6	Full mill at 25mm	Cracking with no ravelling. Base failure
PAV133	4	Full mill at 25mm	Cracking with no ravelling. Base failure
SUR215	7	Key millings	Cracking and ravelling. Base failure
SUR216	8	Full mill at 25mm	Cracking with no ravelling. Base failure
SUR220	7	Full mill at 25mm	Severe scabbing and cracking. Base failure
SUR232	5	Full mill at 25mm	Cracking and scabbing. Base failure
SUR529	6	Full mill at 25mm	Cracking with no ravelling. Base failure
SUR530	7	Full mill at 25mm	Cracking and ravelling. Base failure

Observations on PA mat conditions were recorded. Overwhelmingly, the PA sites visited had issues with the base layers. This was especially true on sites where foamed stabilized bases were used. Three sites, which did not have any visible signs of base failure were severely ravelled (PAV108, PAV119, and PAV 123). There were no records available on aggregate source or binder type used on the majority of the sites. All sites except one were below the expected reported PA life span on Auckland motorways of 10 years. Most sites were between 7 and 8 years old. The way the PA sites were milled is divided into three categories, namely: 1) full milling, where milling was done at 25mm depth; 2) full milling at 35mm, this was done on some sites exhibiting severe issues with base failures, the milling depth of 35mm means some aggregate materials underneath the PA layer were present in the PA millings; and 3) key milling, where only profiling using the miller was carried out to link new areas to old areas.

5. Test methods and material preparation

Aggregates were recovered from PA-derived RAP by using 1-Bromopropane based solvent. Two aggregate fractions, passing the 9.5mm sieve and retained on the 6.7mm sieve, and passing the 6.7mm sieve and retained on the 4.75mm sieve, were prepared and tested for specific gravity (SG) and water absorption in accordance with ASTM C127 [11]. For the MD abrasion testing, the 750g of 9.5-6.7mm plus 750g of 6.7-4.75mm fraction were prepared and tested in accordance with ASTM D6928 [12]. The soaking time for MD was kept constant at 1.5 hours during the test. Each test (MD, SG and absorption) was performed three times. Thin sections of aggregates were prepared for petrographic examination and used to determine the mineralogy of PA-derived aggregates.

6. Test results, analysis, and discussion

Test results on RAP aggregates are shown in Table 2. The 9.5-6.7mm and 6.7-4.75mm fractions were tested separately for SG and absorption because some of the RAP aggregates were a mixture of different aggregate source. Average SG and absorption values shown in Table 2 were calculated from the 9.5-6.7mm and 6.7-4.75mm fractions tested. The SG value shown is oven dried (OD), as per the ASTM C127 definition [11]. The MD loss value is an average of three test results performed on the 9.5-6.7-4.75 fraction. The first named aggregate in the final Mineralogy column represents the majority of the aggregate present in the 9.5-6.7-4.75 fraction used for MD testing.

Table 2. Test results on PA-derived coarse RAP aggregates.

Site ID	Average SG (OD)	Absorption 9.5-6.7 mm (%)	Absorption 6.7-4.75 mm (%)	Average absorption (%)	MD loss (%)	Mineralogy
PAV108	2.593	1.45	1.65	1.55	15.4	greywacke
PAV112	2.781	0.44	0.56	0.50	4.7	greywacke, slag
PAV117	3.713	0.35	0.55	0.45	4.8	slag
PAV118	2.784	0.98	1.24	1.11	8.2	basalt, greywacke
PAV119	2.836	1.19	1.22	1.20	6.4	basalt
PAV123	2.618	1.58	1.46	1.52	11.1	andesite, greywacke, chert
PAV125	2.692	0.68	0.88	0.78	6.2	greywacke, diabase
PAV128	2.722	0.70	0.70	0.70	5.8	greywacke, slag
PAV129	2.698	0.80	0.83	0.82	6.2	greywacke
PAV131	3.050	0.86	0.87	0.87	8.1	slag, greywacke
PAV133	2.683	0.56	0.61	0.58	4.7	greywacke
SUR215	2.752	0.61	0.69	0.65	4.7	greywacke
SUR216	2.696	0.57	0.65	0.61	6.2	greywacke
SUR220	2.717	0.50	0.52	0.51	5.7	greywacke
SUR232	2.686	0.62	0.78	0.70	4.8	greywacke
SUR529	2.670	0.64	0.76	0.70	5.4	greywacke
SUR530	2.678	0.72	0.84	0.78	5.3	greywacke

Most of the aggregates that could be identified in the PA-derived coarse RAP aggregate were from a single source. However, there were 6 sites out of 17 that had a mixture of aggregates. In NZ, coarse aggregates for PA manufacture can be from different sources as long as 85% of all the coarse fraction to be made with the chosen aggregate has the required polished stone value for skid resistance performance [13]. This means that 15% of the coarse aggregates can come from other aggregate sources.

Test results from MD and absorption testing were plotted in Figure 1. A significant positive correlation ($r=0.873$) was found between absorption and MD loss in the tested RAP aggregates. Higher absorption of RAP aggregates resulted in higher MD loss. This relationship is consistent with and reinforces the findings from previous studies by Rismantojo [14], Khandal & Parker [15], and Jayawickrama et al. [10] that were performed on virgin coarse aggregates. Higher porosity aggregates usually have a tendency to be weaker [16]. Absorption of the 6.7-4.75mm fraction tested was generally higher compared to the 9.5-6.7mm fraction possibly due to bigger surface area in the finer fraction. This may mean that finer aggregates of the coarse fraction may have more effect on MD abrasion loss compared to the coarser size aggregate if MD loss is a function of water absorption.

Based on the findings from the NCHRP study by Khandal & Parker [15], MD testing was recommended for prediction of field failures such as pot-holing, pop-outs, and ravelling in hot-mix asphalt (HMA). The triangular dots in Figure 1 represent the PA sites PA108 (8 years old), PAV119 (12 years old), and PAV123 (7 years old), which had significant ravelling with no base issues recorded. The rest of the PA sites visited (circular dots) had base failures (although, it is unknown if the sites PAV112 and PAV117 had base failures as no site visit was possible), so it is hard to say if this ravelling is a function of the aggregate break down (or binder aging), or the flexing of the structurally compromised bases during traffic loading, resulting in aggregate loss in the PA surfacing.

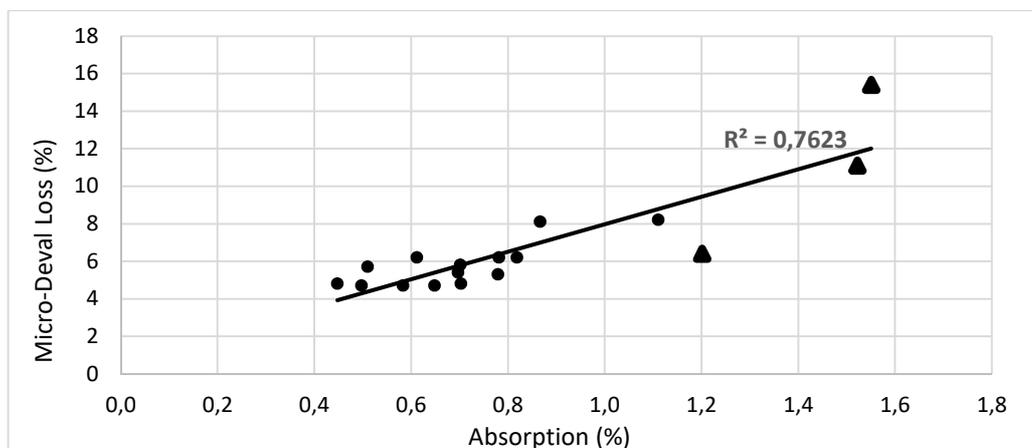


Figure 1. Relationship between Micro-Deval abrasion loss and water absorption in PA-derived RAP coarse aggregates.

All RAP aggregates tested had MD abrasion losses below the: 1) 18% limit reported by Wu, Parker, & Kandhal [6] and Williamson [7] on virgin aggregates; 2) 20% limit for RAP aggregates [8]; and 3) 15% limit for PA virgin aggregates [5] – except for one site, PAV108, which had MD loss of 15.4%. Furthermore, water absorption of all RAP aggregates was well below 2.2% – the maximum limit, which was used together with MD loss limit of 15% to predict PA. If these reported limits were to be implemented in NZ, PA-derived aggregates that had already visually disintegrated in the field prior to milling could end up being used in new PA mixes, and thus, highly likely compromise performance of the new PA mix. This highlights the importance of studying local materials and setting the limits for MD and absorption at a local level rather than relying on other countries' specifications.

It is likely that the age of aggregates in terms of geological terms will play a role in how aggregates perform in the field and therefore local geology properties would be influential.

Over 70% of RAP coarse aggregates from a single aggregate source were identified as greywacke. Most of the greywackes quarried in NZ are Permian-Mesozoic in age, weakly metamorphosed (prehnite-pumpellyite or, less commonly, zeolite facies), may be either volcanoclastic or lithic arkosic in composition, and on a macro-scale consist of interbedded sandstones, siltstones and mudstones. Even within one quarry, the properties of such aggregates may be different due to the heterogeneous nature of the parent rock [4]. In NZ, greywacke is the major source of aggregates for road construction.

Based on the limits set for each mineralogical group by the Ontario Ministry of Transportation [9], greywacke RAP aggregates fall into meta-arkose category with a maximum of 15% MD abrasion loss allowed for premium asphalt wearing courses for heavily traffic motorways. That is all of the PA-derived coarse aggregates from greywacke source tested in this study meet this selection criterion. The highest MD loss for this RAP aggregate was 15.4%. However, the greywacke from the PAV108 site gave very different MD, SG, and absorption results compared to the rest of the greywacke aggregates that were tested. The MD, SG, and absorption and thin section petrographic examination showed that aggregates from the PAV108 site came primarily from the Moutohora quarry, with a small amount of aggregate chips coming from the Hunua Winstones quarry. They are both greywacke aggregates, but are very different in properties. Greywacke aggregates from the Hunua Winstones quarry are still routinely used for asphalt manufacture. In contrast, the Moutohora quarry aggregates are no longer utilized in any asphalt mixes in NZ due to their propensity to erode under traffic. Bartley et al. [4] reported that in the Moutohora aggregates, the sand grains are easily dislodged from the highly porous matrix, which indicates a higher propensity to disintegration of the aggregate under traffic. This possibly explains why ravelling and “hungry” PA surfaces were observed on the PAV108 site, and in agreement with the high MD loss and the high absorption values for the RAP aggregates recovered from this site.

To understand how greywacke RAP aggregates may change in the PA mat with time, the results from the selected sites (PAV125, PAV129, PAV133, SUR216, SUR220, SUR232, SUR529, SUR530) were compared with the virgin greywacke aggregates from two quarries, which are routinely used in PA manufacture for Auckland motorways. The test results are graphed in Figure 2.

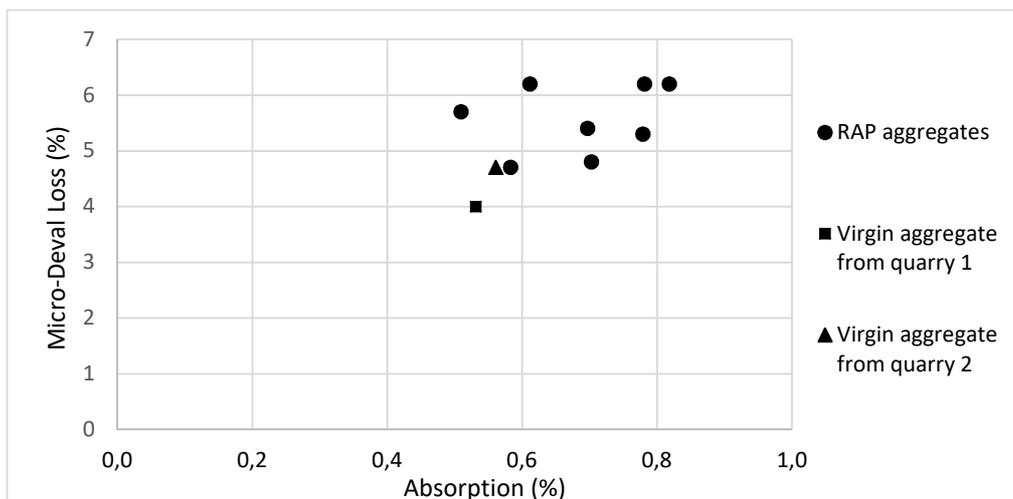


Figure 2. Micro-Deval abrasion loss and water absorption in PA- derived RAP coarse aggregates and virgin aggregates from greywacke aggregate source.

Each virgin greywacke aggregate was tested three times using the same testing conditions as for the RAP aggregates. The virgin aggregates’ MD abrasion loss and water absorption were mostly lower

compared to the RAP aggregates. This may indicate that greywacke aggregates go through chemical and (or) mechanical structural breakdown in a PA mat which is associated with traffic, water, and environment. Furthermore, entrapped pollutants in PA may also contribute to the mechanical breakdown. PA can accumulate various types of pollutants compared to DG surfacing [17]. This property of PA is beneficial to the environment, as it improves storm-water quality, but it may be a contributor to the aggregate degradation in a PA mat. Hajj et al. [18] reported that assessment of RAP aggregate abrasion is questionable as these aggregates were tested prior to use in hot mix asphalt. But if the aggregates are changing, physically or chemically, during service in PA surfacing, the aggregate durability should be taken into account, especially for RAP aggregates which are to be used in high stress demand conditions such as PA surfacing.

Aggregate disintegration was observed on the 7-year old PAV123 site. The MD loss testing on the RAP aggregates from this site gave 11.1% abrasion loss and an absorption of 1.52%, this was the second highest MD loss and absorption in RAP aggregates tested. RAP aggregate from this site were a mixture of predominately andesite with some inclusion of a small aggregate particle sized greywacke, and chert. Chert is a red color aggregate usually used for delineation of the road shoulder. It is not used in PA production. This means that during the milling process some chert material was incorporated in the millings. Chert is rich in silica and iron and it is a very tough material. Based on the petrographic examination, greywacke in this RAP sample matched the greywacke from the Hunua Winstone Quarry, a good performing aggregate currently utilized in many asphalt mixes. The andesite highly likely came from the Bay of Plenty region. After several years of utilizing andesite aggregates in HMA surfacing mixes, it was found that this aggregate could disintegrate under traffic loading. It is currently not used in major NZTA work in NZ for this reason. Again, high MD loss together with high absorption test results in the laboratory were able to reflect poor in-field aggregate performance in PA on the PAV123 site.

The PAV119 site, which had ravelling with no base failures observed, was 12 years old. This site was likely to have failed due to binder aging and subsequent, structural breakdown. RAP aggregates recovered from this site were of volcanic origin, basalt – a highly durable rock. MD abrasion loss and absorption results were relatively low, 6.4% and 1.20%, respectively, compared to the RAP aggregates from the PAV108 and PAV123 sites.

NZ aggregates are mineralogically different and geologically younger than the aggregates used in Europe and North America, where methodologies for assessment of aggregate engineering properties were originally developed. This is especially true for greywacke, the main aggregate used for road construction in NZ. It is less chemically and physically stable compared to sandstone aggregates, which are commonly used in countries like Australia, Europe, North America, and South Africa [4]. Limits for MD loss and water absorption for NZ aggregates need to be established that take into account the NZ aggregate minerology to be able to adequately predict aggregate field performance in asphalt mixes including PA. The term “greywacke” is too broad for setting the limits based on minerology.

7. Conclusions and recommendations

The following conclusions and recommendations can be drawn from this research study:

- Minerology plays an important role when setting limits for MD abrasion loss on PA-derived coarse aggregates
- Adopting limits for MD and water absorption without taking minerology into consideration can result in poor quality RAP aggregates to be erroneously utilized in asphalt mix manufacture.
- MD together with water absorption tests are very useful for the assessment of RAP aggregates for recyclability in new asphalt mixes.

- A strong relationship was found between MD and absorption in RAP coarse aggregates. Aggregates with higher absorption gave higher losses in the MD abrasion test. This finding was consistent with research reported on virgin aggregates.
- Greywacke virgin aggregates had generally lower MD and absorption compared to PA-derived greywacke RAP aggregates. This may indicate chemical and or physical changes in the aggregate during service of the PA surfacing.
- MD and absorption limits for RAP aggregates need to be developed for NZ based on the local aggregate mineralogy, and real field conditions that take into account the type of asphalt mix and traffic volume. The term "greywacke" is too broad for use as a mineralogical group for setting limits for MD and absorption, respectively as there is significant variance in properties and performance by greywacke source across NZ.

References

- [1] Chappell B and Bennett D 2015 *Asphalt Life Analysis 16th NZ Transport Agency & NZIHT Annual Conference (Bay of Islands, New Zealand)*
- [2] Airey G D, Hunter A E and Collop A C 2008 The effect of asphalt mixture gradation and compaction energy on aggregate degradation *Construction and Building Materials* **22**(5) pp 972-80
- [3] Rogers C A and Senior S A 1994 Recent Developments in Physical Testing of Aggregate to Ensure Durable Concrete *Proc. Engineering Foundation Conf. on Advances in Cement and Concrete (Durham)* pp 338-57
- [4] Bartley F G, Peplow R J and Black P M 2010 *Abrasion resistance of aggregates in asphalt* (NZ Transport Agency research report 433)
- [5] Fowler D W, Allen J J, Lange A and Range P H 2006 *The prediction of coarse aggregate performance by Micro-Deval and soundness related aggregate tests* (Research Report ICAR 507-1F)
- [6] Wu Y, Parker F and Kandhal P S 1998 *Aggregate toughness/abrasion resistance and durability/soundness tests related to asphalt concrete performance in pavements* (NCAT Report 98-4)
- [7] Williamson G S 2005 *Investigation of testing methods to determine long-term durability of Wisconsin aggregate resources including natural materials, industrial by-products, and recycled/reclaimed materials* (Virginia Polytechnic Institute and State University, Faculty of Engineering)
- [8] Hajj E Y, Sebaaly P E and Kandiah P 2008 Use of Reclaimed Asphalt Pavements (RAP) in Airfield HMA Pavements *AAPTP Project 05-06: Final Report Appendices* (University of Nevada, Reno)
- [9] Lane B C, Rogers C A and Senior S A 2000 The Micro-Deval Test for Aggregates in Asphalt Pavements *8th Annual Symposium of the International Center for Aggregate Research (Denver)*
- [10] Jayawickrama P W, Hossain M S and Phillips F 2007 Micro-deval test for the assessment of bituminous aggregate durability *Journal of ASTM International* **4**(1) pp 1-13
- [11] ASTM 2015 Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate (*ASTM C127-15*)
- [12] ASTM 2010 Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus (*ASTM D6928-10*)
- [13] New Zealand Transport Agency 2005 Performance Based Specification For Hotmix Asphalt Wearing Course Surfacing (*TNZ P/23:2005*)
- [14] Rismantojo E 2002 *Permanent deformation and moisture Susceptibility Related Aggregate Tests for use in Hot-Mix Asphalt Pavements* (Purdue University, Faculty of Engineering)
- [15] Kandhal P S and Parker F 1998 Aggregate tests related to asphalt concrete performance in pavements *NCHRP Report 405*

- [16] West T R 1995 *Geology Applied to Engineering* (Long Grove, Illinois: Waveland Press Inc.)
- [17] Holleran I, Wilson D J, Holleran G, Walubita L F and James B 2016 Porous Asphalt - More Than Just Safety *IPENZ Transportation Group Conference (Auckland, New Zealand)*
- [18] Hajj E Y, Sebaaly P E and Kandiah P 2008 Use of reclaimed asphalt pavements (RAP) in airfields HMA pavements *AAPTP Project 05-06* (University of Nevada Reno)