Aggregate Blending Model for Hot Mix Asphalt Using Linear Optimization

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Abstract: The main objective of the aggregate-blending process is to combine different aggregate sizes to produce a final blend (called job mix) that can meet the predefined specification limits for each sieve. Traditionally, this step is carried out by trial-and-error or by using graphical methods. These methods are time consuming and depend on the experience of the engineer. With the rapid advancement of computer technology, several models were developed to get the optimum aggregate blend utilizing other techniques such as genetic algorithms, linear programming, and multi-objectives linear programming. This study explores the use of the fuzzy triangular membership function to develop a linear programming model that can be used to determine the optimum aggregate blend taking into consideration the specification design range, tolerances of job mix formula, and variability associated with the percent passing each sieve. The developed model was validated through a numerical example. It was concluded that the proposed approach would be used effectively as an intelligent tool to determine the optimum aggregate blending for hot-mix asphalt.

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1. Introduction

Asphalt concrete pavement consists of an asphalt concrete layer(s), base layer, and subbase layer constructed over a well-compacted subgrade. The top layer (asphalt concrete layer) is constructed from a mixture of coarse aggregates, fine aggregates, mineral filler, and asphalt cement which are mixed together in a hot mix plant to produce hot mix asphalt (Garber and Hoel, 2009). The hot mix asphalt production involves (a) using different aggregate sizes (coarse aggregate, fine aggregate and mineral filler) which are transferred from the stockpiles into the plant; (b) drying and blending the aggregates in a drum dryer; (c) heating the asphalt cement; and (d) mixing the aggregates and asphalt cement to produce the hot asphalt mix. The characteristics and behavior of asphalt mix depends on the aggregates properties, asphalt cement properties, and the percentage of the asphalt cement. The mix characteristics are determined through the mix design process (AI, 2001).

The main objective of the asphalt mix design process is to determine the components of the asphalt mix (percentage of coarse aggregate, percentage of fine aggregate, percentage of mineral filler, and percentage of asphalt cement) that can satisfy the predefined mix characteristics. Aggregate blending process is the first step in the mix design. This step involves determining the blending proportions of two or more aggregates, having different gradations, to provide a final aggregate blend that meets the gradation specification limits. Traditionally, this step is carried out by trial-and-error or by using graphical methods. In the trial-and-error method, a set of trials is carried out to reach a blend that can satisfy the specification limits. On the other hand, the graphical method involves using triangular chart (for three aggregates blend) and rectangular chart (for four aggregates blend) to reach the desired blend. These methods are time consuming and depend on the experience of the engineer (Toklu, 2005).

With the rapid advancement of computer technology, several models were developed to get the optimum aggregate blend. Toklu (2005) utilized the genetic algorithms to formulate the blending process as a multi-objective optimization problem. Awuah-Offei and Askari-Nasab (2011) developed a linear programming optimization models that can be used to minimize the hot mix asphalt aggregate cost. Montemanni *et al.* (2012) employs the robust linear programming to deal with the uncertainty in the input data using probabilistic assumptions. However, none of these models considered the effect of the variability associated with the aggregate gradation.

In recent years, fuzzy logic has been utilized in several civil engineering tasks as an alternative to traditional modeling approaches and has shown a good degree of success. The main concept of fuzzy logic is to assign a number of membership functions $X_1, X_2… X_n$ to each numeric variable x. The purpose of using a membership function is to treat the uncertainty associated with the numeric variables. The membership function may take different shapes such as triangle, trapezium, etc. The relationship between each value of x and each membership function can be described by values called the degree of membership $\mu_{X1}(x)$, $\mu_{X2}(x)$, …, $\mu_{Xn}(x)$. The range of these values is from 0 to 1 (Kikuchi, 2000).

The main objective of this paper is to utilize the triangular membership function to develop a model to get the optimum aggregate blend that satisfies the specification limits taking into consideration the variability of aggregate gradation. This paper includes five parts. The first part involves the experimental investigation carried out to evaluate the variability associated with the aggregate gradation. The second part presents the formulation of the aggregate-blending problem. The third part describes the model development. The fourth part gives a numerical example to illustrate the effectiveness of the developed model. Finally the fifth part is the summary and conclusions.

2. Experimental Investigation

This part deals with the evaluation of the variability associated with the aggregate gradation. Forty asphalt mix samples were taken from the same source. Bitumen extraction and grain size analysis experiments for gradation of aggregates were carried out on all of the collected asphalt concrete samples. Table 1 presents a summary of the output results of the aggregate gradation for all the samples under investigation. The first column includes the sieve size, the second one presents the maximum and minimum values obtained from the gradation test, and the third column gives the standard deviation of the percent passing through each sieve. The standard deviations will be used in this paper to represent the material variability.

The data in Table 1 show that the standard deviation is not constant for all sieves. Sieve No. 4 has the highest value while sieve No. 200 has the lowest value. The output results of the experimental investigation will be used in the model development stage.

Table 1 Output results of the experimental program

Sieve Size	% Passing		Standard Deviations
	Minimum Value	Maximum Value	
3/4"	91.7	100	1.69
3/8"	65.9	85.8	4.68
No. 4	43.5	67.4	4.88
No. 8	33.8	54	4.09
No. 30	18.6	25.9	1.75
No. 50	10.1	15.6	1.08
No. 100	3.5	7.3	0.70
No. 200	1.7	4.4	0.51

3. Formulation of Aggregate-Blending Problem for Hot Asphalt Mix

The main objective of the aggregate-blending process is to combine different number of aggregate sizes to produce a final blend (called aggregate job mix formula) that can meet the predefined specification limits for each sieve size. The specification limits vary according to the type of asphalt mix used. Once the final blend is determined, the contractor shall adjust the plant to produce this blend within the allowed tolerances. These tolerances are defined based on the project specifications. As an example, Table 2 gives the specification limits and job mix tolerances for one of the Egyptian mixes. It should be mentioned that the job mix tolerances, shown in Table 2, should be applied to the job mix gradation to establish a job control grading band. This band must comply with the design range criteria.

Based on the above mentioned discussion, two main factors control the process of obtaining the optimum combined gradation. The first factor is the design range. The second factor is the job mix tolerances. To satisfy these two factors, the gradation of the final blend should satisfy the minimum and maximum optimum range calculated by Equation 1 and 2 respectively. The absolute optimum blend is obtained when final gradation coincides with the mid range of the upper and lower specification limits.

The experimental investigation mentioned above showed that the variability associated with the aggregate gradation is not constant for all sieves. This should be considered during the blend design by trying to make the gradation, for the sieves possessing more variability, closer to the mid range of the upper and lower specification limits than those sieves that possess less variability. It should be mentioned that, a future research should be carried out to evaluate the current job mix tolerance based on material variability.

Table 2 Aggregate Gradation Specification Limits for Mix 4C

Sieve Size	Design Range Percentage by Weight Passing Sieves		Job Mix Tolerances Percent
	Lower Limit	Upper Limit	
3/4"	80	100	± 5
3/8"	60	80	± 5
No. 4	48	65	± 5
No. 8	35	50	±4
No. 30	19	36	± 4
No. 50	13	23	± 4
No. 100	7	15	± 4
No. 200	3	8	± 2

$X_{jmin} = X_{LLj} + T_j$ [1]

$X_{jmax} = X_{ULj} - T_j$ [2]

Where

X_{jmin} = Minimum optimum value for the passing from sieve J

X_{jmax} = Maximum optimum value for the passing from sieve J

X_{LLj} = Specification lower limit for sieve J

X_{ULj} = Specification upper limit for sieve J

T_j = Job mix tolerance percent for sieve J

4. Model Development

The main objective of this part is to utilize the fuzzy triangular membership function to develop a model that can be used to determine the optimal aggregate gradation. In this study, one triangular membership function is assigned for the percent passing, for the job mix, from each sieve X_j to represent its uncertainty within the minimum optimum value X_{jmin} and maximum optimum value X_{jmax}. The degree of membership $\mu(x_j)$ is equal to zero for both X_{jmin} and X_{jmax}. On the other hand, the degree of membership is equal to one at the middle of design range X_{jo}. Figure 1 illustrates the shape of the triangular membership function. As shown in this figure the lower and upper boundaries for the assumed membership function are coincided with the minimum and maximum optimum values. The optimum aggregate blend is obtained when all the membership degrees are maximized to be close to "one" for all sieves. As mentioned before the material variability will be taken into consideration by trying to make the gradation, for the sieves possessing more variability, closer to the mid value of the design range than those sieves that possess less variability.

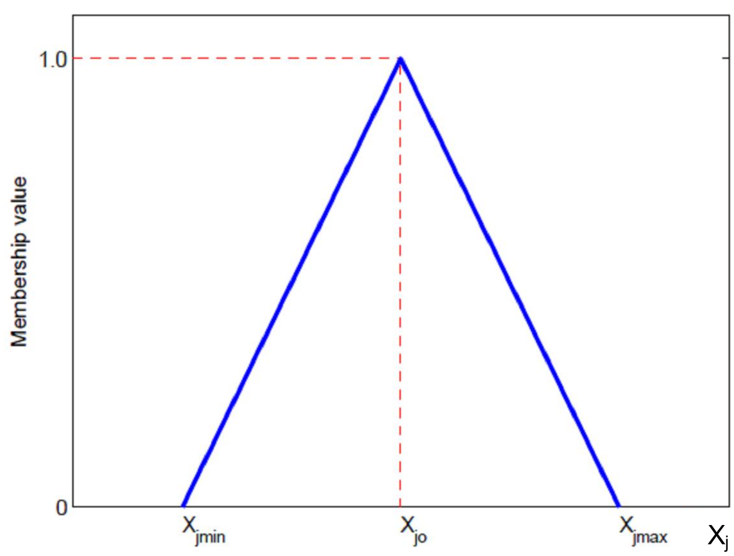

Figure 1 Membership Function.

In order to develop the model; the objective function, constraints, and boundary conditions should be developed taken into consideration the formulation of the aggregate blending problem as described above.

Objective Function:

The objective of the proposed model is to maximize the sum of product of membership degree and the material variability for all sieves as indicated in Equation 3. This can guarantee that the final gradation is the closest one to the mid range that can be obtained taking into consideration the material variability.

$$\text{Minimize } Z = -\sum_{j=1}^{m} \mu_j * V_j \qquad [3]$$

Where

m = Total number of sieves

V_j = Final blend variability for the percent passing sieve j

μ_j = Membership value for the percent passing sieve j

Constraints:

There are two types of constraints which are equality constraints and inequality constraints. Equality constraints deal with the fixed relationship between the variables while the inequality constraints deal with the flexible relationship between the variables. The constraints of this study can be formulated as follows:

Equation 4 is an equality constraint to ensure that the sum of the blending ratios of the different aggregate types is equal to 100%.

$$\sum_{i=1}^{n} R_i = 100 \qquad [4]$$

Where

n = number of Aggregate types

R_i = Blending ratio for aggregate type i

Equation 5 is an equality constraint to join the blending ratio with the percent passing of the final gradation. This equation leads to m linear equations.

$$\sum_{i=1}^{n} R_i * G_{ij} = X_j \qquad [5]$$

Where

G_{ij} = Actual passing percentage for aggregate size i from the sieve j.

X_j = Percent passing for the final blend from sieve j.

Based on the sketch of the triangular membership function illustrated in Figure 2, the degree of membership μ_j can be calculated as indicated in Equation 6 that leads to two inequality equations (Equations 7 and 8). These two equations lead to 4m equations.

$$\mu_j = \min [(X_j - X_{jmin})/(X_{jo} - X_{jmin}), (X_{jmax} - X_j)/(X_{jmax} - X_{jo})] \qquad [6]$$

$$-X_j + \mu_j (X_{jo} - X_{jmin}) \le - X_{jmin} \qquad [7]$$

$$X_j + \mu_j (X_{jmax} - X_{jo}) \le X_{jmax} \qquad [8]$$

Boundary Conditions:

Equation 9 shows the boundary conditions for the blending ratio R_i. This equation leads to 2n inequality equation where n is the number of aggregate types.

$$0 \le R_i \le 100 \qquad [9]$$

Equation 10 shows the boundary conditions for the percent passing for the final blend for each sieve X_j. This equation leads to 2m inequality equations where m is the number of sieves.

$$0 \le X_j \le 100 \qquad [10]$$

Equation 11 shows the boundary conditions for the degree of membership for the final blend for each sieve μ_j. This equation leads to 2m inequality equations where m is the total number of sieves.

$$0 \le \mu_j \le 1.0 \qquad [11]$$

5. Numerical Example

The objective of this numerical example is to examine that the developed model can determine effectively the optimum aggregate blend. In this example, the gradations of four different aggregate types are available. Table 3 illustrates the input data, specification limits, and material variability that are used in the numerical example. As indicated in this table, the first column includes the sieve size, the following four columns include the gradation of each aggregate type, and finally the last four columns include the upper and lower specification limits, tolerances, and standard deviations.

The developed model was utilized to determine the blending ratio for each aggregate type mentioned in Table 3 to get the optimum aggregate blend. The output results of this model are illustrated in Table 4. These results indicate that the optimum aggregate blending ratio is 35.41% for aggregate size 1, 5.99% for aggregate size 2, 23.05 for sand, and 35.54 for dust. These values satisfy the specification limits taking into consideration the tolerance limits and material variability.

Table 3 Input Data and Specification Limits for Numerical Example

Sieve (j)	Passing (G_{ij})%				Specs Limits		Tolerance (T_j)	SD (V_j)
	Size 1 (i=1)	Size 2 (i=2)	Sand (i=3)	Dust (i=4)	Min. (X_{LLj})	Max. (X_{ULj})		
3/4"	57.5	100.0	100.0	100.0	80	100	5.0	1.7
3/8"	26.7	93.5	100.0	100.0	60	80	5.0	4.7
# 4	1.4	15.9	100.0	100.0	48	65	5.0	4.9
# 8	0.0	2.1	76.1	77.7	35	50	4.0	4.1
# 30	0.0	1.9	41.7	40.6	19	36	4.0	1.8
# 50	0.0	1.9	31.8	26.8	13	23	4.0	1.1
# 100	0.0	1.8	25.2	14.3	7	15	4.0	0.7
# 200	0.0	1.7	21.2	2.9	3	8	2.0	0.5

Table 3 Blinding Ratios and Final Blend Gradation

Sieve	Percent Passing					Specs Limits	
	Size 2 35.41 %	Size 1 5.99 %	Sand 23.05%	Dust 35.54%	Final Blend	Upper Limits	Lower Limits
3/4"	20.4	6.0	23.1	35.5	84.9	80	100
3/8"	9.5	5.6	23.1	35.5	73.7	60	80
# 4	0.5	1.0	23.1	35.5	60.0	48	65
# 8	0.0	0.1	17.5	27.6	45.3	35	50
# 30	0.0	0.1	9.6	14.4	24.2	19	36
# 50	0.0	0.1	7.3	9.5	17.0	13	23
# 100	0.0	0.1	5.8	5.1	11.0	7	15
# 200	0.0	0.1	4.9	1.0	6.0	3	8

Summary and Conclusions

Aggregate blending is a critical step among others in the design process of hot asphalt mix. Traditionally, this step is carried out by trial-and-error or by using graphical methods. With the rapid advancement of computer technology, several models were developed to get the optimum aggregate blend utilizing different techniques such as genetic algorithms and linear programming. This study investigated the use of a fuzzy triangular membership function to develop a linear program model that can be used to get the optimum aggregate blend. A model was developed to provide the optimum blend taking into consideration: design range, tolerances of mix job formula, and variability associated with the percent passing for each sieve. An experimental investigation was developed to evaluate the variability associated with the percent passing of each sieve to be taken into consideration during model development. Then, the problem of the aggregate blending process was formulated and the main factors affecting this process were discussed.

In the model development stage a triangular membership function was utilized to treat the uncertainty in the aggregate gradation. The model was developed through three steps. In the first step, the objective function, constraints and boundary equations were determined. In the second step, the linear programming was utilized to solve these equations to develop the model. Finally, the developed model was examined through a numerical example. The output results obtained from this study showed that the model developed using the triangular membership function is able to determine effectively the optimum aggregate blending for hot-asphalt mix. It should be mentioned that the approach followed in this study has the flexibility to be extended to take other parameters into considerations such as material costs.

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