ESTIMATING FOREST ROAD AGGREGATE STRENGTH BY MEASURING FUNDAMENTAL AGGREGATE PROPERTIES

Simon Fairbrother
Assistant Lecturer, School of Forestry, University of Canterbury, New Zealand
Email:simon.fairbrother@canterbury.ac.nz

ABSTRACT

The depth of aggregate required for forest road pavements is dependent on the characteristics of the expected traffic, and the subgrade and aggregate layer bearing strengths. The first two factors are relatively easy to estimate; however, determining aggregate bearing strength is an arduous and expensive task. Forest road engineers typically forgo aggregate testing when using locally sourced material and assume that the aggregate has appropriate strength. This assumption is often erroneous and can lead to pavement depths that are either insufficient or excessive. The risk of over- or under-engineering could be reduced if engineers were able to easily quantify the strength of locally sourced aggregates. The goal of this study is to develop a simple, low-cost method to estimate bearing strength by correlation to fundamental aggregate properties.

Forest road aggregates were collected and tested to determine their fundamental properties and bearing strength. The properties measured for each aggregate included Broken Face Content, Micro-Deval Test value, Plasticity Index, Slenderness Ratio and Solid Density. Bearing strength was determined using the California Bearing Ratio test, with samples prepared at optimum moisture content using standard compaction effort and the Driving Surface Aggregate gradation.

Multiple linear regression analysis of the results shows that aggregate strength decreases when the Slenderness Ratio, Broken Face Content and Micro-Deval Test values increase. The regression is sufficiently robust to enable the approximate bearing capacity of an aggregate to be estimated as poor, fair or good. The quality of this regression may be improved by the addition of further aggregate samples.

Keywords: Aggregate, CBR, forest road, unsealed road

INTRODUCTION

Forest roads in New Zealand are typically constructed using a single layer of unbound aggregate spread over a prepared subgrade. The purpose of the aggregate layer is to provide a high strength material that elastically deforms under truck tyres to disperse, and thus reduce, applied stresses to a level that can be borne by the underlying subgrade. Stress dispersion increases as the thickness and strength of the aggregate layer increases. This aggregate layer is often the most expensive component of forest road construction, contributing up to 60-70% of the total construction cost. The consequence is that forest road engineers need to optimise the trade-off between pavement thickness and cost to produce forest roads that are both affordable and fit for purpose.

The thickness of aggregate used for a forest road pavement is dependent on a number of factors, including the expected traffic characteristics, and the subgrade and aggregate layer strengths. These first two factors are relatively easy to estimate or measure; however, determining aggregate strength is a more arduous and expensive task. Consequently, many forest road engineers forgo aggregate testing when using locally sourced material and assume that the aggregate has appropriate strength for the task. This assumption is often erroneous and can lead to designed pavement depths that are either insufficient or excessive. In the former case, pavements can prematurely fail with costly rehabilitation and serious disruptions to log hauling operations. In the latter case, the road may easily meet the required level of service but will be unduly expensive to construct. The risk of over- or under-engineering the unbound aggregate layer could be reduced if engineers were able to easily quantify the bearing strength potential of locally sourced aggregate materials and adjust the pavement thickness accordingly. The goal of this study is to develop a simple and low-cost method that estimates bearing strength by correlation to easily measured aggregate properties.

LITERATURE REVIEW

Research on the durability of aggregates is well advanced, with numerous tests developed to identify materials that are prone to deterioration and are unsuitable for road construction (Paige-Green 2007). Aggregate standards use these tests to identify whether an aggregate meets minimum specifications, for example, the TNZ M/4 Specification for Basecourse Aggregate (TransitNZ 2006) requires aggregates to meet or exceed specifications for crush and abrasion resistance, chemical weathering, CBR value, plasticity index, broken face content and particle size distribution. Little guidance is provide for the use of aggregates that fail to meet these standards, though use of non-compliant aggregates is commonplace for construction of forest roads and many low-volume public roads.

Research predicting Californian Bearing Ratio (CBR) from fundamental properties has to date primarily focussed on subgrade soils (Black 1962, Agarwal and Ghanekar 1970, NCHRP 2001, Taskiran 2010). Similar research for the aggregate layer is limited. Kamal *et al* (2006) developed a Toughness Index for aggregates based on results from aggregate laboratory tests; however, this index was designed to assess relative quality of roading materials, rather than a quantitative measure of bearing strength. A study by the Colorado Department of Transport (2003) showed that the Micro-Deval Test (MDT) value was a good indicator of aggregate quality. The resulting MDT value was able to rank aggregates as poor, fair or good; but again did not provided a quantitative measure of aggregate strength that could be used in aggregate thickness design algorithms.

Other aggregate research has investigated the behaviour of the aggregate layer under load. Theyse (2002) researched the performance of unbound granular aggregate in South Africa, with specific focus on predicting permanent deformation of the aggregate layer. Theyse concluded that the most influential factors were the dry density of the aggregate, moisture content and a ratio that combined effects of confinement and stress. A study by Barksdale (1989) examined unbound aggregate performance in relation to rutting. The study examined how the size and shape of coarse aggregate particles influenced performance under load. Barksdale concluded that although smooth rounded rocks rutted more readily, they performed similarly to, if not better than, angular rocks in relation to permanent deformation under stress.

Aggregate properties that are understood to significantly affect layer strength are gradation (Arnold *et al* 2007) and compaction. Numerous aggregate grading curves have been developed for use on forest roads (Fairbrother *et al* 2009); with the Driving Surface Aggregate design being an indicator of best-practice for forest roads (Fairbrother 2011). It is also widely accepted that variation in moisture content and compaction effort dramatically affect the maximum dry density and strength potential of aggregate layers (Bowles 1992). Consequently, research evaluating aggregate layer strength from fundamental aggregate properties needs to exclude water content, dry density and aggregate gradation as variables.

METHOD

Representative samples of 18 forest road aggregates were collected from the East Coast, Canterbury and Otago regions of New Zealand. The samples were collected from either quarries or in-forest stockpiles and were representative of materials being used at the time for single-layer, forest road pavements. A 15kg test specimen was then prepared from each sample by standardising the aggregate to comply with a best-practice unsealed road aggregate gradation curve. This standardisation was necessary as many aggregate samples were too coarse for effective laboratory testing, but also enabled aggregate gradation to be excluded as a variable. The Driving Surface Aggregate gradation (PSU 2006) used for this research and is illustrated below in Figure 1.

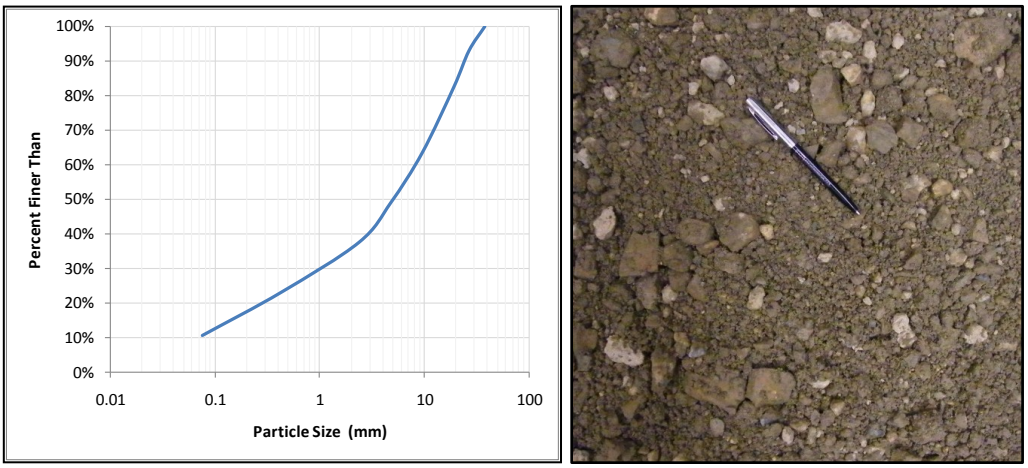

Figure 1: The gradation curve used to prepare each aggregate sample; and a photograph of a DSA graded aggregate sample.

Each aggregate was compacted using a standard compaction effort in accordance with NZS4407 Test 3.15 (Standards NZ 1991) with the specimen prepared at optimum moisture content (OMC) – the moisture content at which maximum dry density can be achieved for a given compaction effort. The OMC for each aggregate was estimated by mixing the specimen with sufficient water so that a hand-compacted ball of material retained its shape. A sample was too dry if the ball crumbled and too wet if it would not compact (PSU 2006). An aggregate sample prepared using this method is show below in Figure 2.

Figure 2: A photograph showing the method used to determine OMC. The samples on the left and right are too dry and too wet respectively. The middle sample has been prepared at OMC.

The bearing strength of the prepared specimens was established using the Californian Bearing Ratio Test, NZS4407 Test 3.15 (Standards NZ 1991). Early testing showed that bearing strength of an aggregate varied widely between tests, most likely due to the random packing of the larger gravel components. Consequently, seven CBR tests were completed for each aggregate in order to establish a median CBR value.

The following fundamental properties of each aggregate were assessed once CBR testing was completed:

- Broken Face Content, NZS4407 Test 3.14, (Standards NZ 1991) – a measure of the percentage of aggregate particles that have at least two broken faces. This test distinguishes between crushed aggregates and rounded 'river run' aggregates.
- Micro-Deval Test, ASTM D6928-06, (ASTM 2006) – a measure of the abrasion resistance and durability of aggregate particles. A lower MDT value indicates a more durable aggregate. An aggregate with MDT>18% is deemed to be poor road construction material (CDOT 2003)
- Plasticity Index, NZS4407 Test 3.4, (Standards NZ 1991) – a measure of the plasticity of the fine material within an aggregate. A plasticity index value between 8 and 12 is appropriate for aggregates used in temperate environments with moderate rainfall (Giummarra, 2009).
- Slenderness Ratio, NZS4407 Test 3.13, (Standards NZ 1991) – indicates whether the aggregate particles are long and slender or short and squat. A lower value indicates a more squat aggregate.
- Solid Density, NZS4407 Test 3.7 (Standards NZ 1991) – the solid density of the aggregate particles in tonnes per cubic metre.

RESULTS

Test results are presented below in Table 1.

Table 1: Aggregate CBR and Fundamental Properties Test Results

Aggregate #	1	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Median CBR (%)	35	44	36	50	41	50	40	48	57	48	48	38	57	69	60	27	28
Slenderness Ratio	2.13	2.45	2.13	2.11	2.20	1.74	2.00	2.22	2.05	2.25	2.65	2.29	1.89	1.90	2.08	2.13	2.52
Plasticity Index	8	8	10	9	10	7	8	9	7	10	8	9	6	0	6	8	8
Broken Faces (%)	100	67	100	60	94	100	100	100	100	98	100	100	42	35	90	100	100
MDT Value (%)	31	28	30	31	26	26	37	11	12	22	16	15	18	22	15	29	34
Solid Density	2.59	2.64	2.55	2.55	2.59	2.50	2.57	2.89	2.78	2.54	2.53	2.60	2.57	2.59	2.62	2.59	2.64

Aggregate #2 has been omitted from the results, as this aggregate had an extreme MDT value of 97.5% that was disproportionately affecting the analysis. This outlier is a consequence of the aggregate being a very weak sandstone that behaved as a fine-grained soil, rather than an aggregate, during the Micro-Deval Test.

ANALYSIS

The results indicate that the median bearing strength of the forest road aggregates varies from a CBR of 27 through to a CBR of 69. This is a significant finding in itself, as the most commonly known unbound granular pavement design methods for light roads in Australia and New Zealand, the APRG 21 method (ARRB 1998) and the AUSTROADS 'Figure 8.4' method (AUSTROADS 1992), both assume that the aggregate will have a minimum CBR bearing strength of 80. None of the tested aggregates meet this standard, while many fall well short. The consequence is that forest roads designed using these methods and constructed with the tested aggregates are likely to be under-engineered and face the prospect of early failure.

Initial exploratory data analysis examined the correlation between single variables and median CBR. This analysis identified that Broken Face Content, Micro-Deval Test Value and Plasticity Index have a moderately strong linear correlation with median CBR. However, the Broken Face Content correlation was over-stated by the limited number of samples comprised of rounded material and the Plasticity Index correlation was significantly over-stated by the single aggregate sample with a plasticity index equal to zero. Slenderness Ratio had a weak correlation, while solid density had no linear correlation. Further aggregate samples are needed to confirm the veracity of theses correlations. Graphs for each variable are presented below as Figure 3.

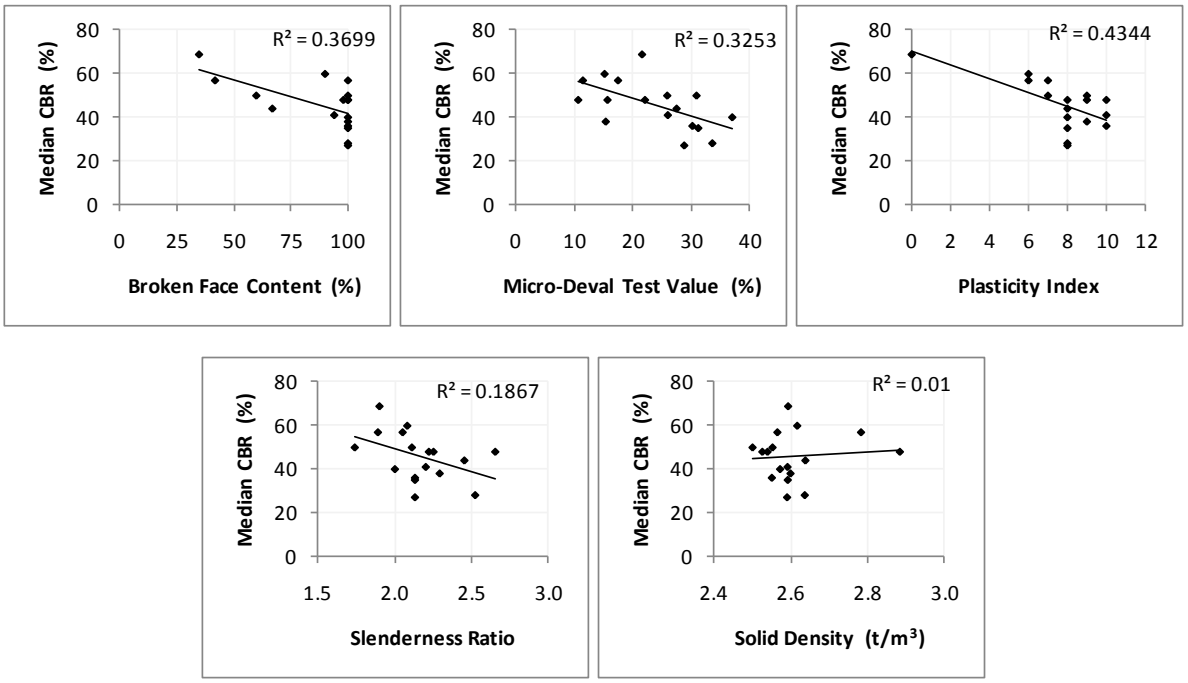

Figure 3: Graphs illustrating the correlation between each of the independent variables and median CBR

The finding that aggregates with rounded rocks have greater bearing strength than those using crushed rocks is consistent with other research (Barksdale 1989) and questions the value of crushing rounded aggregates to improve aggregate strength. Note that this result may be biased, given that the rounded rocks tended to also be squatter and stronger due to the nature of their river-borne transport process. Furthermore, the relative resistance to ravelling of crushed and rounded aggregates on-road is an important property that was not considered by these tests. Further research is required before any conclusions can be drawn on the whether or not to crush rounded aggregates.

The data was further analysed using multiple linear regression to examine whether a combination of fundamental aggregate properties could better predict median CBR. This analysis showed that the best fit was achieved when using Broken Face Content, Micro-Deval Test Value and Slenderness Ratio as the independent variables. The resulting correlation equation is presented below as Equation 1. The adjusted coefficient of determination for this equation is R_{adj}^2=0.68. Note that this regression equation is only applicable for aggregates prepared in accordance with the method used for this research.

$$Median\ CBR = 117 - 25.2\ (BF) - 77.9\ (MD) - 14.4\ (SR) \quad (1)$$

BF = Broken Face Content (%), MD = Micro-Deval Test Value (%), SR = Slenderness Ratio

A plot of predicted median CBR versus actual median CBR is presented below as Figure 4. The regression equation is sufficiently robust to enable the approximate bearing capacity of an aggregate to be estimated as poor (CBR<40), fair (40<CBR<60) or good (CBR>60).

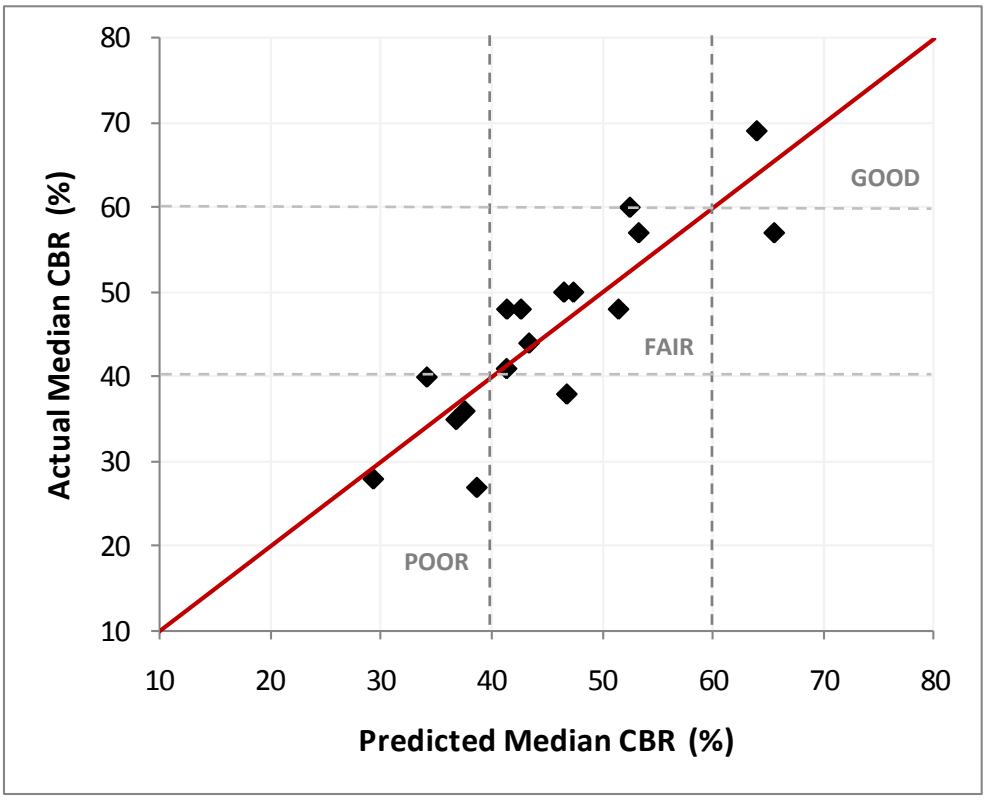

Figure 4: Graph of the correlation between Predicted Median CBR and Actual Median CBR.

CONCLUSION

This research shows that aggregate bearing strength, as measured by CBR, can be estimated from fundamental aggregate properties. Multiple linear regression analysis of the test results shows that aggregate strength decreases when the Slenderness Ratio, Broken Face Content and Micro-Deval Test values increase. Predicting aggregate bearing strength using these three tests is relatively simple, quick and inexpensive when compared to the effort required for repeat CBR testing. The Slenderness Ratio and Broken Face Content tests can be completed using rudimentary laboratory equipment or estimated by the forest road engineer on-site; however, the Micro-Deval Test value is somewhat more difficult to obtain, requiring specialist laboratory equipment.

The regression equation is sufficiently robust to enable the approximate bearing capacity of an aggregate to be estimated as poor (CBR<40), fair (40<CBR<60) or good (CBR>60). This level of precision is sufficient for use in pavement design equations that require the aggregate layer CBR value as an independent variable, such as the aggregate surfaced design method developed for the US Forest Service (Barber et al, 1978). The quality of this regression may be improved by the addition of further aggregate samples.

This research also questions whether rounded aggregates should be crushed, and whether locally sourced forest road aggregates can be used with common pavement thickness design algorithms. Both of these questions warrant further research.

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