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A New Framework for Determining the Gradation of Asphalt Mixtures

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ABSTRACT: Strength and rutting resistance as well as durability are the main quality measures for any asphalt mix. While the strength and resistance of the asphalt mixture to permanent deformation are controlled by the aggregate interlock and aggregate packing, the durability of asphalt mixture depends on adequate volumetric characteristics and film thickness of asphalt mixture. Accordingly, providing an adequate interlock between aggregates and the aggregate packing is of high importance in designing a new asphalt mixture in order to produce desirable volumetric characteristics in asphalt mixture. A new framework for asphalt mixture gradation has been developed and designed following an intensive review of the various currently used approaches. The new framework considers all the controlling factors in the aggregate gradation design for optimum gradation of the asphalt mixtures. Satisfactory interlocking between aggregate particles, proper skeleton within the asphalt mixture, and acceptable volumetric properties are the main parameters to be considered for optimum gradation design for asphalt mix. The framework provides a systematic approach for the gradation process starting from the concentration at different sieves ($\varphi_n \; and \; \varphi_{n+1}$) to finally account for the $FA_f \; Ratio \leq 0.5$. Other parameters including FA_c ratio, CA ratio and D_{avg} are also considered through the current framework.

Keywords: Asphalt, Gradation, Packing Theory, Pavement, Aggregate

1. Introduction

Among all aggregate properties such as particle geometry, particle density, absorption, strength, resistance to polishing, and many others, aggregate gradation is a fundamental parameter which affects the final performance of asphalt mixture. In general, aggregate gradation shows the distribution of different sizes of aggregate particles. The aggregate gradation can be identified through particle distribution test (sieve analysis) by determining the total percentages of aggregates passing through different sieve sizes. Aggregate gradation influences the main characteristics of asphalt mixtures such as stiffness, durability, stability, fatigue resistance, moisture sensitivity, workability and permeability [1] and hence it can be considered as one of the most important factors in asphalt mixture design.

Previous research by some researchers [2-8] highlighted the impact of the gradation on the performance of asphalt mixtures. The gradation which provides the densest blend and the highest interparticle contact was recognized as the best gradation for asphalt mixtures by many early studies [9,10]. For example, Fuller and Thompson [9] developed an equation (Equation 1) describes a maximum density gradation. They proposed that the maximum density of an aggregate blend with a given maximum aggregate size can be achieved by:

$$P = \left(\frac{d}{D}\right)^n \times 100 \qquad (1)$$

where D is the maximum aggregate size in the blend, P is the percentage passing through sieve size d, d is the aggregate size being considered, and n is the adjustment parameter which equals 0.5 or 0.45 according to Fuller and Thompson [9]. Many studies have shown that the geometrical and physical characteristics of mixture components as well as their relative arrangement will affect the mechanical behaviour of the asphalt mixture. Through this information, it can be easily understood that good understanding of the aggregate gradation is vital prior to any asphalt mixture design. The current study aims to investigate different approaches for the determination of aggregate gradation as well as design a new framework for the optimum gradation design. The study highlights the main controlling factors that govern the gradation design as well as account for the best aggregate blend to provide adequate interlock between aggregate particles and acceptable volumetric properties of asphalt mixture. Previous studies assumed that the densest condition for the aggregate gradation will result in the closest aggregate packing and subsequently the best performance. However, further studies showed that sufficient air void is required in asphalt mixtures to allow the incorporation of bitumen and to ensure workability, durability, and prevention of rutting or bleeding. Therefore, many recent studies [8,11,12] were conducted to determine the proper amount of aggregates at each size fraction based on particle packing theory as well as continuous gradation concept. In packing theory, aggregates are assumed as uniform spheres arranged in a unit volume. As the aggregate particles cannot be packed together completely, there are always void spaces between the aggregate particles, as shown in Figure 1. The amount of these voids is controlled by the shape of aggregate particles, degree of compaction, gradation of aggregate particles, and surface texture of aggregate particles.

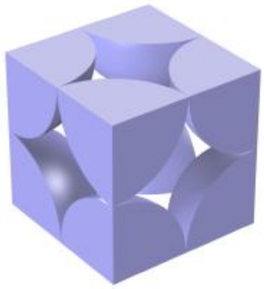

Fig.1 The Packing Theory Assumptions [11].

In addition, recent approaches in aggregate gradation proved that regardless of the individual material properties, the size range carrying the load in the asphalt mixture as well as the various morphological parameters which affect the long-term behaviour of mixture have greater impact on the asphalt mixture [11,13-15]. Based on these theories, in particulate materials, a stress-transmitting path exists that transfers the load through the chain of main particles. In this condition, the smaller particles prevent the buckling of the main chain. Therefore, it is crucial to check the interlock between the aggregate particles of consecutive sieve sizes through the determination of the amount of aggregate particles in each size fractions. The sufficient amount of aggregates at each size fraction ensures the adequate contact between aggregate particles, as aggregate in asphalt mixture must form a continuous network for transferring the load.

In general, the aggregates in asphalt mixtures are typically composed of three fractions of coarse aggregate, fine aggregate, and filler. The combination of all these three fractions provides an aggregate skeleton within the asphalt mixture to resist against permanent deformation and cracking. Among these fractions, coarse aggregate is the primary component providing resistance to deformation in asphalt mixtures since the interlock between coarse aggregate particles provides a path within the asphalt mixture to transmit the induced stresses to the lower layers of pavement while providing a skeleton for rutting resistance. Fine aggregates, in asphalt mixture, complete the aggregate structure by filling the void spaces in the coarse aggregate. Mineral filler is used in the aggregate blend for developing mastic, and for filling the voids between the fine aggregates in the mixture. This confirms that the coarse aggregate is the main fraction in aggregate blend of asphalt mixture which was also confirmed by other researchers [16,17].

Therefore, it is necessary to determine the adequate amount of coarse aggregate in order to provide coarse aggregate interlock. This implies the importance to quantify the maximum and minimum volume of coarse aggregate in the mixture. The maximum volume of coarse aggregate is the amount of coarse aggregate needed to fill the unit volume in a compacted state considering a specified compactive energy, whereas the minimum volume of coarse aggregate is the required amount to fill the unit volume in its loosest state. Asphalt mixtures containing coarse aggregate between the minimum and maximum values will have adequate interlock between their aggregate particles and resistance to deformation, depending on their relative coarse aggregate amount. In addition, the fine aggregate and filler amount would be determined based on the appropriate volume of fine aggregate and mastic that must fill the voids between the coarse aggregates. Considering this information, it is necessary to consider some factors as controlling factors for designing an aggregate blend in an optimized way to provide adequate interlock between aggregate particles and acceptable volumetric properties of asphalt mixture. Accordingly, the following sections will present the information for developing a systematic procedure to determine an adequate aggregate gradation to achieve a satisfactory asphalt mixture performance.

2. Research Methodology

The current study aims at developing an optimum gradation design for asphalt mixture through considering both aggregate interlock and aggregate packing in order to better design an asphalt mixture that meets all volumetric requirements while provides an excellent behaviour during construction and operation. In this research, an adequate framework has been considered for aggregate gradation in order to accomplish these objectives. To develop this framework, the controlling factors are firstly determined based on intensive review of the literature. In addition, the asphalt mixtures are prepared based on the gradations obtained from different methods in order to investigate the effect of gradation on volumetric properties and stiffness of asphalt mixtures.

2.1 Gradation Optimization

Aggregate gradation reflects the percentage of each of the aggregate sizes in a blend. This characteristic is one of the most important aggregate properties which are directly related to the performance of an asphalt mixture, as the mechanical interlock of the aggregate skeleton substantially affect the shear strength and the rutting resistance of asphalt mixtures. Generally, poor gradation results in loss of stability in asphalt mixtures. The dense graded layers usually have higher strength or shear resistance due to the increased contact between the larger particles and hence higher frictional resistance to shear forces.

However, the realization that adequate void structure is necessary, emphasizes that the gradation achieved by Fuller and Thompson [9] should be modified to the grading target based on the packing theory and other present mixture design concepts in order to achieve the densest aggregate gradation with the desired volumetric properties. To obtain this, sufficient interlocking between the aggregate particles of consecutive sieve sizes should be maintained in order to provide a stress-transmitting path in asphalt mixtures. This will be achieved through the determination of the maximum and minimum volume of aggregates in each size fraction. To this point, it is required to consider a minimum value of about 45% [8] for the concentration of load carrying range, in which concentration is defined as:

$$\varphi = \frac{W_{ret}^{n}}{W_{tot}} \qquad (2)$$

where W_{ret}^{n} represents the weight of aggregates retaining on sieve n and W_{tot} is the total aggregates weight. In addition, referring to Miranda (2012), Equation (3) can be used to calculate the average particle diameter (D_{avg}) of the two consecutive sieve sizes:

$$D_{avg} = \frac{\overline{D}_n \varphi_n + \overline{D}_{n+1} \varphi_{n+1}}{\varphi_n + \varphi_{n+1}} \qquad (3)$$

where φ_n and φ_{n+1} are the concentration of each sizes and $\overline{D}_n$ and $\overline{D}_{n+1}$ are the mean diameter at sieve sizes which can be defined as follows:

$$\overline{D}_n = B(D_{min} + D_{max}) \qquad (4)$$

In Equation (4), D_{min} is the opening of the sieve and D_{max} is the opening of the previous size, and B is the parameter which characterizes a continuous size distribution over the materials retained at a certain sieve size. Two consecutive sieve sizes can be in the load carrying range only if the following equation is satisfied:

$$0.311\overline{D}_n + 0.689\,\overline{D}_{n+1} \leq D_{avg} \leq 0.703\,\overline{D}_n + 0.297\,\overline{D}_{n+1} \qquad (5)$$

To follow this procedure, the gradation obtained from the Fuller and Thompson [9] is considered as an initial gradation. By employing this procedure and considering the Australian gradation limits, the aggregate gradation for asphalt mixture using the Fuller and Thompson [9] will be changed to the modified gradation, as presented in Table 1.

Table 1 The Aggregate Gradation based on Different Approaches

Sieve Size (mm)	Fuller & Thompson Method		Mixture Morphology Framework				Australian Standards Gradation Limits (%)	
	n = 0.45	n = 0.5	D_{avg}	Min Range for Interaction	Max Range for Interaction	Modified Gradation (%)	Min	Max
19	100	100	14.007	17.277	15.004	100	100	100
13.2	85	83	10.745	12.101	10.651	96	90	100
9.5	73	71	8.618	8.668	7.571	81	72	83
6.7	63	59	6.059	6.121	5.356	68	54	71
4.75	54	50	3.958	4.040	3.103	58	43	61
2.36	39	35	2.201	2.261	1.547	42	28	45
1.18	29	25	1.234	1.008	0.780	30	19	35
0.600	21	18	0.617	0.511	0.393	20	13	27
0.300	15	13	0.310	0.255	0.197	13	9	20
0.150	11	9	0.163	0.128	0.098	8	6	13
0.075	8	6	0.031	0.053	0.023	5.5	4	7

As presented in this table, the sieve sizes of 13.2, 9.5, 6.7, 4.75, and 2.36 mm are in the load carrying range, according to Equation 5. This indicates that these aggregate particles act like the skeleton in the asphalt mixture. In addition, the modified combined gradation of aggregate can be analysed using the particle packing concepts. The use of particle packing involves applying the appropriate parameter to show the void relationships that result from the filling of voids with particles of different size. Referring to [11], the particle diameter ratio can be the most appropriate parameter for the examination of aggregate gradation in HMA mixtures. The particle diameter ratio is defined based on the following equation:

$$\text{Particle Diameter Ratio} = \frac{\text{Particle Fitting in Void}}{\text{Large Particle Creating Void}} \quad (6)$$

The particle diameter ratio has a range from 0.155 to 0.42 [18]. The review of literature has presented evidence that a particle diameter ratio of 0.22 is an appropriate value for the evaluation of the gradation of asphalt mixture. By applying the particle diameter ratio to the standard set of sieves, the primary control sieve (PCS) can be achieved which is the closest sieve to the nominal maximum particle size in millimetres multiplied by 0.22. In this definition, the nominal maximum particle size (NMPS) is the first sieve larger than the first sieve which retains more than 10%. As presented in Table 2, the nominal maximum particle size in this research is 14 mm. The list of standard sieve sizes considered in this study and the particle parameters is given in Table 2.

Table 2 The Gradation Limits and Grading Target for a 14 mm Nominal Size Dense Graded Asphalt Complying with AS 2150

Sieve Size (mm)	Particle Size × 0.22	Primary Control Sieve (PCS)	Gradation (%)	Border	Grading Target (%)	
19	4.18	4.75	100		100	Coarse Aggregate Portion
13.2	2.75	2.36	96	NMPS	96	
9.5	2.09	2.36	81		81	
6.7	1.47	1.18	68	Half Sieve (NMPS×0.5)	68	
4.75	1.05	1.18	58		58	
2.36	0.52	0.600	42	MPCS (NMPS × 0.22)	43	
1.18	0.26	0.300	30		30	Fine Aggregate Portion
0.600	0.13	0.150	20	SCS (MPCS × 0.22)	21	
0.300	0.07	0.075	13		13	
0.150	0.03	-	8	TCS (SCS × 0.22)	8	
0.075	0.02	-	5.5		5.5	

All the parameters used in establishing ratios for the evaluation of the aggregate gradation and the values for this research are presented in Tables 2 and 3.

In this regard, as shown in Table 2, the PCS is the border between coarse and fine aggregate in the total aggregate blend, and therefore it can be named as Mixture Primary Control Sieve (MPCS). In addition, another term called "Half Sieve" is required for providing the optimum packing of coarse aggregates. The half sieve can be obtained by the multiplication of NMPS by 0.5. The particles passing the half sieve are termed as interceptor. The amount of interceptors influences the asphalt mixture voids, mainly through the change in the voids size. Therefore, the determination of interceptors' amount affects the compatibility of asphalt mixture and its resistance to deformation by providing a balanced structure for coarse aggregate portion [11]. Moreover, there are two other terms called Secondary Control Sieve (SCS) and Tertiary Control Sieve (TCS) which are required for determination of the appropriate aggregate gradation based on the packing theory and providing information on the fine fraction of aggregates blend. As given in Table 2, SCS is defined as MPCS multiplied by 0.22, whereas TCS can be calculated from the multiplication of SCS by 0.22. In general, the main factor affecting the constructability of asphalt mixtures is the packing of coarse aggregate portion which can be determined by the introduction of the coarse aggregate (CA) ratio. The coarse aggregate ratio can be determined based on the half sieve, as given in Equation 7. This parameter is an appropriate parameter for characterizing aggregate voids [11].

$$\text{CA Ratio} = \frac{\text{\% Passing Half Sieve} - \text{\% Passing Primary Control Sieve}}{100 - \text{\% Passing Half Sieve}} \quad (7)$$

The desired value of CA ratio for dense graded mixture is between 0.40 and 0.80. This range ensures a balanced coarse aggregate structure. The asphalt mixtures with the CA ratio less than this range have coarse aggregate containing voids with smaller size, and tend to segregate during construction. Approaching the CA ratio to 1 is an indication of unbalanced coarse aggregate portion because of the increase in the quantity of interceptors. In this condition, the fine fraction of coarse aggregates creates the coarse aggregate skeleton, whereas the larger particles in the coarse aggregate fraction just float between the finer particles while are not significantly involved as part of aggregate structure. This results in some problems in the design and construction of asphalt mixtures. The packing of the fine aggregate fraction is also an important factor in asphalt mixture design, as it has a substantial influence on VMA of the asphalt mixture because of the creation of voids in the fine portion of the aggregates. The packing of the fine aggregate fraction can be examined using the fine aggregate coarse fraction ratio (FAc). If the fine aggregate fraction of the blend be defined as part of particles passing the MPCS, it would be possible to view this portion in two parts of coarse and fine part of fine aggregate portion. In this regard, FAc is used for characterization of the packing behaviour of the coarse part of fine aggregate portion (Equation 8).

$$\mathrm{FA_c\ Ratio} = \frac{\%\ \text{Passing Secondary Control Sieve}}{\%\ \text{Passing Primary Control Sieve}} \qquad (8)$$

Decreasing FAc ratio will increase the voids in the mixture. It is desirable to have this ratio between 0.4 and 0.5. The ratio with a value lower than 0.4 will create a gradation that is not uniform, resulting in a mixture with the characteristics of gap gradation in the fine fraction of the blend, and subsequently causing the compaction problems and instability in asphalt mixtures. Increasing this ratio to values higher than 0.5 will tend to produce the tender mixtures, which will over densify and give early failure under traffic.

On the other hand, the fine part of fine aggregate portion is responsible for filling the voids made by the coarse part of fine aggregate fraction. The packing of the fine part of fine aggregate portion can be obtained by the fine aggregate fine fraction ratio (FA_f) given in Equation 9. This ratio characterizes the packing behaviour of the smallest portion in the aggregate blend.

$$\mathrm{FA_f\ Ratio} = \frac{\%\ \text{Passing Tertiary Control Sieve}}{\%\ \text{Passing Secondary Control Sieve}} \qquad (9)$$

In typical dense graded asphalt mixtures, FA_f ratio should not be more than 0.50 because the decrease in FA_f ratio results in the increase in the mixture [11].

Table 3 The Ratios and Controlling Factors based on Packing Theory

Nominal Maximum Particle Size (NMPS)	Mix Primary Control Sieve (MPCS)	Half Sieve	CA Ratio	Secondary Control Sieve (SCS)	FAc Ratio	Tertiary Control Sieve (TCS)	FA_f Ratio
13.2 (14 mm)	2.36	6.7	0.78	0.600	0.49	0.150	0.38

A complete list of controlling sieves and calculation results for different ratios for the sample considered in this research are given in Table 3, whereas the finalized grading target modified through the morphology framework and packing theory based on the controlling factors of CA ratio, FA_f ratio, and FAc ratio is presented in Table 2.

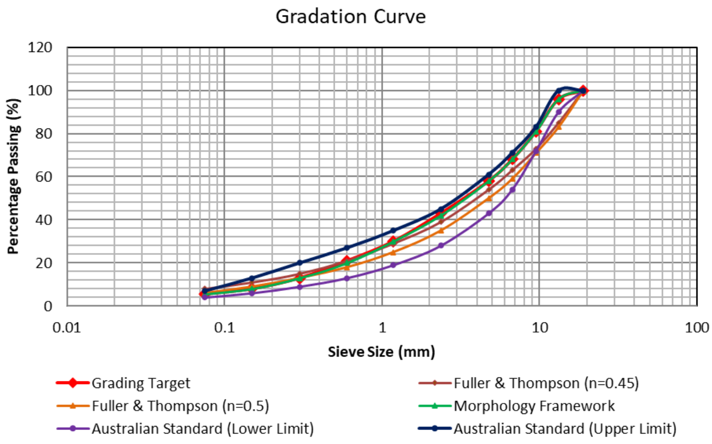

Fig.2 The Gradation Curves Based on Different Approaches

In addition, to compare the gradation curve obtained from different approaches, including [11], morphology framework, and finalized grading target controlled by the packing theory ratios, these gradation curves as well as the Australian standard gradation limits are illustrated in Figure 2.

2.2 Aggregate Size Groups

The proper analysis of mixture gradation for asphalt mixtures using the concept of aggregate interlock and packing theory requires changing the traditional definition of coarse and fine aggregates. Traditionally, the coarse aggregates are defined as the particles retained on sieve size of 4.75 mm, whereas the fine aggregates are the particles passing sieve size of 4.75 mm and retained on sieve size of 0.075 mm. Based on the concept of aggregate interlock and packing theory, however, the coarse and fine aggregates are defined as follows:

- Coarse aggregates are the large aggregate particles which create voids when they are placed in a unit volume.
- Fine aggregates are the aggregate particles which fill the voids between the coarse aggregate particles.

Referring to the packing theory and morphology framework [12], different aggregate size groups are identified within the mineral aggregates, as follows:

- Oversized Structure (OS)
- Primary Structure (PS)
- Secondary Structure (SS)
- Filler particles

Primary Structure (PS) is the portion of aggregate which forms a network and plays a vital role in transferring the load through the mixture. The aggregates between Primary Structure and filler particles in terms of size are termed as Secondary Structure (SS). SS directly affects the PS stability. In addition, particles larger than PS, which are called OS, are not interconnected to the PS and hence do not have any contribution to the load carrying capacity of PS. In asphalt mixture, the filler particles combined with bitumen form a matrix which coats the Secondary Structure. This matrix is termed as mastic. An adequate percentage of all these groups are necessary to provide an asphalt mixture with proper performance properties. Therefore, it is necessary to determine the boundary limits between these sub-structures.

Following the analysis based on the packing theory and morphology framework for providing the proper contact between aggregate particles as well as the aggregate interlock, the ranges and boundary limits between all these structures for the sample considered in this research, are illustrated in Figure 3.

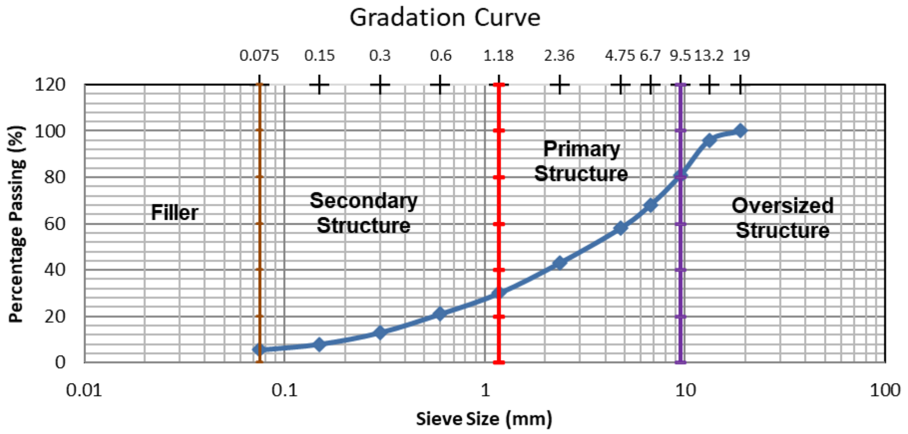

Fig.3 Sub-structure Ranges for the Considered Grading Target

As shown in this figure, according to the calculations (Table 2), the minimum size for the PS is defined as particles passed the 2.36-mm sieve or retained on the 1.18-mm sieve. These results are compatible with the results presented in Table 1.

3. Gradation Framework

Based on the research conducted in this study, a framework has been developed regarding the process of controlling the aggregate gradation as well as determining the Primary Structure range which is summarized in Figure 4. In this framework, the basis for the selection of the aggregate blend gradation is achieving a satisfactory interlock between aggregate particles, a proper skeleton within the asphalt mixture, and acceptable volumetric properties.

4. Summary and Conclusions

The objective of asphalt mixture design is optimization of the asphalt mixture properties in terms of rutting resistance, durability, fatigue resistance, stability, flexibility, permeability, skid resistance, and workability. As aggregate gradation influences most of the important properties in asphalt mixtures, considering an adequate aggregate gradation based on comprehensive theories will result in improving different aspects of asphalt mixture design, construction, and operation. Unfortunately, although the aggregate gradation affects the asphalt mixture performance, in many cases, it is still selected based on generalized target gradations and local experience. If local experience is not available, the trial-and-error process will be employed for the selection of target gradation which is time consuming and costly. To this point, enhancing the understanding of the aggregates gradation and its effect on the resulting mixture would lead to a substantial improvement in asphalt mixtures performance. The concepts discussed in this paper provide an outline for asphalt mixture design ensuring the existence of a stress-transmitting path and coarse aggregate interlock in asphalt mixture. The establishment of these properties in aggregate blend will put an end to the trial-and-error process which is normally employed in the target gradation selection while providing an adequate aggregate structure to resist the deformation as well as developing proper volumetric properties in the final asphalt mixture.

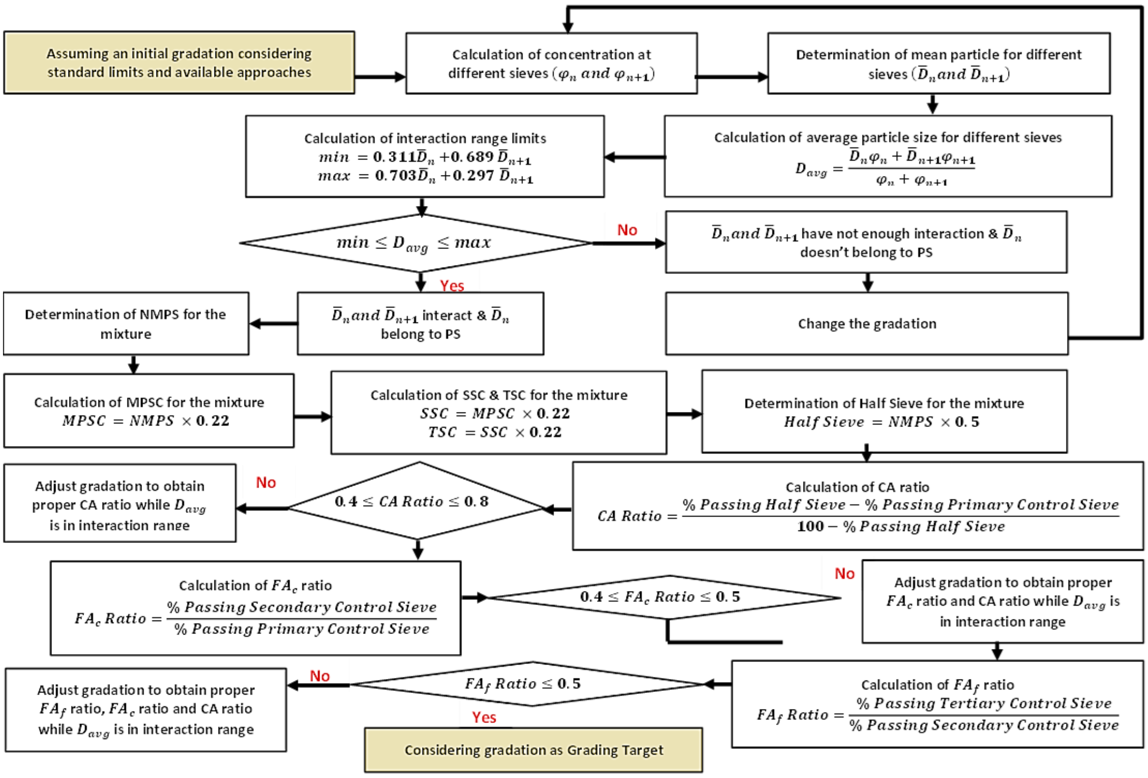

Fig.4 Flowchart of Controlling the Aggregate Gradation

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