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Modelling Effect of Aggregate Gradation and Bitumen Content on Marshall Properties of Asphalt Concrete

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***Abstract*— Current selection of aggregate gradation fails to explain completely the position of the aggregate gradation on a continuous scale. This study proposes a gradation index (GI) as a new parameter to determine the position of the aggregate gradation of the asphalt mixture on the continuous scale. The GI was used to develop a model of the Marshall properties. The aim of this study was to develop a model between the GI and bitumen content of the Marshall properties that includes density, voids in the mix (VIM), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), stability, and flow. The materials used were unmodified Asphalt Cement 60/70 with bitumen content variation of 4.5% to 8.0% of the mix and five variations of the aggregate gradation. Curve fitting method is used to find partial correlation factor of the aggregate gradation and the bitumen content of the Marshall properties. Multiple Polynomial Regression (MPR) models were specified to find the relationship between the GI and bitumen content of the Marshall properties. The visualization of the relationship between the GI, bitumen content and Marshall properties used contour charts. The results showed that the MPR determines the model of the relationship between the GI and bitumen content of the density, VIM, VMA, VFA, stability, and flow that have a very strong relationship (R^2 > 0.9). Therefore, the model can be used to predict the Marshall properties.**

***Keywords*— gradation index; asphalt concrete; Marshall properties; multiple polynomial regression**

I. INTRODUCTION

Aggregate gradation strongly influences the characteristics of asphalt mixture, namely stiffness, stability, durability, permeability, workability, fatigue resistance, skid resistance, and resistance to moisture damage [1], [2]. The aggregate gradation is assigned to the mid-range as the target of the gradation with the assumption that the value of the center is the gradation that gives the best performance.

Some researchers have conducted studies related to the aggregate gradation. Twelve mixtures were evaluated with several combinations of parameters to examine the relationship between the aggregate gradation with moisture damage and rutting [3]. The combination of the parameters includes the three types of the aggregate gradation (upper limit, mid range, and lower limit), the two types of asphalt (conventional and modified asphalt), and the two types of mixtures (bituminous concrete and dense bituminous macadam). Gradation ratio was formulated to predict rutting and moisture damage of the asphalt mixture. The results showed that the ratio of the gradation could be used to predict the rutting and moisture damage. The formulation ratio of the gradation only specifies certain sieve diameter that does not represent the overall sieve in determining the aggregate gradation.

Band specification is divided into several segments as the upper limit of the range variation has upper variation, the mid range has mid-variation, and the lower limit has lower variation [4]. The results showed that the changes of the aggregate gradation affect the Marshall properties, namely stability, flow, air voids, void in mineral aggregate, creep stiffness and permanent deformation. The range of the variation in the specification band did not quantify the aggregate gradation position, so it could not be able to show any changes in the behavior of the aggregate gradation

Encoding can be used to identify changes in the aggregate gradation [5]. Code for fine aggregate gradation (upper limit) is +1, for the coarse aggregate gradation (lower limit) is -1, and for the middle of aggregate gradation is between 0 and +1 and 0 and -1. This encoding does not indicate the actual position of the aggregate gradation by the argument that it interprets the behaviour of the asphalt mixture. Thus, a quantitative classification with continuous scale is needed[6].

The nature of the aggregate gradation was measured by using a uniformity coefficient (Cu), curvature coefficient (Cc), shape factor (n) and gravel to the sand ratio (G/S) [6,7]. Cu values were used to measure the difference gradation of the aggregate used in designing large stone gradation (maximum aggregate size > 37.5 mm) [8]. Cu and Cc values are determined based on the size of the diameter of the sieve that can pass on the aggregate in a certain amount. Determining the size of a particular sieve diameter does not represent the whole sieving. A shape factor determines the shape of the gradation by the fuller equation. But not all the boundaries of the gradations in the specification have a specific shape factor value unless the aggregate gradation has certain shape factor and determination coefficient (R^2) above 0.9. Rated G/S showed that the greater it is, the coarser aggregate gradation is or vice versa. The aggregate gradation in the gravel and sand can not be defined precisely if the gradation does not have the specific shape factor.

Gradation index (GI) was proposed in this study to quantify actual position of the aggregate gradation. The GI can also be used to determine if the aggregate gradation is finer or coarser. Thus, the purpose of this study was to determine the GI and bitumen content effect on the Marshall properties. The model with the GI and bitumen content as independent variables were expected to be used to predict the Marshall properties of the asphalt mixture as the dependent variable.

II. Material and Method

A. Material Selection

Unmodified asphalt cement (AC) 60/70 ex. Pertamina was used as a binder. The asphalt AC 60/70 is recommended by the Indonesian Directorate General of Highways according to the tropical climate in Indonesia [9]. The bitumen test results meet the requirements of Indonesian Highway Specification [9].

The aggregate obtained from the Tinalah River, Kulon Progo, Yogyakarta Indonesia is one of the quarries to the construction of roads and buildings in Yogyakarta and surrounding areas. The aggregate test results have complied the requirements of the Indonesian Highway Specification [9]. The selection of the aggregate gradation was based the 2010 Indonesian Highway Specification of the third revised edition for asphalt concrete wearing course [9] by five types of the aggregate gradations, namely (1) upper limit or UL; (2) The middle of the lower limit and the mid-range or UM; (3) mid-range or MR; (4) middle of mid-range and upper limit or ML; and (5) lower limit or LL as seen in Fig. 1.

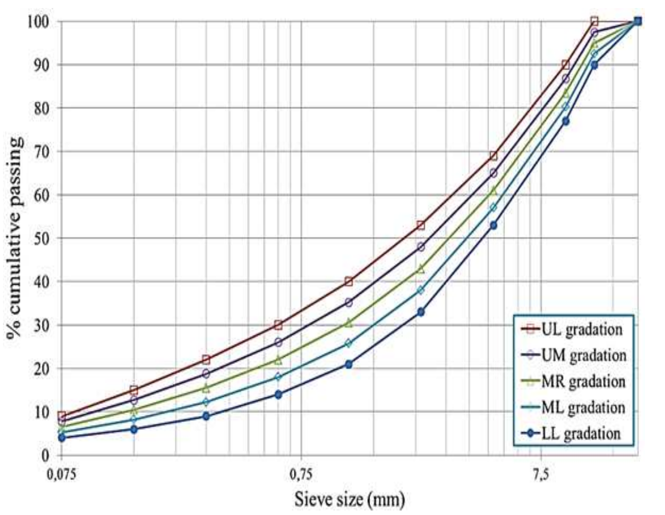

Fig. 1 Types of aggregate gradation

B. Mix Design

Marshall method is used for designing mixture and determining the stability, flow, void in the mix (VIM), voids filled with asphalt (VFA), and voids in mineral aggregate (VMA) of each gradation type of mixture. Fifteen specimens were prepared for each gradation with bitumen content variation of 4.5% to 6.5% of the mix, interval 0.5% for UM, MR, and ML gradation; UL gradation using bitumen content variation 5% to 7% at intervals of 0.5%; and gradation LL variation bitumen content of 6% to 8% with intervals of 0.5%. Mixing and compaction temperatures were measured at the viscosity of 0.2 Pa.s and 0.4 Pa.s [9], respectively. The test results showed that the mixing and compaction temperatures are 157 °C and 143 °C, respectively.

C. Gradation Index (GI)

The gradation index (GI) proposed in this study was to quantify the actual position of the aggregate gradation, the relationship that constantly determines the effect of the treatment on the aggregate gradation and determines if the gradation is coarser or finer. The GI is defined as the ratio of the area of the retained area curve and the total area of the aggregate gradation curve [11]. The calculation is defined in Equation 1 and 2 with an illustration presented in Fig. 2. The advantage of the GI is to take into account all the sieve size, unlike the research [5,6,7,8] that did only on certain sieve diameter. Another advantage of the GI is a simple calculation.

$$GI = (a/A)\ 100 \quad (1)$$

$$a = \sum_{i=0}^{n} \left(\frac{Sr_i + Sr_{i+1}}{2}\right)\left(T_i - T_{i+1}\right) \quad (2)$$

where the GI is gradation index (%), *a* is area retained of the curve (mm^2), *A* is total area (mm^2), Sr is sieve size (mm), and T is cumulative retained aggregate [10%=10mm](mm).

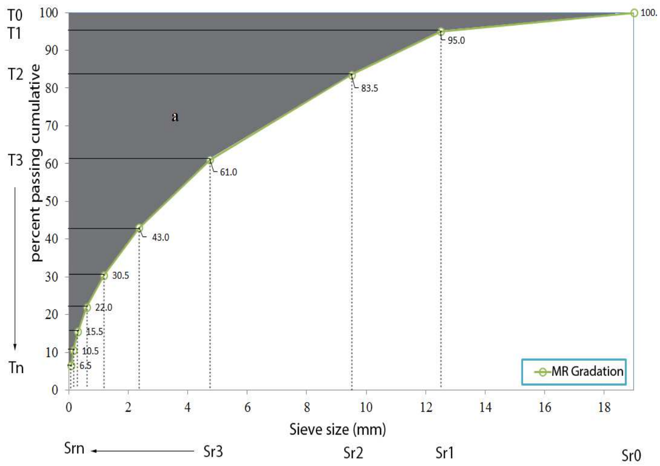

Fig. 2 Retained area of aggregate gradation

D. Model Development

A polynomial regression model was used in this study to test the suitability of the model and the research data based on the coefficient of determination. The coefficient of determination can be used to measure the quality of the fit of the model to the data [12]. The determination coefficient indicates that the independent variables are selected to explain the dependent variable for R^2 [5], [10], [12]. All residuals are zero and thus $R^2 = 1.0$, so the fit is perfect [12]. The relationship between the bitumen content and the Marshall properties used by quadratic polynomial regression models is shown in Equation 3, while the relationship between the GI and bitumen content using multiple polynomial regression by the proposal of Montgomery [13] is shown in Equation 4.

$$Y_{ij} = a_{ij} X_{ij}^{\ 2} + b_{ij} X_{ij} + c_{ij} \quad (3)$$

Where a_{ij}, b_{ij} and c_{ij} are the regression coefficients, i is the coefficient of the bitumen content and j is the coefficients of the Marshall properties (density, VFA, VIM, VMA, stability and flow).

$$Y = b_0 + \sum_{i=1}^{2} b_i X_i + \sum_{i=1}^{2} b_{ii} X_i^2 + \sum_{i=1} \sum_{j=i+1} b_{ij} X_i X_j \quad (4)$$

Where Y is response variables (i.e. density, VFA, VIM, VMA, stability, and flow) and b_0, b_i,b_{ii},b_{ij} are constant coefficients of intercept, linear, quadratic and interaction terms, respectively, and X_i and X_j represent the two independent.

III. Results and Discussion

A. Effect of Bitumen on Marshall Properties

The results of the Marshall test on the five aggregate gradations and the Marshall properties are shown in Table 1.

TABLE I
MARSHALL PROPERTIES OF THE ASPHALT MIXTURE

1. UL aggregate gradation								
Properties	**Bitumen contents**							
	4.5*	**5.0**	**5.5**	**6.0**	**6.5**	**7.0**	**7.5***	**8.0***
Density	2.30	2.33	2.35	2.36	2.37	2.38	2.38	2.38
VFA	49.54	59.24	67.93	75.89	82.88	88.90	94.09	98.36
VIM	8.46	6.72	5.18	3.86	2.75	1.81	1.12	0.60
VMA	17.00	16.49	16.14	16.01	16.08	16.29	16.73	17.34
Stability	1563.14	1798.74	1890.50	1978.30	1944.78	1791.21	1586.84	1284.80
Flow	2.81	2.80	3.00	3.20	3.45	4.00	4.52	5.18
2. UM aggregate gradation								
Properties	**Bitumen contents**							
	4.5	**5.0**	**5.5**	**6.0**	**6.5**	**7.0***	**7.5***	**8.0***
Density	2.29	2.33	2.35	2.38	2.39	2.39	2.39	2.37
VFA	47.98	59.13	68.54	77.64	85.56	92.49	98.48	103.50
VIM	8.96	6.58	4.98	3.45	2.22	1.44	0.96	0.82
VMA	17.23	16.10	15.71	15.39	15.36	15.75	16.43	17.44
Stability	1535.73	1655.73	1781.25	1823.01	1901.74	1926.09	1932.86	1915.87
Flow	3.00	3.07	3.23	3.43	3.57	3.79	4.03	4.28
3. MR aggregate gradation								
Properties	**Bitumen contents**							
	4.5	**5.0**	**5.5**	**6.0**	**6.5**	**7.0***	**7.5***	**8.0***
Density	2.30	2.34	2.36	2.37	2.38	2.38	2.37	2.35
VFA	53.07	64.23	73.31	81.74	88.89	94.66	99.24	102.58
VIM	7.80	5.61	4.10	2.78	1.72	1.12	0.84	0.90
VMA	16.60	15.66	15.35	15.22	15.33	15.88	16.72	17.89
Stability	1520.93	1700.82	1753.58	1790.30	1770.40	1676.3	1527.4	1319.1
Flow	3.07	3.03	3.17	3.47	3.73	4.20	4.76	5.43
4. ML aggregate gradation								
Properties	**Bitumen contents**							
	4.5	**5.0**	**5.5**	**6**	**6.5**	**7.0***	**7.5***	**8.0***
Density	2.28	2.32	2.34	2.35	2.36	2.36	2.36	2.35
VFA	53.96	64.16	72.14	80.84	87.37	93.44	98.48	102.57
VIM	7.79	5.78	4.45	3.01	2.01	1.25	0.77	0.55
VMA	16.91	16.13	15.96	15.73	15.87	16.27	16.92	17.82
Stability	1397.55	1534.03	1590.37	1556.10	1469.49	1291.17	1039.38	710.92
Flow	3.10	3.30	3.50	3.80	4.07	4.40	4.76	5.16
5. LL aggregate gradation								
Properties	**Bitumen contents**							
	4.5*	**5.0***	**5.5***	**6.0**	**6.5**	**7.0**	**7.5**	**8.0**
Density	2.20	2.24	2.26	2.29	2.31	2.32	2.33	2.34
VFA	34.52	44.25	53.31	61.74	69.34	76.25	83.00	88.30
VIM	12.24	10.29	8.50	6.88	5.43	4.19	3.00	2.10
VMA	19.68	18.96	18.38	17.97	17.70	17.63	17.62	17.86
Stability	811.59	985.60	1119.87	1204.67	1287.02	1288.95	1235.31	1206.33
Flow	4.57	4.53	4.52	4.53	4.57	4.60	4.73	4.80

* calculated by the model

The density and volumetric data are obtained from the average measurement result of the Marshall specimens. The average value of the stability and flow was obtained from the Marshall test.

Table 2 shows the results of the modelling the relationship between the Marshall properties and bitumen content variation with a quadratic polynomial model. The R^2 of the models are above 0.9. The density, the higher of the bitumen content raises the density value served as an adhesive, but after reaching the peak, increasing bitumen content will lower density because of the bitumen changes to the lubricant. Consequently, it is difficult to compact the aggregate. VFA, adding the bitumen content, will increase the bitumen that fills the voids between the aggregate, so the higher bitumen will raise VFA. VIM has the opposite trend with the VFA. The higher bitumen will lower the VIM because the bitumen will reduce air void in the mix. VMA is the air void plus the volume of the bitumen as a binder. The addition of the bitumen content will reduce the VMA to the minimum value and then it will rise. The increasing of VMA after it reaches the minimum caused by increasing the bitumen content and the density decrease.

TABLE II
QUADRATIC POLYNOMIAL OF MARSHALL PROPERTIES ON BITUMEN CONTENTS

Properties	**Equations**	**R^2**
1. UL or GI = 18.65		
Density	$y = -0.0103x^2 + 0.1511x + 1.8275$	0.9998
VFA	$y = -1.8028x^2 + 36.484x - 78.131$	0.9999
VIM	$y = 0.4029x^2 - 7.2844x + 33.064$	0.9999
VMA	$y = 0.3763x^2 - 4.606x + 30.105$	0.9961
Stability	$y = -174.85x^2 + 2106.1x - 4373.6$	0.9456
Flow	$y = 0.2143x^2 - 2.0014x +7.4771$	0.9889
2. UM or GI = 21.53		
Density	$y = -0.0175x^2 + 0.2423x + 1.5532$	0.9965
VFA	$y = -1.9311x^2 + 39.975x - 92.712$	0.9999
VIM	$y = 0.6774x^2 - 10.777x + 43.682$	0.9987
VMA	$y = 0.6464x^2 - 8.0033x + 40.098$	0.9872
Stability	$y = -47.518x^2 + 702.55x - 663.38$	0.9913
Flow	$y = 0.0476x^2 - 0.2238x + 3.0267$	0.9878
3. MR or GI = 24.41		
Density	$y = -0.0177x^2 + 0.2361x + 1.5963$	0.9968
VFA	$y = -2.4789x^2 + 45.099x - 99.567$	0.9998
VIM	$y = 0.6953x^2 - 10.647x + 41.579$	0.9990
VMA	$y = 0.6516x^2 - 7.764x + 38.298$	0.9844
Stability	$y = -118.74x^2 + 1423.9x - 2472.7$	0.9827
Flow	$y = 0.219x^2 - 2.0562x + 7.8667$	0.9873
4. ML or GI = 27.29		
Density	$y = -0.0138x^2 + 0.1897x + 1.7112$	0.9952
VFA	$y = -1.8917x^2 + 37.511x - 76.447$	0.9993
VIM	$y = 0.5409x^2 - 8.8161x + 36.462$	0.9985
VMA	$y = 0.5101x^2 - 6.1042x + 34.009$	0.9713
Stability	$y = -153.37x^2 + 1720.3x - 3235.8$	0.9953
Flow	$y = 0.0667x^2 - 0.2467x + 2.86$	0.9985
5. LL or GI = 30.17		
Density	y = -0.0084x2 + 0.1447x + 1.7218	0.9991
VFA	y = -1.36x2 + 32.395x - 83.721	0.9998
VIM	y = 0.3336x2 - 7.07x + 37.296	0.9998
VMA	y = 0.3095x2 - 4.3938x + 33.188	0.9784
Stability	y = -79.492x2 + 1103.2x - 2543.1	0.8339
Flow	$y = 0.0476x^2 - 0.5267x + 5.9762$	0.9722

B. Effect of Gradation Index (GI) on Marshall Properties

Table 3 shows that quadratic polynomial is suitable for modelling of the GI and Marshall properties (i.e. density, VFA, VIM, VMA, stability, and flow).

TABLE III
QUADRATIC POLYNOMIAL OF GI AND MARSHALL PROPERTIES

Bitumen contents	**Equations**	**R^2**
1. Gradation Index versus Density		
4.5	$y = -0.0014x^2 + 0.0634x + 1.6074$	0.8735
5.0	$y = -0.0017x^2 + 0.0782x + 1.4654$	0.9374
5.5	$y = -0.0016x^2 + 0.0706x + 1.5758$	0.9639
6.0	$y = -0.0015x^2 + 0.069x + 1.6095$	0.9760
6.5	$y = -0.0014x^2 + 0.0611x + 1.7092$	0.9927
7.0	$y = -0.001x^2 + 0.043x + 1.9226$	0.9965
7.5	$y = -0.0005x^2 + 0.0197x + 2.1864$	0.9878
8.0^+	$y = 9E-05x^2 - 0.008x + 2.4965$	0.9622
2. Gradation Index versus VFA		
4.5	$y = -0.3439x^2 + 15.954x - 130.97$	0.7017
5.0	$y = -0.3852x^2 + 17.937x - 143.73$	0.7654
5.5	$y = -0.3856x^2 + 17.934x - 134.56$	0.8144
6.0	$y = -0.4019x^2 + 18.75x - 135.94$	0.8367
6.5	$y = -0.3983x^2 + 18.567x - 126.47$	0.8786
7.0	$y = -0.3869x^2 + 18.039x - 114.26$	0.8995
7.5	$y = -0.355x^2 + 16.558x - 92.128$	0.9160
8.0^+	$y = -0.3262x^2 + 15.191x - 71.998$	0.9143
3. Gradation Index versus VIM		
4.5	$y = 0.0778x^2 - 3.5769x + 48.705$	0.7248
5.0	$y = 0.0898x^2 - 4.1651x + 53.654$	0.8141
5.5	$y = 0.0837x^2 - 3.8713x + 48.706$	0.8443
6.0	$y = 0.0815x^2 - 3.7838x + 46.442$	0.8608
6.5	$y = 0.0749x^2 - 3.4804x + 41.881$	0.8901
7.0	$y = 0.0608x^2 - 2.809x + 33.295$	0.8752
7.5	$y = 0.0416x^2 - 1.9061x + 22.397$	0.8345
8.0^+	$y = 0.0191x^2 - 0.8398x + 9.77$	0.6813
4. Gradation Index versus VMA		
4.5	$y = 0.0518x^2 - 2.3536x + 43.208$	0.8227
5.0	$y = 0.0632x^2 - 2.9149x + 49.09$	0.9145
5.5	$y = 0.0575x^2 - 2.6404x + 45.57$	0.9477
6.0	$y = 0.0551x^2 - 2.5432x + 44.386$	0.9649
6.5	$y = 0.0488x^2 - 2.2504x + 41.132$	0.9885
7.0	$y = 0.035x^2 - 1.5971x + 33.92$	0.9886
7.5	y = 0.0163x2 - 0.7154x + 24.385	0.9709
8.0^+	$y = -0.0055x^2 + 0.319x + 13.268$	0.8614
5. Gradation Index versus Stability		
4.5	$y = -10.548x^2 + 457.94x - 3352.4$	0.9416
5.0	$y = -8.8013x^2 + 368.96x - 2081.2$	0.9197
5.5	$y = -7.3842x^2 + 300.34x - 1181.8$	0.9588
6.0	$y = -5.1099x^2 + 186.47x + 248.15$	0.9776
6.5	$y = -3.8591x^2 + 127.72x + 920.46$	0.9809
7.0	$y = -3.5251x^2 + 115.17x + 942.21$	0.8240
7.5	$y = -3.2943x^2 + 105.4x + 909.09$	0.5628
8.0^+	$y = -2.4338x^2 + 71.533x + 1031.7$	0.2602
6. Gradation Index versus Flow		
4.5	$y = 0.0217x^2 - 0.9361x + 12.839$	0.8672
5.0	$y = 0.0192x^2 - 0.8093x + 11.337$	0.9149
5.5	$y = 0.017x^2 - 0.7136x + 10.511$	0.9322
6.0	$y = 0.0112x^2 - 0.4408x + 7.5958$	0.9645
6.5	$y = 0.008x^2 - 0.2972x + 6.2126$	0.9981
7.0	$y = 0.0051x^2 - 0.1882x + 5.645$	0.8674
7.5	$y = 0.0017x^2 - 0.041x + 4.5417$	0.3441
8.0^+	$y = -0.0029x^2 + 0.1475x + 3.173$	0.0120

+ removed from model development

Almost all R^2s are more than 0.9. The density at the same bitumen content, higher GI will increase the density until it reaches the peak and then it decreases. Additionally, it also shows that the aggregate gradation that is close to the upper limit is a denser gradation. The denser aggregate gradation means that more bitumen fills voids (VFA). As a result, the air void (VIM) and VMA are getting low. The stability at close to upper limit is higher than others because the aggregate gradation is denser. The higher GI at the same bitumen content will raise the flow because the bitumen contents are not enough to make asphalt mixture stiffer. Thus, it has a higher flow value. The higher flow decreases the deformation resistance. However, The higher flow has no problem if stability Marshall flow ratio or Marshall quotient is increased. Specification requirement for the Marshall quotient is more than 250 kg/mm [14].

The bitumen content of 8.0 (% of mix) will be eliminated from the modelling because it has a different trend line with another bitumen contents (4.5% to 7.5%). Besides that, the relationship between the GI, stability, and flow has the lowest coefficient of determination (R^2). Table 3 shows that the GI could show the behaviour of the asphalt mixture.

C. Model Development of Gradation Index (GI) and Bitumen Content on Marshall Properties

Based on the results presented in Table 2 and Table 3, the modelling of the GI and bitumen content could be developed with multiple polynomial regressions to get the equation to predict the value of the Marshall properties as the response variable. The models are shown in Table 4, where the GI is the gradation index, and BC is the bitumen content.

TABLE IV
MODEL OF MARSHALL PROPERTIES

Properties	**Models**	R^2
Density	$-0.001\ GI^2 + 0.0007\ GI.BC - 0.014\ BC^2 + 0.053\ GI + 0.174\ BC + 1.186$	0.961
VFA	$-0.380\ GI^2 + 0.018\ GI.BC - 1.881\ BC^2 + 17.572\ GI + 37.717\ BC - 282.177$	0.971
VIM	$0.066\ GI^2 - 0.037\ GI.BC + 0.532\ BC^2 - 2.825\ GI - 8.039\ BC + 66.894$	0.953
VMA	$0.047\ GI^2 - 0.032\ GI.BC + 0.498\ BC^2 - 1.954\ GI - 5.386\ BC + 54.141$	0.900
Stability	$-6.076\ GI^2 + 0.833\ GI.BC - 116.026\ BC^2 + 232.489\ GI + 1405.043\ BC - 4651.578$	0.869
Flow	$0{,}012\ GI^2 - 0.029\ GI.BC + 0.120\ BC^2 - 0.315\ GI - 0.315\ BC + 5.821$	0.913

The graphs in Fig. 3 to Fig. 8 can be used to look at the overall trend and predict the value of the Marshall properties resulting from the changes in the bitumen content and GI. The graphs created for visualization models in Table 4 are the contour types. The selection of the types of the graphs is that they are very easy to use and fast in predicting the Marshall properties.

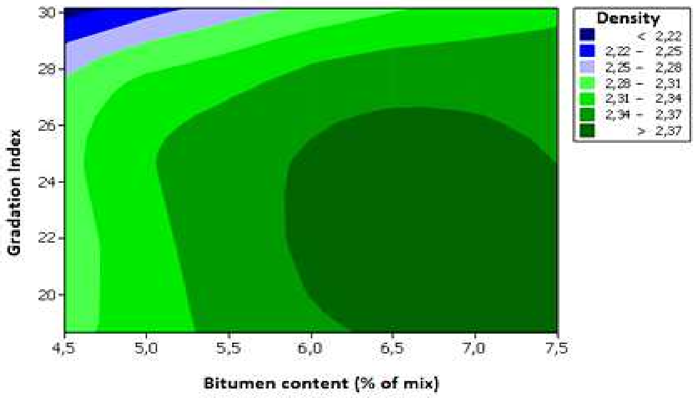

Fig. 3 Contour plot of density versus bitumen content and gradation index

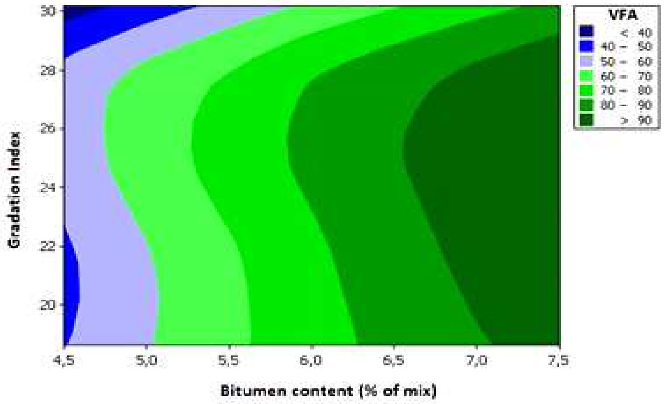

Fig. 4 Contour plot of VFA versus bitumen content and gradation index

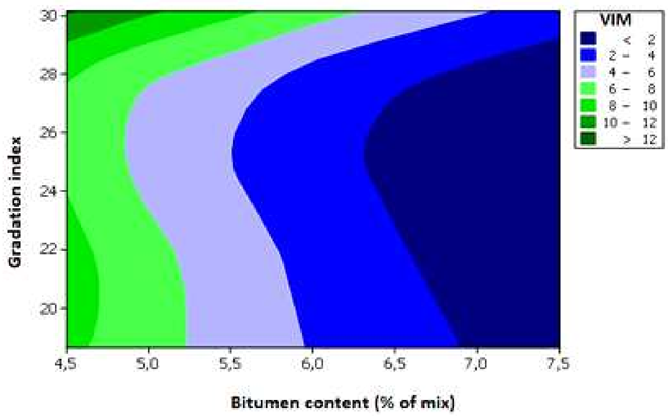

Fig. 5 Contour plot of VIM versus bitumen content and gradation index

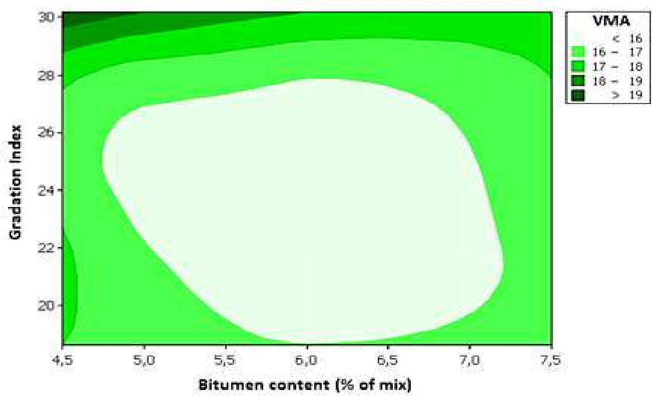

Fig. 6 Contour plot of VMA versus bitumen content and gradation index

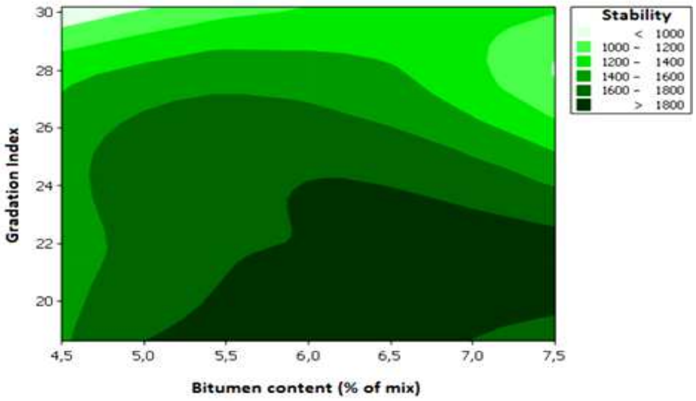

Fig. 7 Contour plot of stability versus bitumen content and gradation index

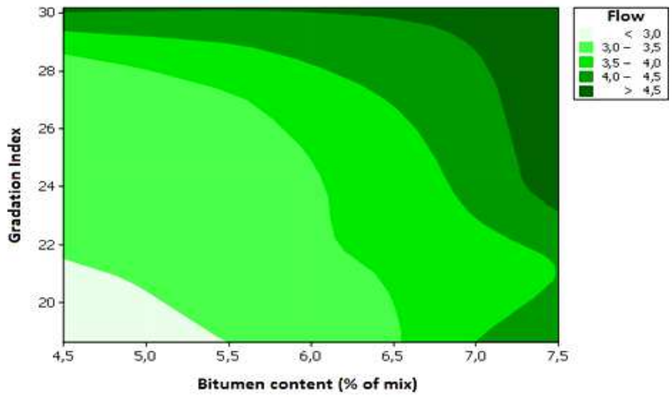

Fig. 8 Contour plot of flow versus bitumen content and gradation index

The modelling methods used in this study were also able to be applied in the gradation changes for other aggregates. Thus, they produced a new equation. The new equation with a factor of change in the gradation by the GI gives choices of the gradation because it is not only a factor of the bitumen content that is just to reach a certain performance of the asphalt mixtures, but it also looks at the aggregate gradation changes.

Fig. 9 to Fig. 13 shows the correlation of Marshall characteristics between the model and the observed. The equality line shows the position of the model and the observed at the same value. The coefficient of determination (R^2) showed that the relationship between the model and the observed are strong with the R^2s more than 0.8.

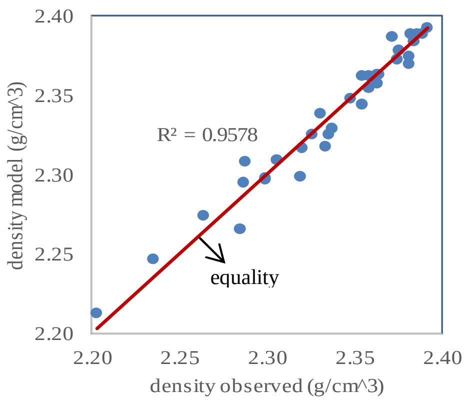

Fig. 9 Correlation of density between the experimental result and the model

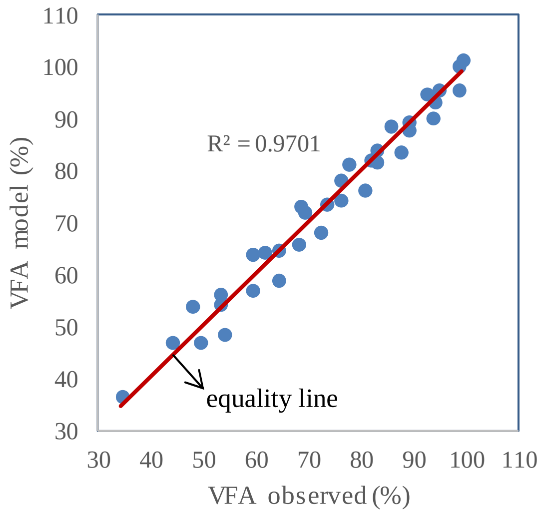

Fig. 10 Correlation of VFA between the experimental result and the model

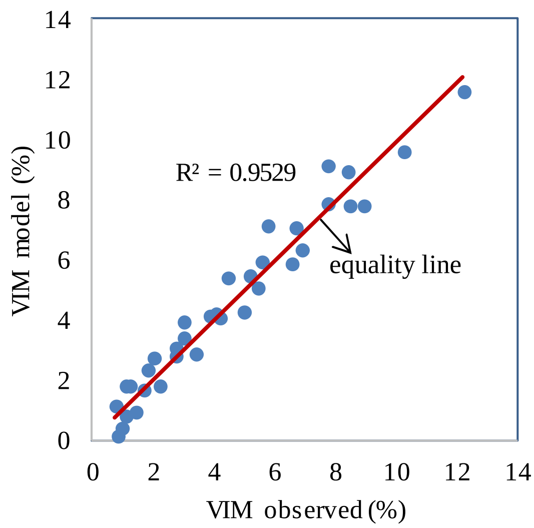

Fig. 11 Correlation of VIM between the experimental result and the model

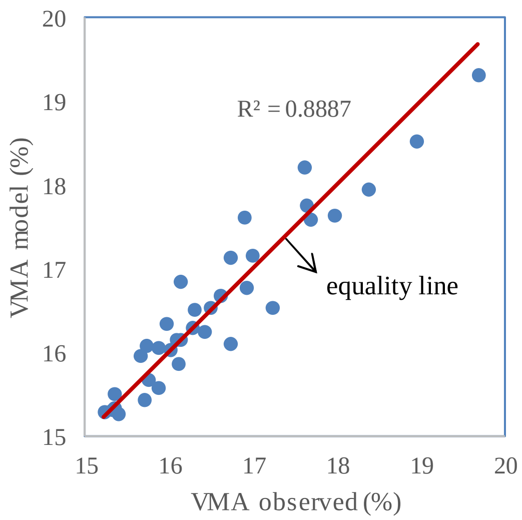

Fig. 12 Correlation of VMA between the experimental result and the model

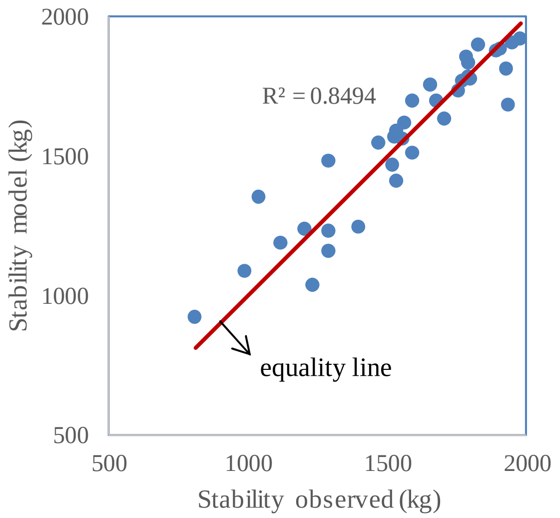

Fig. 13 Correlation of Stability between the experimental result and the model

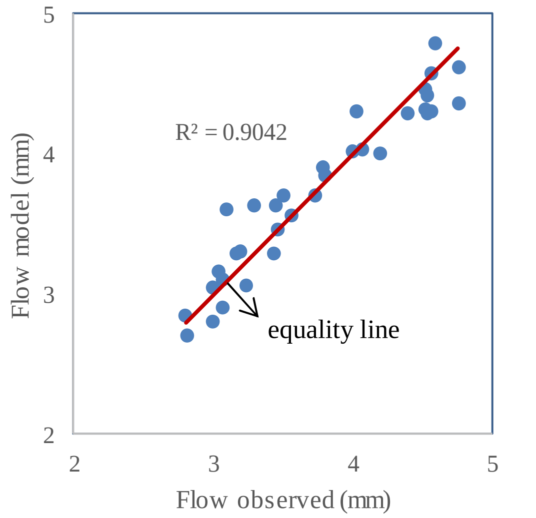

Fig. 14 Correlation of flow between the experimental result and the model

IV. Conclusions

This study was conducted to determine the gradation effect index and bitumen content on the Marshall properties in a model. The following conclusions were made based on the experimental results:

- Multiple polynomial regression is suitable to develop the model of the Marshall properties with the aggregate gradation and bitumen content as independent variables.
- The coefficients of the determination of the model are more than 0.9. Therefore, the model can be used to predict the Marshall properties on the bitumen content and certain aggregate gradation.
- The GI can show the behaviour of the Marshall properties.
- The estimation of the optimum bitumen content comply with the specification by entering the GI and bitumen content will provide many options for designers asphalt mixture to meet the specification criteria.

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