Simple Approach for Determination of Optimum Gradation Considering the Combined Index and Angularity Number of Stone Aggregates

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Abstract - A satisfactory bituminous mix should have aggregate gradation, which will ensure maximum density and minimum voids in the mix to fulfill requirements of bituminous mix design specifications. In India organizations such as Indian Roads Congress and Ministry of Surface Transport (MOST) [1] have laid down specifications regarding the range of percentage passing of different size of aggregate in the mix. The conventional procedure is to aim at mid values of these specified ranges for the design of bituminous mix. However, this mid point gradation does not produce a satisfactory mix as it often fails to fulfill the specified requirements of the bituminous mix. This is because the density and voids in a mix depend on the shape factors namely Angularity Number (AN), Flakiness Index (FI) and Elongation Index (EI) of different aggregates in the mix.

An experimental study has been made to develop a relationship between the aggregate shape factors in terms of Combined Index (CI) and Angularity Number and the gradation index 'n' in the Fuller – Thompson ideal gradation equation (2) to arrive at the optimum gradation. The results obtained using the conventional mid point of gradation range and those using the proposed optimum gradation concept have been compared in this paper. It is generally observed that the mixes prepared at the optimum gradation considering the CI and AN have higher density and lower voids compared to those at mid point of gradation ranges. The empirical equation developed in the study could be advantageously made use of for mix design.

Index Terms
Aggregates, Combined Index, Angularity Number, Dry density, Voids, Optimum Gradation

I. INTRODUCTION

It is essential to arrive at the most appropriate gradation of the aggregate in order to obtain a good bituminous mix as the mix properties such as stability, density and the voids depend on the gradation of aggregates. Several organizations in different countries have specified recommended gradation of aggregates to obtain the desired dense bituminous mix such as bituminous concrete [1,3]. The most common practice adopted by the designers during mix design is to try to achieve the grain size distribution corresponding to the mid point of the specified range. The basic objective is to adopt the grain size distribution of the aggregate mix that gives the highest dry density and the specified range of voids in mineral aggregate on compaction. Even though the density and voids in a mix depend to a large extent on the shape factors of the coarse aggregates, this aspect is not generally considered in the initial stages of mix design.

The preliminary attempt to consider the shape factors along with aggregates gradation during mix design was reported by Rajagopal etal[2]. However the effect of one of the shape factors, namely Angularity Number (AN) of coarse aggregate only was considered. However, apart from (AN), the effect of Combined Index (CI) of coarse aggregate on the desirable grain size distribution to achieve maximum dry density is also to be studied.

The objective of this study is therefore to investigate the effect of the aggregate shape factors namely AN and CI on the desirable grain size distribution in order to achieve maximum density and minimum voids in dry mix of aggregate meant for use in bituminous concrete.

II. METHODOLOGY

The desired quantity of coarse aggregate samples required for conducting the proposed experimental study, consisting of assorted aggregate sizes having a wide range of shape factors in terms of Angularity Number (AN), Flakiness Index (FI) and Elongation Index (EI) were collected from thirty four different quarries and crushers located within a distance of about 10 KM from the location of laboratory. According to Fuller [2] the ideal gradation of aggregate consisting of spherical and rounded particles that could produce maximum dry density is given by the relation

$$P\,\% = 100 \sqrt{(d/D)} \qquad \text{------} \quad 1$$

where p is the percentage aggregate passing any sieve size d and D is the maximum aggregate size in the mix.

According to Rajagopal et al [2] the gradation equation may be given by the general gradation equation:

$$P\,\% = 100\ (d/D)^{n} \qquad \text{--------} \quad 2$$

where 'n' is termed as gradation index, the maximum value of 'n' being 0.5 for spherical shape of aggregate, whose

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Angularity Number is equal to zero. As the shape of coarse aggregate becomes more angular, the value of AN also increases and there is a need of greater fraction of finer aggregate to fill up the voids in between the coarser fractions. This could be obtained by lowering the value of gradation index 'n' in the general gradation equation. However the effects of other shape factor namely CI on the need for modification in gradation index 'n' have not been studied and reported in the published literature. Therefore in this study, it was decided to carryout experimental investigations using the 34 samples of coarse aggregate by mixing them in various proportions so as to obtain grain size distribution corresponding to gradation index values varying from 0.5 upto 0.2. The set of sieves, thickness and length gauges were used as per IS 2386 part I 1963 [4].

III. EXPERIMENTAL INVESTIGATIONS

Thirty-four different aggregate samples were collected from different crushers covering a wide range of shape factors. Each sample was mechanically sieved and separated into different fractions such as 25 – 20, 20 – 16, 16 – 12.5, 12.5 – 10 and 10 – 6.3 mm sizes. The average values of shape factors such as Flakiness Index (FI), Elongation Index (EI), Combined Index (CI) and Angularity Number (AN) for each fraction for each sample was determined. The laboratory experiments were carried out and the values of FI, EI and AN were determined as per IS 2386 Part – I 1963[4] and the value of CI was determined as per the note given under Table 500.8 vide MOST Specification for Road and Bridge works. Typical values of shape factors obtained for few aggregate samples are presented in Table1.

As the aggregate samples collected from different crushing plants were found to have a wide range of shape factors in terms of FI, EI, CI and AN, it was decided to carry out experimental studies in order to determine the optimum gradation which results in maximum dry density and hence minimum air voids in the compacted mix. Thus this experimental investigation will be useful to study the effect of shape factors of aggregate on the optimum gradation corresponding to maximum density. The gradation of the aggregate mixes were varied by adopting different values of gradation index 'n', namely 0.50, 0.45, 0.40, 0.35, 0.30, 0.25, and 0.20 in the general gradation equation 2. Apart from the seven gradations obtained by varying the gradation index as above, the mid point of the recommended range of aggregates passing the specified sieve sizes given in Table 500.18 of MOST Specification for BC mix was made use of in the experimental study. The eight gradations thus selected for the experimental study are presented in Table 2.

From each aggregate sample, the required quantities of the specified aggregate sizes were weighed and mixed in the desired proportions as given, so as to obtain the desired gradations in Table 2. Thus eight different gradations of the aggregate were obtained in each of the 34 aggregate samples chosen. Each of these aggregate mixes was subjected to a standard method of compaction in Proctor density test mould by vibrating on a table vibrator at a frequency of 60 Hz and amplitude of 1.0 mm for duration of 60 seconds. The density of the compacted mix in the mould and the volume of voids were determined experimentally for each compacted mix of aggregate sample. Each experiment was repeated eight times and the average density values were determined.

IV. ANALYSIS OF RESULTS AND DISCUSSIONS

1. Optimum Values of Gradation Index

Making use of the experimental results of average values of density and voids in the compacted samples of aggregate, graphs were plotted for each sample of aggregate with gradation index 'n' values on the X axis and density values on the Y axis as shown in Fig. 1. From these graphs, the optimum value of gradation index (n-opt) was determined corresponding to maximum density value for each sample of aggregate. The values of optimum gradation index (n – opt), maximum density (g/cc) and minimum voids (%) experimentally obtained were determined for the 34 samples of aggregate are presented in Table 3. Also the density values obtained by adopting the mid – range values of gradations (m – r) of standard specification for BC determined are presented in Table 3. The weighted average values of FI, EI, CI and AN determined based on the two approaches are presented in Table 4. From Table 3, it is observed that the maximum density values obtained for optimum gradation index (n-opt) are consistently higher than the density values obtained by adopting mid range values of specified gradation for BC mix, for all the 34 aggregate samples.

In view of this observation, attempts have been made to establish empirical relationships between some of the shape factors and the optimum values of graduation index that were determined in the experimental studies. The density values obtained by adopting mid-range values of the specified gradation were also determined

2) Relationship Between Combined Index (CI) and optimum Gradation Index (n-opt)

The relationship between CI and n-opt obtained in this study is presented in Fig.2. The correlation equation obtained is given by

$$Y = 0.4566\ e^{-0.0062x} \qquad \text{---------- } 3$$

Where coefficient of correlation $R^2 = 0.9839$

3) *Relationship Between AN and Optimum Gradation Index 'n'*

The relationship between the AN values and optimum gradation index (n-opt) obtained in this experimental investigation are shown in Fig. 3. The correlation developed is given by the equation

$$Y = 0.46\ e^{-0.0451x} \qquad \text{------------- } 4$$

The Coefficient of correlation obtained $R^2 = 0.6911$, where the number of observations N=34

3) Correlation between Weighted Average Combined Index, Angularity Number and the Gradation Index 'n'

The dry density test results of thirty-four different aggregate samples with varying shape factors presented in Table 3 were used. The multiple regression analysis between the combined index, angularity number and the gradation index was carried out using the Excel package and the following equation was obtained.

n =0.439–2.22X10^{-3}(CI)+ 1.415 x 10^{-3} (AN)----- 5

The value of correlation coefficient R^2 is 0.99 and the standard error of estimate is 4.809 X 10^{-3}. The validity of the equation was checked by substituting the values of combined index and angularity number of the mixes studied and the equation results in almost the same value of gradation index 'n' experimentally determined for the respective mixes. The following illustration explains the validity of the equation.

Sample D23

Optimum value of 'n' determined experimentally = 0.33

Combined index = 52.23 %

Angularity number = 8.90 %

Gradation index 'n'

$$n = 0.439 – 2.22 \times 10^{-3} (52.23) + 1.415 \times 10^{-3} (8.90)$$

n = 0.336

The multiple regression equation listed above can be used to approximately estimate the optimum value of gradation index 'n' for a dry aggregate mix. The following procedure is proposed.

i. Prepare the dry aggregate mix corresponding to the conventional mid point of gradation range.

ii. Determine the weighted average values of aggregate combined index and angularity number of the dry mix.

iii. Using the graphs shown in Figures 4 and 5, obtain the respective values of combined index and angularity number of the mix that could be obtained had the mix been prepared at optimum value of gradation index 'n' in the gradation equation – 2.

iv. Now substitute these values in the multiple regression equation – 5 and obtain the value of optimum gradation index 'n'.

v. Substitute this value of 'n' in the gradation equation – 2 and calculate optimum gradation of aggregates.

This procedure reduced trial and error approach This procedure reduces the trials to arrive at optimum gradation, thus resulting in considerable saving in time and effort for deciding the best possible gradation of aggregates during mix design.

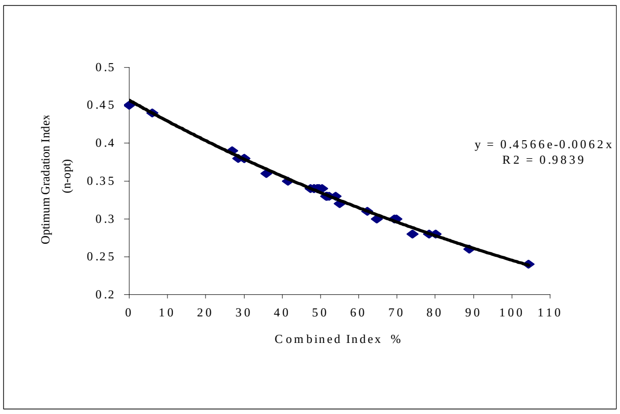

Fig. 1 Determination of Optimum Value for Sample 27

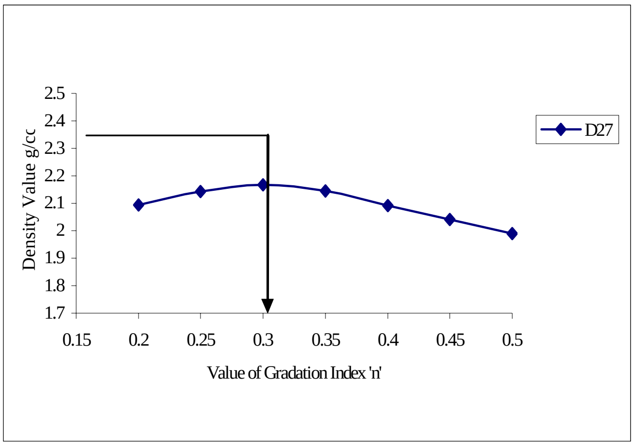

Fig.2 Weighted Average Combined Index Vs Gradation Index n

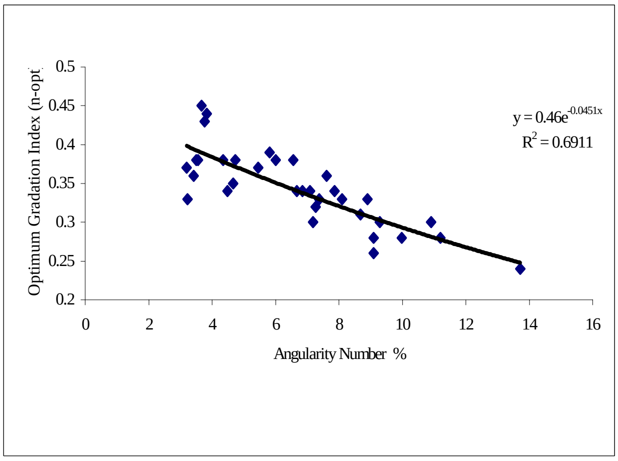

Fig. 3 Weighted Average Angularity Number Vs Gradation Index at Optimum n Gradation

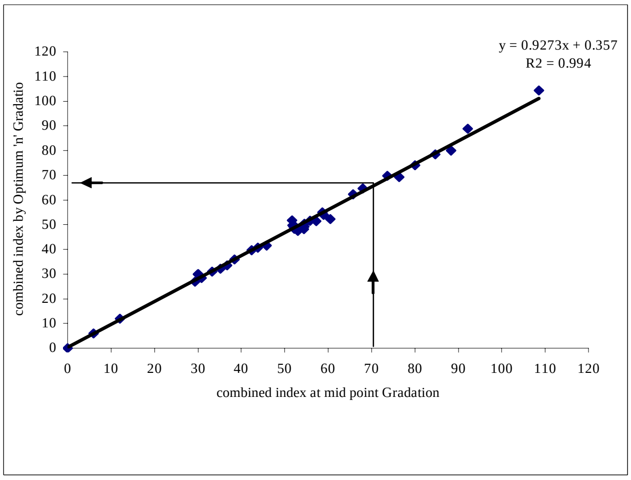

Fig. 4 Relation between Combined Index at Mid Point and Optimum n Gradation

ISBN: 978-988-19251-5-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

TABLE I TYPICAL VALUES OF SHAPE FACTORS (%) OF FEW AGGREGATE TEST SAMPLES STUDIED

Sample	Shape Factors	25-20 mm	20-16 mm	16-12.5 mm	12.5-10 mm	10-6.3 mm
D20	FI	8.31	11.58	21.24	39.43	40
	EI	8.58	26.25	29.71	30	32.67
	CI	16.89	37.83	50.95	69.43	72.67
	AN	5.07	6.48	6.89	7.16	7.72
D21	FI	15.53	12.93	16.77	32.47	36.57
	EI	13.46	22.67	36.52	21.62	28.22
	CI	28.99	35.60	53.29	54.09	64.79
	AN	2.24	3.71	4.19	5.4	6.07
D22	FI	13.16	18.18	21.66	37.2	44.75
	EI	29.17	35.36	37.74	31.97	40.17
	CI	42.33	53.54	59.40	69.17	84.92
	AN	7.23	7.98	7.32	9.51	9.71
D23	FI	11	18.6	20.6	25.3	25.45
	EI	29.7	38.8	44.3	72.15	75.45
	CI	40.70	57.40	64.90	97.45	100.90
	AN	9.05	9.53	10.2	10.7	11.23
D24	FI	7.97	12.43	27.13	39.23	28.18
	EI	21.54	40.48	20.36	22.74	39.1
	CI	29.51	52.91	47.49	61.97	67.28
	AN	6.66	7.39	8.02	8.31	8.62
D25	FI	10.53	13.84	30.84	36.55	38.55
	EI	12.25	27.89	27.22	34.85	49.23
	CI	22.78	41.73	58.06	71.40	87.78
	AN	3.66	4.88	8.28	8.86	10.88
D26	FI	23.94	23.75	30.19	37.10	48.00
	EI	14.59	26.63	16.86	34.09	40.45
	CI	38.53	50.38	47.05	71.19	88.45
	AN	6.18	7.34	9.47	10.06	10.39
D27	FI	7.82	11.81	21.1	29.77	31.29
	EI	31.07	34.73	38.09	45.17	56.45
	CI	38.89	46.54	59.19	74.94	87.74
	AN	6.71	8.34	8.28	8.62	10.01
D28	FI	31.38	32.84	60.04	67.26	59.11
	EI	22.02	31.76	27.37	35.36	55.50
	CI	53.40	64.60	87.41	102.62	114.61
	AN	5.81	7.50	11.10	10.11	9.9
D29	FI	33.15	38.84	39.23	39.6	26.32
	EI	14.73	28.71	38.46	37.22	49.61
	CI	47.88	67.55	77.69	76.82	75.93
	AN	8.66	10.22	10.75	11.70	12.80
D30	FI	11.67	13.3	17.2	27.47	42.73
	EI	7.02	12.65	37.68	29.92	38.13
	CI	18.69	29.85	54.88	37.39	80.86
	AN	2.51	2.4	3.3	3.17	3.32

TABLE II GRADATION ADOPTED FOR EXPERIMENTAL STUDY

Sieve Size mm	Percent Passing Each Size								
	n = 0.5	0.45	0.40	0.35	0.30	0.25	0.20	MOST Specifications for B.C [1]	
								Range	Mid Range
26.5	100	100	100	100	100	100	100	100	100
19	84.7	86.1	87.5	89	90.5	92	93.6	90-100	95
9.5	59.9	63	66.3	69.8	73.5	77.4	81.5	56-80	68
4.75	42.3	46.1	50.3	54.8	59.7	65.1	70.9	35-65	50
2.36	29.8	33.7	38	42.9	48.4	54.6	61.7	23-49	36
0.30	10.6	13.3	16.7	20.8	26.1	32.6	40.8	5.0-19	12
0.075	5.3	7.1	9.6	12.8	17.2	23.1	30.9	2.0-8.0	5

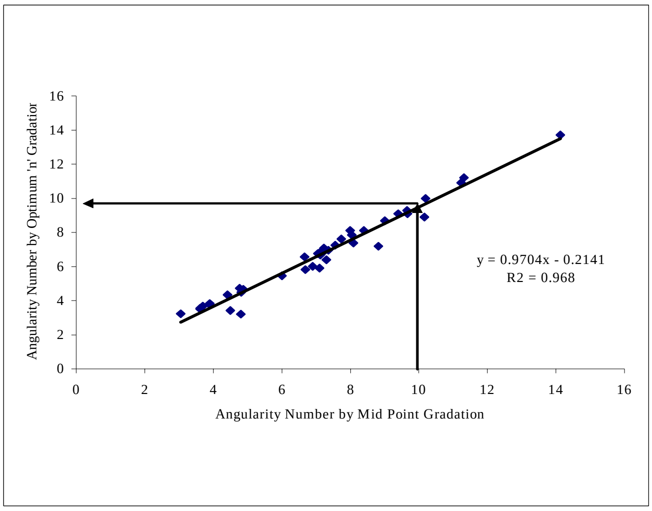

Fig. 5 Relationship between Angularity Number at Mid Point and Optimum n Gradation

V. CONCLUSIONS

1. 1. Variation in shape factors of aggregate namely CI and AN results in variation in voids and density of the graded mix. Therefore, there is a need to vary the gradation of aggregate depending on the combined index and angularity number of aggregate fractions to obtain the highest density of the mix.

2. 2. The empirical equation developed correlating the combined index, angularity number and gradation index 'n' values with desirable properties of aggregate mixes such as maximum density in the mix could be advantageously made use of for mix design.

3. 3. A simple approach has been suggested to obtain the optimum gradation of aggregate, if the combined index and angularity number values of various aggregate sizes in the graded mix at mid point of specified range gradation are known.

ISBN: 978-988-19251-5-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

TABLE III VALUES OF MAXIMUM DENSITY, MINIMUM VOIDS AND OPTIMUM GRADATION INDEX

Sample No.	Weighted Average CI and AN determined by Two Approaches			
	CI %		AN %	
	Mid Range	n-opt	Mid Range	n-opt
D1	0	0	3.7	3.67
D2	6	6	3.9	3.83
D3	29.3	26.9	6.69	5.81
D4	30.9	28.5	6.9	6.01
D5	30	30	4.77	4.73
D6	30	30	4.41	4.34
D7	30	30	3.62	3.5
D8	30	30	6.66	6.56
D9	30	30	3.62	3.56
D10	38.4	35.85	4.5	3.42
D11	45.86	41.54	4.87	4.67
D12	52.98	47.41	8.39	8.1
D13	54.43	48.25	7.23	7.09
D14	52.2	48.37	7.25	6.92
D15	51.98	49.15	4.82	4.49
D16	54.51	49.18	7.12	6.85
D17	52.23	49.58	7.36	6.96
D18	51.84	49.64	7.12	6.67
D19	54.49	50.46	8.04	7.86
D20	57.3	51.4	7.05	6.76
D21	55.85	51.55	3.05	3.22
D22	51.74	51.75	7.99	8.1
D23	60.49	52.23	10.16	8.9
D24	59.02	53.9	8.09	7.38
D25	58.66	55	7.56	7.26
D26	65.79	62.25	9.01	8.68
D27	68.03	64.67	8.82	7.18
D28	76.37	69.29	9.66	9.29
D29	73.68	69.85	11.23	10.91
D30	79.99	74.01	10.2	9.98
D31	84.7	78.4	9.4	9.09
D32	88.36	80.04	11.32	11.2
D33	92.22	88.93	9.67	9.1
D34	108.59	104.35	14.13	13.72

ACKNOWLEDGEMENT

The author sincerely acknowledge the ideas, guidance, suggestions and inspiration received from Prof. C.E.G Justo, former Professor and Emeritus Fellow & Dr. Krishnamurthy, former Professor and Chairman, Department of Civil Engineering, University Visweswaraya College of Engineering, Bangalore University, Bangalore.

TABLE IV WEIGHTED AVERAGE VALUES OF CI AND AN DETERMINED BY TWO APPROACHES

Sample No.	Weighted Average CI and AN determined by Two Approaches			
	CI %		AN %	
	Mid Range	n-opt	Mid Range	n-opt
D1	0	0	3.7	3.67
D2	6	6	3.9	3.83
D3	29.3	26.9	6.69	5.81
D4	30.9	28.5	6.9	6.01
D5	30	30	4.77	4.73
D6	30	30	4.41	4.34
D7	30	30	3.62	3.5
D8	30	30	6.66	6.56
D9	30	30	3.62	3.56
D10	38.4	35.85	4.5	3.42
D11	45.86	41.54	4.87	4.67
D12	52.98	47.41	8.39	8.1
D13	54.43	48.25	7.23	7.09
D14	52.2	48.37	7.25	6.92
D15	51.98	49.15	4.82	4.49
D16	54.51	49.18	7.12	6.85
D17	52.23	49.58	7.36	6.96
D18	51.84	49.64	7.12	6.67
D19	54.49	50.46	8.04	7.86
D20	57.3	51.4	7.05	6.76
D21	55.85	51.55	3.05	3.22
D22	51.74	51.75	7.99	8.1
D23	60.49	52.23	10.16	8.9
D24	59.02	53.9	8.09	7.38
D25	58.66	55	7.56	7.26
D26	65.79	62.25	9.01	8.68
D27	68.03	64.67	8.82	7.18
D28	76.37	69.29	9.66	9.29
D29	73.68	69.85	11.23	10.91
D30	79.99	74.01	10.2	9.98
D31	84.7	78.4	9.4	9.09
D32	88.36	80.04	11.32	11.2
D33	92.22	88.93	9.67	9.1
D34	108.59	104.35	14.13	13.72

REFERENCES

[1] Ministry of Surface Transport Specifications for Road & Bridge Works, Third Edition, 1998.
[2] Rajagopal, A.S., Veeraragavan, A, and Justo, C.E.G, 'A Simplified Approach for Mix Design Based on Shape Factors for Coarse Aggregates, International Symposium on Aggregates, organized by the International Association of Engineering Geology, Nice, France, May 1984.
[3] IRC: 29-1988, "Specifications for Bituminous Concrete", Indian Roads Congress, 1996.
[4] Methods of Test for Aggregates for Concrete Particle Size and Shape, 2386 (Part I) -1963.