MARGINAL MATERIAL EVALUATION AND SELECTION USING ANALYTIC HIERARCHY PROCESS MODEL

Wentao Li
University of Auckland
New Zealand
wli783@aucklandunil.ac.nz

Doug Wilson
University of Auckland
New Zealand
dj.wilson@auckland.ac.nz

Tam Larkin
University of Auckland
New Zealand
t.larkin@auckland.ac.nz[1]

ABSTRACT

Marginal materials, also called sub-standard materials, have the potential to replace premium materials in local roads. However, the current definition of marginal materials suffers from the limitation of focusing on whether or not each single property meets the corresponding requirement of specifications rather than reflecting the overall performance of the materials. To overcome this limitation and to better understand the concept of ‘marginal material’, this study was conducted using the Analytic Hierarchy Process (AHP) framework to evaluate the overall performance of five aggregates and an assumed boundary aggregate based on multiple factors (various engineering properties and performance). The aggregates were ranked through comparing the overall weight of each material, which was obtained based on the analysis of the relative weights of criteria and sub-criteria along with data processing of engineering properties.

The AHP model is a good method to select the best aggregates within a number of given aggregates. It can describe the overall performance of aggregates in a quantitative way, which allows the qualities of the aggregates to be compared to each other so that the proper aggregates can be selected for different road construction purposes.

The validation of the AHP model demonstrates that the AHP analyzed qualities of the aggregates match well to their qualities in field road construction, but there is a need

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to make a combination analysis on the individual properties (specification pass/fail criteria) and overall performance (AHP model) in the process of evaluating the quality of aggregates.

Keywords: Analytical Hierarchy Process; relative weights; marginal aggregates; road construction;

1. Introduction

Marginal materials, also called sub-standard materials, are “those that do not entirely meet the specifications for normal road materials to be used in a country or region, but which still have the potential to be used successfully in some applications” (Brunschwig, 1989). High-quality aggregate materials are being depleted and there are many environmental and other restrictions being placed on the expansion of existing quarries and on the exploitation of new resources. Thus, there is now a strong economic and sustainability imperative to preserve premium aggregates for use only where this quality is required, and to better use local marginal materials in appropriate in-service conditions and/or to improve their engineering performance with special treatments.

However, local marginal materials are not defined clearly. Apart from Brunschwig’s definition, another definition by Brennan (1984) is that a marginal grade aggregate is an aggregate produced from a more weathered or weather prone rock, or hard rock containing weathered seams or weaker sedimentary rocks, which after processing contain moderate or highly plastic fines, is sensitive to weathering and when compacted will produce a soaked California Bearing Ratio (CBR) value between 40% and 100%. The two qualitative definitions concentrate on the single properties performance of marginal aggregates (e.g. a property failing to meet a specific specification rather than the overall quality of marginal aggregates). These pass /fail definitions may make some qualified materials appear to be unqualified marginal materials, which results in their failure to be used in roads, causing further waste of materials. For example, if a specific property of a material is slightly lower than the requirement of standards/specifications but the other properties are much higher than the corresponding requirements, the material would be automatically categorized as a ‘marginal’ material. However, this could be a controversial conclusion when considering the repeatability and reproducibility of test methods in standards/specifications which allow a range value for the specific property of the material (ASTM, 2002; BSI, 2013). Furthermore, the recipe specifications result from the classical empirical engineering approach of design on the basis of long-term monitoring of full-scale test roads and index tests (Evans & Vuong, 2003; Rogers, Fleming, & Frost, 2004). Empirical standards/specifications cannot completely assure in-field performance, especially when the conditions change (e.g. loading magnitudes or patterns change, novel materials are proposed, etc.). Therefore, the pass/fail requirements of specifications/standards for materials only considering single index properties cannot accurately differentiate marginal materials from premium materials. There is a need to develop a statistical method which can combine the multiple properties and provide an overall evaluation on the quality of the materials.

The next challenge is how to rank materials based on multiple properties. In other words, the difference in the quality between materials needs to be identified quantitatively so that people can understand which material is better and which is worse when considering performance. General standards/specifications set requirements for materials in single parameter performance of materials (e.g. each property) rather than the overall combined performance of materials. Therefore, results are obtained for each property without any effect on other properties if tests are conducted following the current standards/specifications. For example, assume that there are two materials, with a CBR value of 78% and 82% (pass criteria >80), and a Sand Equivalent (SE) value of 42 and 38 (Pass criteria >40), respectively. It cannot be concluded which material is better by only comparing their CBR or SE test results alone. The better way is to combine the two material properties to obtain the overall performance of each material and then make a more rational decision.

The above evidence illustrates that the pass/fail specifications/standards for materials only considering single index properties cannot accurately differentiate marginal materials from premium materials. There is, therefore, a need to develop a mathematical model which can combine the multiple properties and provide an overall evaluation on the quality of the materials so that the materials can be ranked and marginal materials can be identified. Specifically, there are tools that achieve the need to integrate the multiple properties of materials. One of these tools is a multi-criteria decision-making tool called the Analytic Hierarchy Process (AHP).

This research was undertaken to develop a multi-factor mathematical model using an AHP framework to assess the overall performance and ranking of aggregate materials. The objective was to define marginal materials quantitatively, and further to advance the knowledge and understanding of marginal materials using an AHP model.

2. Methods and materials

2.1. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) developed by Saaty (1980) is a multiple criteria decision-making tool that allows subjective and objective factors to be considered in a decision-making process. It is used to determine the relative weights of selected criteria and sub-criteria in order to obtain an assessment on given alternatives. Saaty (1980) established 9 as the upper limit and 1/9 as the lower limit in his scale, which ranges from 1/9 for ‘least important than’, to 1 for ‘equal’, and to 9 for ‘absolutely more important than’ covering the entire spectrum of the comparison. The AHP has been used in a wide range of areas, including engineering, social sciences, and economics (Roux III & Makrigeorgis, 2016; Saaty & Vargas, 2001; Strojny & Hejman, 2016). A literature overview gives a detailed summary about the application of AHP, which has extended to education, manufacturing, personal and political areas (Vaidya & Kumar, 2006).

Some key and basic steps involved in this AHP methodology are (Saaty & Vargas, 2001) :

1. Identify the overall goal. State the main problem. In this study, the overall goal is to rank all the given materials and further to identify the marginal materials from the given materials.
2. Broaden the objectives of the main problem or consider all actors, objectives and its outcome.
3. Identify the criteria that must be satisfied in order to fulfill the overall goal. In this study, the goal is to rank all the given materials. According to the New Zealand specification, each material in this study is evaluated based on seven engineering properties (stated in Section 2.2). Therefore, the criteria used to characterize the goal are the seven engineering properties.
4. Develop a hierarchy of different levels constituting goal, criteria, sub-criteria and alternatives based on structuring the problem.
5. Develop the pairwise comparison matrix (priority matrix) for each level. Compare each element in the corresponding level, and then calibrate them on the numerical scale. This requires comparisons, where n is the number of elements with the considerations that diagonal elements of the matrix are equal or '1' and the other elements will simply be the reciprocals of the earlier comparisons.
6. Do a consistency test. Calculate to find the maximum Eigen value λ_{max}, consistency index CI, consistency ratio CR, and normalized values for each criteria/alternative. If the maximum Eigen value, CI, and CR are satisfactory then the decision is made based on the normalized values; otherwise the procedure is repeated until these values lie in a desired range.

2.2. Introduction to engineering properties (factors) of materials

In New Zealand, the New Zealand Transport Agency (NZTA) M4 specification is the reference or standard specification that sets out requirements for premium basecourse aggregate for use on highways and other heavily trafficked roadways (NZTA, 2006).

Each material property is introduced as follows:

Crushing Resistance: In the aggregate industry the Crushing Resistance (CR) test provides the relative measure of rock strength. New Zealand standards specify that it measures the percentage of fines produced by a specified load which is either 130 kN for aggregate to be used as base course (NZS, 1991), or if aggregates for concrete the number of KiloNewtons which produce 10% fines passing a 2.36mm sieve (Standard, 1986).

California Bearing Ratio: The California Bearing Ratio (CBR) provides a measure of resistance of materials to penetration of a standard plunger under controlled density and moisture conditions. In some cases, the soaked CBR test of materials (at least 4 days soaking) is conducted to simulate load-bearing capacity of materials in rainy weather. A soaked CBR of more than 80 is specified in New Zealand standard (NZTA M4 specification). Although it is widely acknowledged as being not wholly satisfactory when used as a performance parameter, CBR has been correlated with pavement performance in many countries over many years and provides a reliable empirical indicator of material behavior (Rogers et al., 2004).

Weathering Quality Index : The Weathering Quality Index (WQI) provides a method to assess the resistance of an aggregate to the effects of wetting, drying, heating and cooling (NZS, 1991). The WQI test involves the rolling force and the expansion/contraction forces of existing clays to physically disaggregate the aggregate thus it is really a measure of the degree of lithification of the material and the nature of its matrix (Black, 2009). The WQI consists of the aggregate percentage retained on a 4.75mm sieve fraction and the cleanness value and might be assessed as anyone of AA, AB, BA, AC, CA, BB, BC, CB, and CC. Table 1 shows the requirements for Weathering Quality Index specified by NZTA M4 specification.

Table 1
Requirements for weathering quality index in NZTA M4 specification

Cleanness value	Percentage retained on 4.75mm sieve		
	96 to 100	91 to 95	Up to 90
91 - 100	AA	BA	CA
71 - 90	AB	BB	CB
Up to 70	AC	BC	CC

Although the WQI test is designated to measure the original source rock's degree of weathering, other variables, such as rock matrices and multistage processing (designed to select tougher, high crushing resistance and more durable parts of rocks) also significantly influence the WQI values of rocks, even having a predominant control on the WQI (Black, 2009). Thus, the WQI, in some cases, is not an appropriate test to determine the level of weathering.

Sand Equivalent: The Sand Equivalent (SE) method covers a field or laboratory test for measuring the relative amounts of silt or clay size particles in fine aggregates or fine fractions of aggregates (NZS, 1991). The SE test method is regarded as a rapid method for detecting the presence or absence of detrimental fines or clay-like materials in soils and mineral aggregates; it has been used for over 60 years and is still being used even though there are a number of problems with it (Hveem, 1953. Black (2009) reported that the crushing regime and the density, size and shape of the sediment particles can cause inaccurate results about percentage of the clay size fraction or the presence or proportion of clay minerals in the material in SE test. Other researchers also comment on the risk of a poor material being classified as acceptable, and conversely good material being rejected on the basis of a low SE value (Sameshima, 1977; Van Barneveld, Bartley, & Dunlop, 1984).

Clay Index: The Clay Index (CI) test outlines the method for a methylene blue titration test used to estimate the percentage of expansive clay minerals in natural fines or rock powders (NZS, 1991). The CI test is considered to be a quicker and more cost effective production test than the x-ray diffraction (XRD) or differential thermal analysis (DTA) methods (Cole & Sandy, 1980; Stapel & Verhoef, 1989). However, all minerals or substances present which have exchangeable cations (ie Zeolites) will result in a high CI test results causing a wrong assessment for the material quality (Stapel & Verhoef, 1989).

Plasticity Index: The Plasticity Index (PI) method covers the determination of the plasticity of the fine fraction less than 0.425mm of an aggregate (NZS, 1991). This test is derived from a group of tests collectively known as Atterberg limits, including Shrinkage Limit test, Liquid Limit test, Plastic Limit test, PI test, and Liquidity Index test. The plasticity index is the size of the range of water contents where the soil exhibits plastic properties. The PI is the difference between the liquid limit and the plastic limit (PI=LL (Liquid Limit)-PL (Plastic Limit)). The determination of the liquid and plastic limits is very subjective and dependent on the experience of the tester (Black, 2009). As a consequence, there has been criticism of the Plasticity Index test (Prowell, Zhang, & Brown, 2005). The clay mineral particle size has a significant impact on its plasticity. For example, highly fine grained illite and kaolinite minerals are strongly plastic while larger grain sizes generally have very low plasticity (Black, 2009).

Particle Size Distribution: The Particle Size Distribution (PSD) is a wet or dry sieving test which can help to develop the interlock between particles so that aggregates have enough strength to resist repeated loads. The cumulative weights of material passing the standard set of sieves are recorded and then the cumulative PSD curve can be obtained by displaying the results on a grain size versus percentage passing each individual sieve graph. The tested aggregate’s cumulative particle size curve is used to evaluate the PSD grade of aggregates through being compared to a defined desirable particle size distribution envelope.

PSD is very dependent on both the crushing regime and the strength of the material. “Crushed volcanic rocks consistently fall within the allowable particle size distribution envelope while many types of greywacke have difficulty doing so” (Black, 2009).

2.3. Application of AHP method

The AHP framework was used to rate the overall performance of the aggregates used in this research based upon the engineering properties and furthermore to identify the aggregates qualities. In the process, a ‘boundary’ aggregate is assumed to be the boundary between premium and marginal aggregates. Any aggregate with higher (or lower) overall performance than the ‘boundary’ aggregate would be a premium (or marginal) aggregate. Each engineering property of the ‘boundary’ aggregate is assigned a qualified value with the minimum requirement specified by the NZTA M4 specification. For example, with the California Bearing Ratio (CBR) test, NZTA M4 specification (2006) specifies that M4 aggregates must have a CBR value of not less than 80. Hence, the CBR value of 80 is assigned to the ‘boundary’ aggregate. Any aggregate with higher overall performance (i.e. overall weights) than the ‘boundary’ aggregate condition in the AHP framework is regarded as a premium aggregate, and any with lower overall performance than the ‘boundary’ aggregate is regarded as a marginal aggregate.

The ‘real’ five aggregates were tested with respect to NZTA M4 specification. Test data obtained for different properties were transformed into the same unit to make them relatively comparable to each other. The data of ‘boundary’ aggregate conditions were processed with the same method. The data process is shown in Section 3 ‘Results and Discussion’.

The following steps were adopted to rank the materials:

1. Identify the overall goal. In this study, the overall goal or the main problem is to rank all the given materials, and further to identify the marginal materials from the given materials.
2. Identify the criteria that must be satisfied in order to fulfil the overall goal. In this study, the goal is to rank all the given materials. According to the New Zealand specification, each material in this study is evaluated based on seven engineering properties (stated in Section 2.2). Therefore, the criteria used to characterize the goal are the seven engineering properties.
4. Develop a hierarchy of different levels constituting goal, criteria, sub-criteria and alternatives based on structuring the problem. The criteria WQI and PSD are divided

into sub-criteria as WQI are directly determined by the result of 'Percentage retained on 4.75mm sieve' and 'Cleanness value', and PSD by the results of ten sieve apertures. To achieve the goal (finding marginal aggregate materials), six aggregates were provided as alternatives.

Figure 1 shows the evaluation model on the overall performance of aggregates given multiple factors in the AHP framework. Level I is the goal – Selecting marginal aggregates based on ranking the six aggregates given multiple properties. Levels II and III are the criteria and sub-criteria considered for the selection. Level IV is the alternatives, six aggregates.

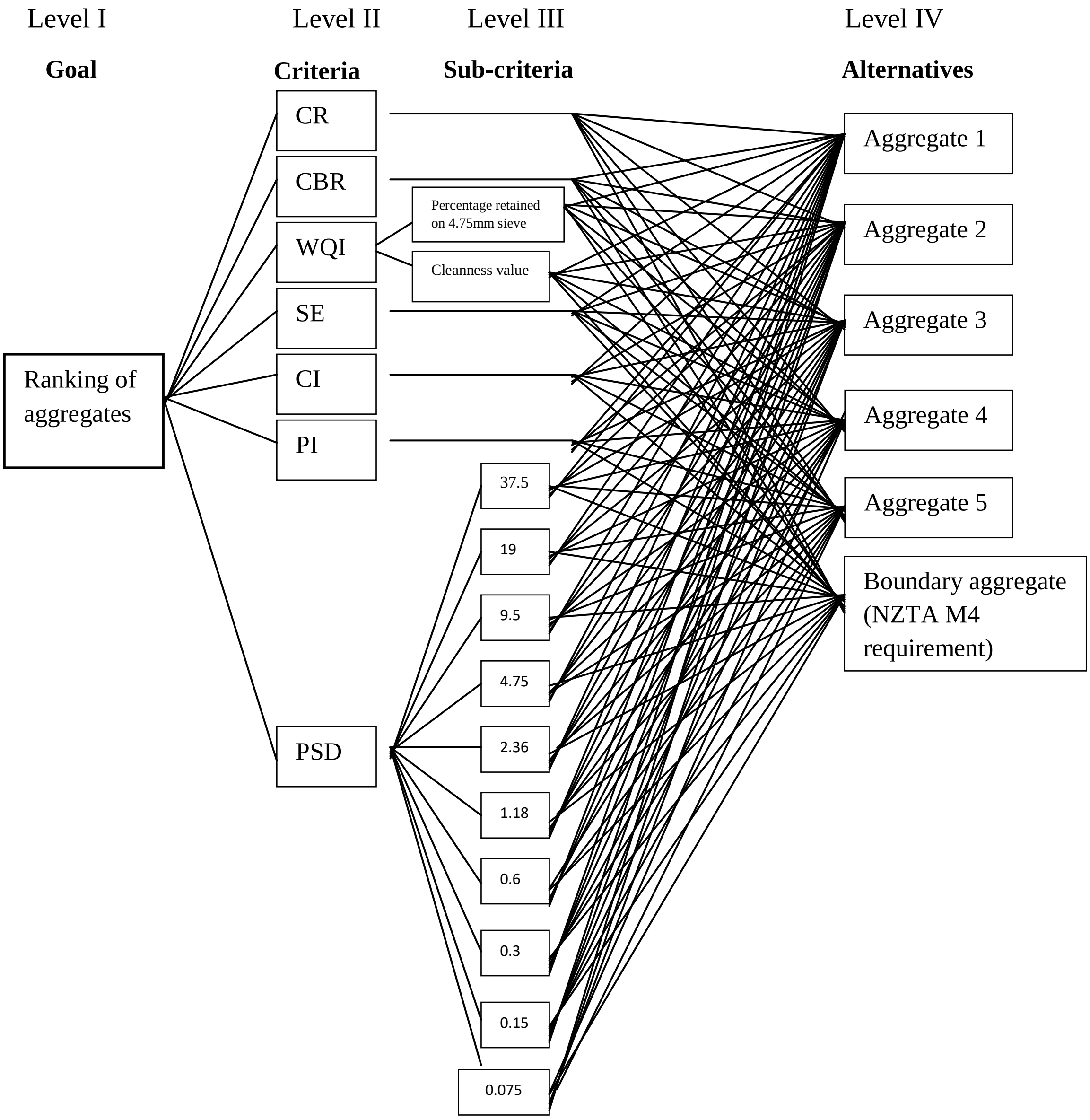

Figure 1. AHP model for evaluation of the overall performance of aggregates given multiple factors

There are two types of measurements when ranking alternatives involved in the AHP, relative and absolute (Saaty, 1986; Saaty, 1980). The first ranks a few alternatives by comparing them in pairs and is particularly useful in new and exploratory decisions. The latter rates a number of alternatives by comparing them with a standard in memory developed through experience. It is particularly useful in decisions where there is considerable knowledge to judge the relative importance of the intensities and develop priorities for them (Saaty & Vargas, 2001).

In this case, the aggregates (alternatives) are evaluated using absolute measurement as each property of aggregates (criteria) are tested according to standard testing methods and the corresponding testing values (the ratings of the criteria or sub-criteria) are assigned to them. Saaty and Vargas (2001) explain that absolute measurement, sometimes called scoring, is applied to rank the alternatives (e.g. aggregates) with regard to either the criteria and sub-criteria (e.g. properties of aggregates) or the ratings of the criteria and sub-criteria (e.g. the test results for each property). However, relative measurement is applied to obtain the relative weights of aggregate properties (criteria and sub-criteria) as shown in Tables 6, 7 and 8.

2.4. Aggregates

This paper includes five aggregates from two hard rock greywacke quarries in the Auckland – Waikato Region of New Zealand’s North Island in terms of their physical and geological properties and four assumed ‘boundary aggregates’. The materials studied were aggregates with a maximum particle size of 40 mm (AP 40) which can be categorized as either premium, or of marginal quality. Within the marginal classification there are three aggregates from two quarries which will be considered here, three marginal aggregates and two premium aggregates (the two M4 aggregates).

In the following part, these five aggregates are named as M4 aggregate 1 (M4 aggregate from Quarry 1), M4 aggregate 2 (M4 aggregate from Quarry 2), marginal aggregate 1A and 1B (both from Quarry 1) and marginal aggregate 2 (from Quarry 2) in accordance with their utilization in field road construction. For example, the two M4 aggregates are applied to basecourse where the premium quality aggregates are needed whilst the three marginal aggregates are applied to low-volume roads as sub-standard aggregates.

Engineering property tests were conducted according to NZS (New Zealand Standard) 4407: 1991 (NZS, 1991). The qualities of the five aggregates were monitored by the quarries and the results were recorded every month from 2010 to 2013. The data of each property during each year were averaged and then listed in Tables 2, 3, 4 and 5, of which Tables 4 and 5 show the results in 2013 to demonstrate how to process the data in the AHP model. The results of data processing in the other three years will be given in the ‘Results and Discussion’ section. Note that N/A is filled in the tables for the missing data of M4 aggregate 2 in 2010 and 2011.

Table 2
Testing results of the aggregates in 2010 to 2012

			M4 aggregate1	M4 aggregate2	Marginal aggregate 1A	Marginal aggregate 1B	Marginal aggregate 2
California Bearing ratio (CBR/%)	2010		278	N/A	240	173	125
	2011		291	N/A	224	105	165
	2012		261	213	194	165	175
Crushing resistance (%)	2010		1.1	N/A	2.6	3.6	3.8
	2011		1.1	N/A	2.7	2.8	2.7
	2012		1.4	2.9	2.0	2.3	3.0
Weathering quality index	2010	Percentage retained on 4.75mm sieve	98	N/A	93	94	89
		Cleanness value	97	N/A	89	89	79
	2011	Percentage retained on 4.75mm sieve	98	N/A	93	92	91
		Cleanness value	96	N/A	90	95	75
	2012	Percentage retained on 4.75mm sieve	95	93	93	94	88
		Cleanness value	91	87	88	98	79
Sand equivalent	2010		48	N/A	43	43	38
	2011		48	N/A	40	42	41
	2012		51	49	39	42	40
Clay index	2010		1.0	N/A	2.0	2.6	3.5
	2011		1.4	N/A	1.9	2.4	2.9
	2012		1.1	1.9	2.0	2.3	3.3
Plasticity index	2010		6	N/A	8	11	12
	2011		3	N/A	9	9	12
	2012		3	7	8	11	11

Table 3
PSD results of aggregates in 2010 to 2012

NA		37.5mm	19mm	9.5mm	4.75mm	2.36mm	1.18mm	0.6mm	0.3mm	0.15mm	0.075mm
M4 aggregate 1	2010	98.8	73.0	53.1	38.1	25.5	15.9	10.4	6.9	5.2	4.2
	2011	99.1	76	52.3	37.6	24.4	15.4	9.9	6.7	5.1	4
	2012	99.3	76	53.9	41.2	28.6	18.1	11.4	7.5	5.6	4.5
M4 aggregate 2	2010	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	2011	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	2012	99.8	73	49.4	36.4	23.5	15.1	10.2	7.4	5.8	4.8
Marginal aggregate 1A	2010	99.4	71.2	48.3	33.6	22.2	14.5	10.0	7.1	5.5	4.4
	2011	99.5	76.1	52.4	35.9	23.9	15.8	11.1	8.2	6.5	5.4
	2012	98.9	72.9	50.0	35.4	23.1	15.4	10.5	7.8	6.1	4.9
Marginal aggregate 1B	2010	100	76.7	46.0	25.3	16.7	10.7	8.3	6.3	5.0	4.7
	2011	99.3	71.3	44.7	26.0	16.3	11.0	8.0	6.3	5.3	4.3
	2012	99.3	71.3	47.0	29.7	18.7	12.7	9.3	7.3	6.0	5.0
Marginal aggregate 2	2010	100.0	80.5	51.7	31.7	20.8	14.2	10.8	8.2	6.2	4.5
	2011	99.8	77.2	46.8	27.8	18.0	12.5	9.0	7.0	5.8	4.7
	2012	99.7	68.3	40.8	24.8	16.0	11.0	8.2	6.5	5.2	4.2

Table 4
Engineering property data for the five aggregate materials studied

NA	California Bearing ratio (CBR/%)	Crushing resistance (%)	Weathering quality index		Sand equivalent	Clay index	Plasticity index
Requirement by NZTA M4 specification	80	maximum 10%@130kN	Percentage retained on 4.75mm sieve	Cleanness value	40 (minimum)	maximum 3.0	maximum 5 or Non-plastic (NP)
M4 aggregate1	265^{p}	0.6^{p}	98^{p}	98^{p}	58^{p}	2.0^{p}	6^{n}
M4 aggregate2	190^{p}	2.6^{p}	94^{p}	92^{p}	43^{n}	1.7^{p}	4^{n}
Marginal aggregate 1A	204^{p}	2.0^{p}	92^{p}	92^{p}	48^{p}	2.2^{p}	11^{f}
Marginal aggregate 1B	185^{p}	1.7^{p}	91^{p}	95^{p}	42^{n}	2.4^{p}	9^{f}
Marginal aggregate 2	165^{p}	3.6^{p}	90^{p}	85^{p}	38^{n}	2.9^{n}	13^{f}
Boundary aggregate	80^{n}	10^{n}	75^{n}	91^{p}	40^{n}	3.0^{n}	5^{n}

Note 1: The 'p' represents pass value. The 'n' represents near-failure value. The 'f' represents failure value.

Table 5
PSD results of the aggregates and NZTA M4 specification PSD envelope

NA	37.5mm	19mm	9.5mm	4.75mm	2.36mm	1.18mm	0.6mm	0.3mm	0.15mm	0.075mm
M4 aggregate 1	97.8	67	48.3	37	24	15.3	9.8	6.7	5.1	4
M4 aggregate 2	99.8	73.5	50.4	35.9	23.6	15.2	10.4	7.6	5.9	4.6
Marginal aggregate 1A	99.0	71.8	48.5	33.8	21.8	14.2	10.0	7.3	5.8	4.8
Marginal aggregate 1B	97.0	61.5	33.5	17.5	10.0	6.0	4.0	3.0	2.5	1.5
Marginal aggregate 2	100.0	87.5	61.0	37.5	25.0	17.0	13.0	10.0	8.0	7.0
Boundary aggregate	100	66-81	43-57	28-43	19-33	12-25	7-19	3-14	0-10	0-7
Maximum	100	81	57	43	33	25	19	14	10	7
Minimum	100	66	43	28	19	12	7	3	0	0

Note 1: 0.075mm, 0.15mm, 0.3mm ..., 37.5mm are the test sieve apertures.

Note 2: The PSD results of the four boundary aggregates are shown in an interval form because they are supposed to sit in the PSD envelope specified by NZTA M4 specification and any value in the specified envelope is supposed to be equally important.

3. Results and discussion

3.1. The weights of engineering properties (criteria)

As mentioned earlier, the priorities of criteria and sub-criteria (aggregate properties) were obtained through analyzing pairwise comparison matrices. The pairwise comparison was conducted through interviewing four experts in this field and averaging their scales for individual comparison. Pairwise comparisons of homogeneous elements are made in the matrices with a 1-9 scale to represent the degree of importance as shown in Tables 6, 7 and 8.

Table 6 shows the pairwise comparison matrix for material properties and the priority vector (relative weight of each property) in the last column. Note in this study the priority vector/importance was worked out by using the programming tool ‘Matlab’. Clay Index with the highest value of 0.259 is the most important criterion influencing the overall performance of aggregates. It is probably because the clay index can more accurately reflect the percentage of expansive clays and better respond to the weathering than the other properties (Bartley et al., 2007). The priority vector is used to determine the final relative weight of each aggregate material, which will be discussed in ‘Ranking of The Materials’.

Table 6
Pairwise comparison matrix for material properties

NA	CR	CBR	WQI	SE	CI	PI	PSD	Priority vector
CR	1	1	2	1/2	1/3	1/2	1/2	0.092
CBR	1	1	1	1	1/3	1/2	1/3	0.085
WQI	1/2	1	1	1	1/4	1/3	1/2	0.076
SE	2	1	1	1	1/2	1	1/2	0.120
CI	3	3	4	2	1	2	1	0.259
PI	2	2	3	1	1/2	1	1	0.167
PSD	2	3	2	2	1	1	1	0.202

The maximum eigenvalue λ_{max}=7.198, CI (the consistency index) =0.033, and CR (consistency ratio) =0.025.

Tables 7 and 8 list the pairwise comparison matrices for the sub-criteria of WQI and PSD, respectively. The pairwise comparison was also obtained through interviewing the four experts and averaging their scales for each pair comparison. The two sub-criteria of WQI with the same value of 0.5 are equally important as shown in Table 7. In Table 8, test sieve aperture 2.36mm and 0.075mm are supposed to be the two most important sub-criteria of PSD, both with a priority value of 0.173. It is probably because the test sieve aperture 2.36mm is considered as the boundary size between coarse and fine particles of aggregates, and 0.075mm is a key sieve aperture to measure the cleanness of aggregates.

Table 7
Pairwise comparison matrix for sub-criteria of weathering quality index (WQI**)**

NA	Percentage retained on 4.75mm sieve	Cleanness value	Priority vector
Percentage retained on 4.75mm sieve	1	1	0.5
Cleanness value	1	1	0.5

CI=0 and RI (Random Index) =0.

Table 8
Pairwise comparison matrix for sub-criteria of particle size distribution (PSD)

mm mm	37.5	19	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	importance
37.5	1	2	1	1/3	1/3	1/2	1/2	1/2	1/2	1/3	0.051
19	1/2	1	1/2	1/5	1/5	1/3	1/3	1/4	1/3	1/5	0.029
9.5	1	2	1	1/3	1/3	1	1/2	1	1/2	1/3	0.059
4.75	3	5	3	1	1	2	2	2	2	1	0.166
2.36	3	5	3	1	1	2	3	2	2	1	0.173
1.18	2	3	1	1/2	1/2	1	1	1	1/2	1/2	0.079
0.6	2	3	2	1/2	1/3	1	1	1	1/2	1/3	0.079
0.3	2	4	1	1/2	1/2	1	1	1	1	1/2	0.087
0.15	2	3	2	1/2	1/2	2	2	1	1	1/2	0.105
0.075	3	5	3	1	1	2	3	2	2	1	0.173

λ_{max}=10.162, CI =0.018, and CR =0.012.

3.2. Data process on numeric rating for engineering properties

The numeric rating for each property is listed in Table 4, which are transformed to Table 9 using the tool ‘Excel’ according to Equations (1) and (2) below (Cheng, 1999; Strojny & Hejman, 2016; Torfi, Farahani, & Rezapour, 2010; Yang & Hung, 2007; Zhang, Zhang, Wu, Shu, & Hao, 2005) . The purpose of the transformation is:

(i) to make all data/information uniform and further to make the results of the properties comparable (i.e. CI and PI are the ‘smaller-the-better type’ while CBR, CR, sub-criteria of WQI, and SE are the ‘larger-the better type’). If the data of the two types are not processed before conducting an AHP process, the relative weights in AHP cannot be obtained reasonably),
(ii) to normalize each numeric element into the range of [0, 1] and
(iii) to obtain the scoring of each aggregate material under criteria or sub-criteria.

(I) The larger the better type:

$$r_{ij} = \frac{[x_{ij} - \min\{x_{ij}\}]}{[\max\{x_{ij}\} - \min\{x_{ij}\}]} \tag{1}$$

(II) The smaller the better type:

$$r_{ij} = \frac{[\max\{x_{ij}\} - x_{ij}]}{[\max\{x_{ij}\} - \min\{x_{ij}\}]} \tag{2}$$

where x_{ij} , i =1, 2, …6, j =1, 2, …, 7, is the numeric element in the matrix of Table 4 and r_{ij} , i =1, 2, …6, j =1, 2, …, 7, is the normalized numeric element based on Equations (1) and (2).

Table 9
The scoring of each aggregate under each property

	California Bearing ratio (CBR/%)	Crushing resistance (%)	Weathering quality index		Sand equivalent	Clay index	Plasticity index
			Percentage retained on 4.75mm sieve	Cleanness value			
Requirement by NZTA M4 specification	0	0	0	0.462	0.100	0	0.889
M4 aggregate 1	1.000	1.000	1.000	1.000	1.000	0.769	0.778
M4 aggregate 2	0.595	0.787	0.826	0.538	0.250	1.000	1.000
Marginal aggregate 1A	0.670	0.851	0.739	0.538	0.500	0.615	0.222
Marginal aggregate 1B	0.568	0.883	0.696	0.769	0.200	0.462	0.444
Marginal aggregate 2	0.459	0.681	0.652	0	0	0.077	0
Boundary aggregate	0	0	0	0.462	0.100	0	0.889

(III) The closer to the specified interval the better type:

The passing percentage at each sieve aperture neither belongs to the smaller-the-better type nor the larger-the better type, but belongs to the closer to the specified interval- the better type. For example, the passing percentage at 4.75mm is between 28% and 49% with respect to AP 40 (all materials passing 40mm sieve), specified by NZTA M4 specification. Any number in the interval of 28% - 49% is supposed to be the best and equally important. Out of the interval, 26% is supposed to be better than 16% as it is closer to the minimum number of the interval (28%). Similarly, 46% is supposed to be better than 56% as it is closer to the maximum number of the interval (49%). Consequently, Table 5 shows the numeric ratings under the sub-criteria of PSD (the passing percentage at each sieve) is transformed to Table 10 using the tool ‘Excel’ according to Equation (3) (Zhang et al., 2005).

$$r_{ij} = \begin{cases} \dfrac{x_{ij}-\mathrm{m}}{q_1-\mathrm{m}}, x_{ij} < q_1 \\ 1.0, \quad x_{ij} \in [q_1, q_2] \\ \dfrac{M-x_{ij}}{M-q_2}, x_{ij} > q_2 \end{cases} \tag{3}$$

Where x_{ij} , i =1, 2, …6, j =1, 2, …, 10, is the numeric element in Table 5; r_{ij} , i =1, 2, …6, j =1, 2, …, 10, is the normalized numeric element based on Equation (3); m is the allowable minimum number for x_{ij} and M is the allowable maximum number for x_{ij} ; q_1 is the minimum number of the interval and q_2 is the maximum number of the interval. See the previous example, q_1 is 28%, q_2 is 49%, m is 0, and M is 100%.

Table 10
The scoring of each aggregate under each sieve aperture (sub-criteria of PSD)

NA	37.5mm	19mm	9.5mm	4.75mm	2.36mm	1.18mm	0.6mm	0.3mm	0.15mm	0.075mm
Requirement by NZTA M4 specification	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
M4 aggregate 1	0.980	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
M4 aggregate 2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Marginal aggregate 1A	0.990	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Marginal aggregate 1B	0.970	0.930	0.780	0.630	0.530	0.500	0.570	1.000	1.000	1.000
Marginal aggregate 2	1.000	0.660	0.910	1.000	0.789	0.833	1.000	1.000	1.000	1.000
Boundary aggregate	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Note: The PSD results of the boundary aggregate are assumed to be in the PSD envelope specified by NZTA M4 specification.

3.3. Ranking of the aggregates

The data analysis for ranking the aggregate materials is shown in Table 11. The overall weight was worked out using ‘Excel’. Based on mathematical analysis, the aggregates can be ranked as follows:

M4 aggregate 1 (0.904) > M4 aggregate 2 (0.833) > Marginal aggregate 1A (0.642) > Marginal aggregate 1B (0.558) > Boundary aggregate (0.346) > Marginal aggregate 2 (0.380)

Where ‘>’ does not mean ‘bigger’, but ‘better’. It reflects a preference for the alternatives (aggregates).

The ranking process for the properties of the five aggregates in Year 2010, 2011, and 2012 are shown in Table 12. A consistent result is obtained, M4 aggregate 1 > M4 aggregate 2 > Marginal aggregate 1A > Marginal aggregate 1B > Boundary aggregate > Marginal aggregate 2.

Validation of the AHP model

3.3.1. Ranking

It can be found that the AHP model can describe the overall performance of aggregates in a quantitative way, which allows the qualities of the aggregates to be compared to each other so that the proper aggregates can be selected for different road construction purposes. As per the ranking for the five aggregates in 2010, 2011, 2012 and 2013, M4 aggregate 1 and 2 are the two best aggregates from among the five aggregates. Based on the information provided by the quarries, the two aggregates are used as premium aggregates in field road construction and the other three aggregates are used as sub-standard aggregates in low-volume roads. Therefore, the AHP model is a good method to select the best aggregates within a range of aggregates.

3.3.2. Selection of marginal aggregates

The two M4 aggregates, Marginal aggregate 1A and Marginal aggregate 1B are better than the boundary aggregate due to the higher overall weight, whilst Marginal aggregate 2 with a lower overall weight is worse than the boundary aggregate. As the boundary aggregate is the boundary between premium aggregates and marginal aggregates, the two M4 aggregates, Marginal aggregate 1A and Marginal aggregate 1B can be defined as 'premium' material theoretically based on AHP model analysis whilst the Marginal aggregate 2 as 'marginal'.

However, Marginal aggregate 1A and 1B are finally utilized in road construction as 'sub-standard/marginal' materials rather than premium materials. The reason for the inconsistency is the original individual pass/fail criteria mentioned previously, their PI values obviously exceeding the limit specified by NZTA M4 specification and the PSD results of Marginal aggregate 1B out of the specified limit of the specification.

As the real 'premium aggregates', M4 aggregate 1 and M4 aggregate 2 are still slightly exceeding the limit of specification in terms of the PI values, i.e. in 2010 and 2013 for M4 aggregate 1, and in 2012 for M4 aggregate 2. But it is not rational to arbitrarily regard them as marginal aggregates because their PI values meet the requirement of NZTA M4 specification in the other years. In this scenario, it is probably essential to compare the overall performance of the two M4 aggregates and the boundary aggregate. Considering that the overall weights of the two M4 aggregates are much greater than that of the boundary aggregate in Table 12, theoretically, the two M4 aggregates can be categorized as premium aggregates, which reconfirm their application as good-quality materials in field road construction.

Therefore, the validation of the AHP model demonstrates that there is a need to make a combination analysis on the individual properties (specification pass/fail criteria) and overall performance (AHP model) in the process of evaluating the quality of aggregates.

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Table 11
Data analysis for ranking the materials

Criteria	Weights for criteria	Sub criteria	weights	M4 aggregate 1	M4 aggregate 2	Marginal aggregate 1A	Marginal aggregate 1B	Marginal aggregate 2	Boundary aggregate
WQI	0.076	Percentage retained on 4.75mm sieve	0.5	1	0.826	0.739	0.696	0.652	0
		Cleanness value	0.5	1	0.538	0.538	0.769	0	0.462
CI	0.259			0.769	1	0.615	0.462	0.077	0
SE	0.12			1	0.25	0.5	0.2	0	0.1
CBR	0.085			0.778	1	0.222	0.444	0	0.889
CR	0.092			1	0.787	0.851	0.883	0.681	0
PI	0.167			1	0.595	0.67	0.568	0.459	0
PSD	0.202	37.5	0.051	0.98	1	0.99	0.97	1	1
		19	0.029	1	1	1	0.93	0.66	1
		9.5	0.059	1	1	1	0.78	0.91	1
		4.75	0.166	1	1	1	0.63	1	1
		2.36	0.173	1	1	1	0.53	0.789	1
		1.18	0.079	1	1	1	0.5	0.833	1
		0.6	0.079	1	1	1	0.57	1	1
		0.3	0.087	1	1	1	1	1	1
		0.15	0.105	1	1	1	1	1	1
		0.075	0.173	1	1	1	1	1	1
Overall weights				0.904	0.833	0.642	0.558	0.346	0.38

Table 12
Ranking the materials in 2010, 2011 and 2012

	M4 aggregate 1	M4 aggregate 2	Marginal aggregate 1A	Marginal aggregate 1B	Marginal aggregate 2	Boundary aggregate
2010	0.977	N/A	0.709	0.529	0.309	0.470
2011	0.999	N/A	0.625	0.515	0.437	0.360
2012	0.987	0.739	0.609	0.543	0.344	0.397
2013	0.904	0.833	0.642	0.558	0.346	0.380

4. Summary and conclusions

Current definitions about whether a material is classified as a ‘marginal’ material can cause difficulties in fully characterizing and understanding the predicted in-field performance of materials. The understanding of marginal materials suffers from the limitation of not focusing on the overall performance of the materials but on single pass/fail test properties. To overcome this limitation and better understand ‘marginal materials’, this study was conducted using the AHP mathematical model based on multiple factors (various engineering properties and performance). The first step was to determine the relative weights of criteria, including CBR, WQI, CR, SE, CI, PI and PSD, and the relative weights of sub-criteria, including ‘percentage retained on 4.75mm sieve’ and ‘cleanness value’ of WQI, and sieve apertures of PSD. The second step was to process data on the engineering properties of each material using mathematical methods. The third step calculated the overall weight of every material and further ranked the overall performance of the materials.

The identification of the AHP analyzed marginal materials was conducted along with the setting of boundary aggregate conditions using the monitored data from 2010 to 2013. The following conclusions can be drawn:

Clay Index (CI) with the highest relative weight is supposed to be the most important property (criterion) influencing the overall performance of aggregates through the weight analysis. The ‘percentage retained on 4.75mm’ and ‘Cleanness’ with the same relative weights are of equal importance for Weathering Quality Index (WQI). The sieve 2.36mm and 0.075mm are supposed to be the two of the most important test sieve apertures in affecting the results of Particle Size Distribution (PSD)

The AHP model provides a good method to select the best aggregates within a range of aggregates. It can describe the overall performance of aggregates in a quantitative way, which allows the qualities of the aggregates to be compared to each other so that the proper aggregates can be selected for different road construction purposes. The setting of a boundary aggregate is very important in the process of analyzing the quality of aggregates using the AHP model. It provides a boundary line of the overall performance between premium and marginal aggregates.

The validation of AHP model demonstrates the AHP analyzed qualities of the aggregates match their qualities in field road construction, but there is a need to make a combination analysis on the individual properties (specification pass/fail criteria) and overall performance (AHP model) in the process of evaluating the quality of aggregates.

The AHP model still has the disadvantage of not completely removing subjectivity from the decision model resulting from deciding pairwise comparison matrices. Another disadvantage is that the AHP model may be very time-consuming when obtaining pairwise comparison matrices, which will involve interviews and/or questionnaires. Additionally, in many practical cases, the pairwise comparison matrices obtained from interviews and/or questionnaires are uncertain or unable to make precise numerical comparisons, so it is difficult to make a decision with high accuracy. However, it is an improvement over the present practice. The application of the model for ranking materials provides a good quantitative method to transform the values of all material properties into the same unit and r to better compare the overall performance of materials, rather than the limited comparison of single properties. The proposed AHP method enables better decision making when selecting aggregate materials to perform through the lifecycle of the in-field asset and will lead to a better and more economic utilization of local non-renewable mineral resources.

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