Journal of Soft Computing in Civil Engineering 7-1 (2023) 1-19

Contents lists available at **SCCE**

Journal of Soft Computing in Civil Engineering

Journal homepage: www.jsoftcivil.com

The Optimization of Mix Proportion of Hot Mix Asphalt for Sustainable Flexible Pavements: Experimental Study and Grey Taguchi Relational Analysis

Samanasa Krishna Rao[1*], P. Sravana[2]

1. Professor, Civil Engineering, Department, Vignana Bharathi Institute of Technology, Hyderabad, Telangana, India
2. Professor, Civil Engineering Department, JNTUH College of Engineering, Hyderabad, Telangana, India
Corresponding author: *snkrishnarao@gmail.com*

https://doi.org/10.22115/SCCE.2022.343508.1447

ARTICLE INFO

Article history:
Received: 21 May 2022
Revised: 13 August 2022
Accepted: 12 October 2022

Keywords:
Optimization;
HMA;
Fiber;
Grey Taguchi;
Orthogonal array;
ANOVA.

ABSTRACT

Most of the Indian black topped roads have been damaged due to adverse weather and heavy load distresses. Many researchers have focused on improving durability of Hot Mix Asphalt (HMA) pavements. The factors influencing durability of HMA are Binder content, Combined aggregate gradation, type of Filler and addition of Fiber. In order to optimize the combination of variables used in HMA mix design, Grey relational analysis by using Taguchi technique is used, where many parameters can be analyzed at a time with more accuracy. Multiple performance measurements like Stability, Flow, Bulk specific gravity of the mix (G_{mb}), Theoretical maximum specific gravity of the mix (G_{mm}), Voids in Mineral Aggregate (VMA), Air voids (V_a) and Voids Filled with Bitumen (VFB) are considered. Bituminous Concrete (BC) mix was optimized using L9 Orthogonal array considering four parameters such as Fiber content, Filler combination, Binder content and Combined Aggregate Gradation, with three levels having seven performance measurements. The most significant parameter and percent contribution of each parameter of BC mix are analyzed by Analysis of Variance (ANOVA) using Grey Taguchi technique. The analysis was done by considering two Gradation conditions (Coarse gradation and Fine gradation) based on voids in mix. From the analysis, it can be concluded that all parameters are significant except bitumen content for optimizing BC mix.

How to cite this article: Krishna Rao S, Sravana P. The optimization of mix proportion of hot mix asphalt for sustainable flexible pavements: experimental study and grey taguchi relational analysis. J Soft Comput Civ Eng 2023;7(1):1–19. https://doi.org/10.22115/scce.2022.343508.1447

1. Introduction

One of the most influential factors for Economic growth in a developing country like India is the road network system. Durability and performance is the most important requirement in pavement construction, and its ability to resist the action of temperature changes, moisture, and air and traffic effect. Asphalt pavements have been damaged due to one of the main reasons for moisture penetration through the surface courses [1]. Arriving at the optimum proportion of ingredients of the HMA mix involves a large number of experimentation and it involves the consumption of a lot of time [2]. The Grey Taguchi method has a systematic approach to optimizing various control parameters in hot mix asphalt mixtures [3]. Many researchers have studied the use of the Taguchi technique for optimizing pavement mixes [4–10].

Ozbay et al., [11] investigated the mix proportions of high-strength self-compacting concrete using Taguchi Method. Nirmala and Raviraj [12] studied the application of the Taguchi approach to obtain optimal mix proportion for Self-Compacting Concrete containing spent foundry sand and manufactures sand. Abdullah, W. S., et al., [13] studied the effect of Air voids on the durability of asphalt concrete pavement. They concluded that high air voids lead to ill effects in pavements such as embrittlement of asphalt binder, and striping of asphalt from aggregate due to interrupted air and moisture. Low air voids lead to rutting of pavement and pavements ravel under the action of traffic.

Volumetric properties of Hot Mix Asphalt (HMA) are highly influenced by the aggregate type and gradation. High voids are seen at the coarse gradation region, and it is most adaptable to resist secondary compaction. In general, a dense gradation region is acceptable for all mixed design conditions. Shen, S., & Yu, H. [14] studied the effect of Voids in Mineral Aggregate (*VMA*) in HMA and its influencing factors. The studies, it has found that maintaining a sufficient amount of *VMA* is necessary for HMA mix design to sustain against temperature changes, and moisture effects and to allow secondary compaction without damaging pavement.

Awuah-Offei, K., & Askari-Nasab, H. [15] investigated that more than 94% by weight and 84% by volume of HMA mix is structured with aggregate. From the studies, it can be found that the strength of the HMA mix depends on the type of aggregate and its properties. Rahman, A., et al., [16] studied the effect of filler on *VMA* in the HMA mix design. They concluded that fillers should in optimum content in the mix, excesses amount of fillers demands more binder to coat the surface of aggregate, influencing the workability, and viscoelastic properties of the mix.

Do, H. S., et al., [17] studied the usage of lime in the mix and it is seen that hydrated lime is the best suitable filler in HMA mix design to act as an anti-stripping agent and to improve mechanical properties of soil. Additives like fibers (polyester, glass, basalt, polypropylene, etc.) in the HMA mix will increase the durability and tensile property of the mix, it makes a strong bond between aggregate particles. Tapkın, S. [18] investigated that polypropylene fiber is the most acceptable fiber as a modifier in HMA mix design. From the study, it is seen that fibers are added to the mix by dry processes.

It is seen that due to the addition of polypropylene fiber specific gravity of specimens reduces and the volume of voids increases with an increase in fiber quantity, Marshall Stability and flow values improve. Tortum, A., et al., [19] investigated that designing a modified mix with more number of parameters is a complicated job. It shows different mechanical properties with every level of parameters. They adopted the Taguchi method to get optimum working conditions for the HMA mix design. From the studies, it can be found that this method is the most adaptable method to analyze the HMA mix with more number of influencing parameters with less experimental cost and time. Tzeng, C. J., et al., [20] suggested that with more parameters having the multiple performance measurements using Grey relational analysis by using the Taguchi technique is most adaptable. They concluded that using this approach Optimization is effective, less cost, and less time-consuming.

In this study the Grey relation analysis by using the Taguchi technique to Optimize the HMA mix design of BC grade-2 specification [21] with 4 parameters having 3 levels of each parameter.

In each parameter is being adopted levels were taken as 0%, 0.5% and 1% of Polypropylene fiber, 0%-2%, 1%-1% and 2%-0% filler combination for Cement and Lime. Varying Binder (Bitumen/Asphalt) content in 5%, 5.5%, and 6% of Viscosity Grade (VG)-30 and 3-Combined Aggregate Gradation (CAG) with a nominal aggregate size of 13.2mm as lie in the specified limits [21]. They studied Fibers that were added in the mix in the dry process to the aggregate before the addition of asphalt at 140^0C. These processes are adopted to obtain a uniform mix and to reduce fuel consumption and time.

This method is adopted by selecting the L9 Orthogonal Array to Optimize 4 parameters and Grey relational analysis is carried out to analyze the multiple performance measurements of Bulk specific gravity (*Gmb*), Theoretical maximum specific gravity (*Gmm*), Voids in the Mineral Aggregate (*VMA*), Air Voids (*Va*), Voids Filled with Bitumen (*VFB*), Marshall stability and Marshal flow. For this study, the traditional approach has to do 'n' number of combinations to test, in this study L9 OA is generated by the Taguchi tool which analysis 3^4 = 81 number of combinations, by taking 9 best combinations.

Changing in temperature, moisture and voids play a vital role in the HMA mix design, performance, and durability of pavements based on these criteria. To study the HMA mix two conditions of gradation were selected coarse gradation and Fine gradation. For this study expected performance measurements and their target values are presented in Table 1. These target values were taken as within the limits [21].

Table 1

Target values of performance measurements.

Specifications	**Coarse gradation**	**Fine gradation**
Bulk specific gravity (G_{mb})	Maximum	Maximum
Theoretical maximum specific gravity (G_{mm})	maximum	Maximum
Voids in mineral aggregate (*VMA*)	15%	13%
Air voids (V_a)	5%	3%
Voids filled with bitumen (*VFB*)	65%	75%
Marshall stability ($\geq$ 9KN)	maximum	Maximum
Marshall flow	2mm	4mm

Maximum *VMA*, *Va*, and minimum *VFB* and Flow values were considered at Coarse gradation conditions to create no bleeding situation. The phenomenon is due to a temperature rise, the asphalt will get melt and leads to bleeding, by providing the excess number of voids, the asphalt will fill in those voids, due to this bleeding will not occur. Minimum *VMA*, *Va*, and maximum *VFB* and Flow values were considered for Fine gradation conditions to avoid the moisture present in the pavement layers and for damage-free roads due to moisture. The moisture in pavement layers gets between asphalt film and aggregate surface and breaks the bond between them which leads to the stripping of aggregates. This process further leads to potholes. And also in extremely cold conditions water that is present in the pavements layer leads to freeze and thaw action.

From the study, all 4 parameters were having a significant amount of influence on the HMA mix. For the Coarse gradation condition Fiber and Filler, the combination was having more influence, whereas in the case of the Fine gradation condition aggregate gradation and the Filler combination have more influence on the HMA mix. The data was analyzed by using Analysis of Variance (ANOVA), to find the most significant factors at coarse gradation and Fine gradation conditions, used to know the percentage contribution of each factor for both considerations.

2. Grey relational analysis

2.1. Taguchi Method

The various steps involved in the Taguchi method are as in the flowchart as shown in Figure 1. In the Taguchi method, orthogonal array (OA) of different experiments are used. The OA would impart a balanced and minimum number of tests. In this method, we have some standard and defined OAs. Each arrays group is stipulated for some specific number of variables and levels. Upon its usage number of trials or tests would be reduced. ANOVA (Analysis of Variance) is a tool by which we can compare the means of two or more groups.

2.2. Data processing

The Grey relational analysis is an effective method in which analysis is done among the sequence groups and requires that all sequences satisfy comparability conditions, and non-dimension, it can be used for solving the complicated interrelationships among the multi responses. This method is used to analyze the multi performances in experimental studies and as some advantage of the statistical method. When the experimental method can't be carried out exactly grey relational analysis helps to compensate for the shortcoming in statistical regression. Grey relation analysis is an effective means of analyzing the relationship between sequences with fewer data and can analysis many parameters that can overcome the disadvantages of the statistical method. The range of data processing is '0 to 1' there are three different types of data processing lower is better, higher is better and nominal is the best. But in this study, only two conditions are considered higher is better and nominal is best.

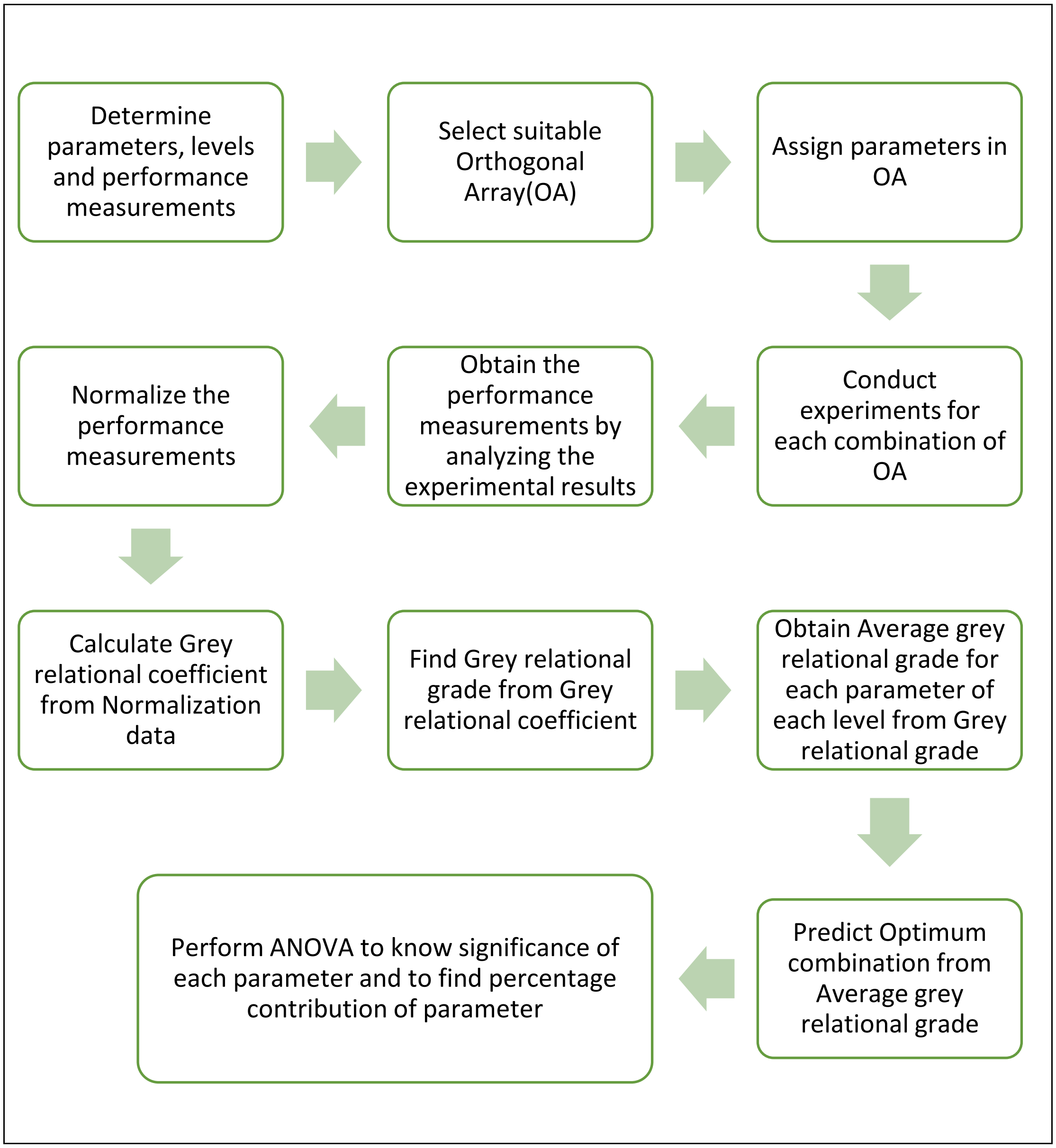

Fig. 1. Steps involved in Taguchi method.

For higher the better quality, normalizing data is calculated by:

$$X_i^*(K) = \frac{X_i^o(K) - min.X_i^o(K)}{max.X_i^o(K) - min.X_i^o(K)} \tag{1}$$

For lower the better quality, normalizing data is calculated by:

$$X_i^*(K) = \frac{max.X_i^o(K) - X_i^o(K)}{max.X_i^o(K) - min.X_i^o(K)} \tag{2}$$

For nominal the best quality, normalizing data is calculated by:

$$X_i^*(K) = 1 - \frac{|X_i^o(K) - OB|}{max.\{max.X_i^o(K) - OB, OB - min.X_i^o(K)\}} \tag{3}$$

Where k = 1 to n, i = 1 to 9; “n” is the performance characteristic and “i” is the trial number $X_i^o(K)$→is the original sequence, $X_i^*(K)$→is the sequence after data normalizing, OB → is the target value, $\max. X_i^o(K)$ → is the largest value of $X_i^o(K)$, $\min. X_i^o(K)$ → is the smallest value of $X_i^o(K)$

2.3. Grey relational coefficient and Grey relational grade

The grey relational coefficient is calculated from the normalized experimental data to express the relationship between the ideal and the actual experiment. The grey relational coefficient $\varepsilon_i(k)$ for the k_{th} performance characteristics in the i_{th} experiment is:

$$\varepsilon_i(K) = \frac{\Delta_{min}+\varphi\Delta_{max}}{\Delta_{oi}+\varphi\Delta_{max}} \tag{4}$$

$$\Delta_{oi}(K) = \|X_o^*(K) - X_i^*(K)\| \tag{5}$$

$$\Delta_{min}(K) = min.\|X_o^*(K) - X_i^*(K)\| \tag{6}$$

$$\Delta_{max}(K) = max.\|X_o^*(K) - X_i^*(K)\| \tag{7}$$

Where $X_o^*(K)$ is the reference sequence, $X_i^*(K)$ is the compatibility sequence, φ is the distinguishing coefficient, 0 to 1, $\varphi \in (0,1)$ in general $\varphi = 0.5$

The Grey relation grade is computed by averaging the Grey relational coefficient corresponding to each processes response. The overall evaluation of the multiple processes responses is based on the grey relational grade. High grey relational grade gives the optimal solutions.

The Grey relational grade is obtained by:

$$Y_i = \frac{1}{n}\sum_{K=1}^{n} \varepsilon i(K) \tag{8}$$

Where $Y_i$the grey relational grade and n is is the number of performance characteristics.

The predicted optimal grey relational grade (GRG_{opt}) is predicted by using:

$$GRG_{opt} = GRG_{mean} + \sum_{i=1}^{n}(GRG_i - GRG_{mean}) \tag{9}$$

Where GRG_{mean} is the average of Grey relational grade. GRG_i is the average of grey relational analysis at optimum level and n is the significantly affecting process parameters.

3. Materials and methods

Physical requirement tests were conducted on aggregate and Asphalt, based on IS specifications. Aggregate gradation was done as per MoRTH [21]. Marshall tests were conducted based on the ASTM-D1559 [16] code of practices.

The crushed granite was used as the aggregate. Typical gradation for bituminous concrete (BC) Grade-2 with 13.2 nominal aggregate size as per Table 500-17 MoRTH [21] specification was selected. Gradation in the specification limits is shown in Figure 2. Properties of aggregates are given in Table 2.

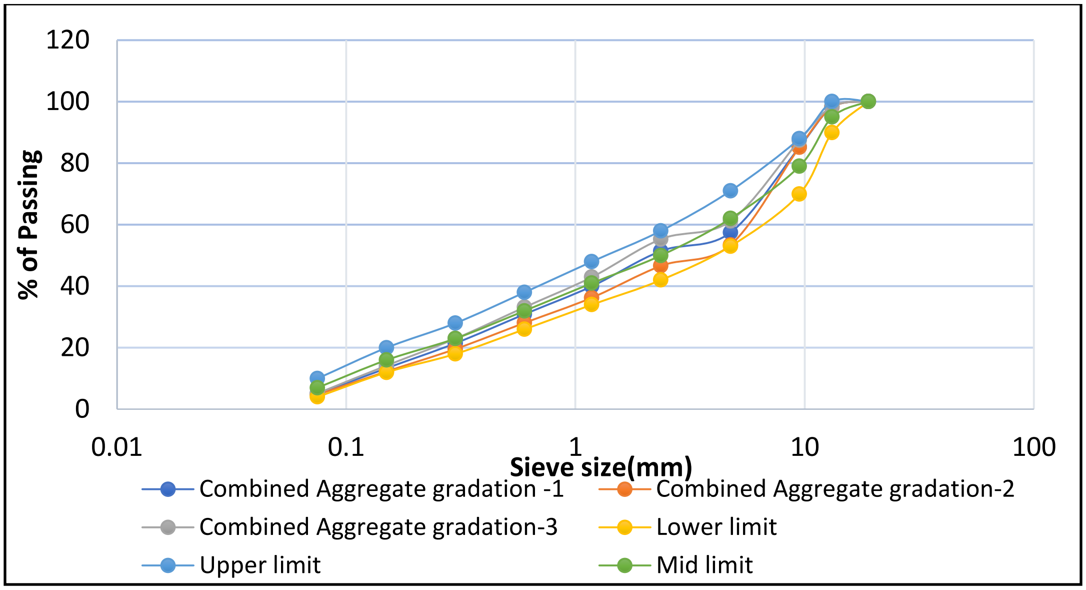

Fig. 2. Combined aggregate gradation for BC Grade 2.

Table 2

Test results of Aggregate and Fillers based on IS 2386 [22–24].

Specifications	**Value**
Bulk specific gravity of 12 mm Aggregate	2.80
Bulk specific gravity of 6 mm Aggregate	2.73
Bulk specific gravity of Stone dust	2.63
Bulk specific gravity of Cement	2.90
Bulk specific gravity of Lime	0.93
Aggregate Impact Value (%)	23.66
Combined Flakiness and Elongation Index (%)	24.18
Water absorption of Aggregate (%)	0.75

Cement, Lime were used as filler combination in HMA mix. Specific gravities of Cement and Lime are shown in Table 2. VG 30 Bitumen was used as binder and results of these test are presented in Table 3.

Table 3

Test Results of Binder (Bitumen).

Specifications	**Value**	**Code of practice**
Penetration, 25˚C, 100g. 5s (1/10 mm)	56.33	IS 1203 [25]
Softening point (˚C)	57.67	IS 1205 [25]
Bulk specific gravity	1.01	IS 1202 [25]
Flash point (˚C)	265	IS 1209 [25]
Kinematic Viscosity (cSt), 135 ˚C	363	IS 1206 (part-3) [25]

In this study, polypropylene fiber as additive are used in HMA mix using dry process. Marshall Test specimens were casted and tested according to ASTM D 1559 [26] and test results obtained are within limits of MoRTH [21] specifications.

The Marshall test is a compaction test to find Marshall Stability and Flow values. And for all combinations of mixes Theoretical Maximum specific gravity values (G_{mm}) was found using rice apparatus with air extracting pressure of 25KPa. Moreover, Bulk specific gravity(G_{mb}), Voids in mineral aggregate(VMA), Air voids(V_a), Voids filled with Bitumen(VFB)/Voids filled with Asphalt(VFA) were observed.

The experimental parameters and their levels considered for studying are presented in Table 4.

Table 4

Experimental control factors and levels.

Levels	**(A)-Fiber (%)**	**(B)-Filler combination (%)**	**(C)-Binder (%)**	**(D)-Combined aggregate gradation**
1	0	0-2	5	1
2	0.5	1-1	5.5	2
3	1	2-0	6	3

The selected L9(3^4) Orthogonal array with 4 parameters each with 3 levels are represented in Table 5. The responses of G_{mb}, G_{mm}, VMA, V_a, VFB, Marshall Stability and Flow which are considered according to MoRTH [21] specifications.

Table 5

L9-Orthogonal Array.

Run Numbers	**A**	**B**	**C**	**D**
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The experimental values of responses were shown in Table 6 were obtained from 27 specimens of 9 combinations. The selected parameters effecting HMA mix are Fiber(A), Filler combination(B), Binder(C) and Aggregate gradation(D).

Table 6

Experimental runs and results.

Trial Number	A	B	C	D	G_{mb}	G_{mm}	*VMA* (%)	V_a (%)	*VFB* (%)	Stability (KN)	Flow (mm)
1	1	1	1	1	2.3779	2.4473	12.56251	2.84	77.43	19.43	4.12
2	1	1	1	1	2.3826	2.4473	12.3892	2.64	78.66	18.90	3.89
3	1	1	1	1	2.3962	2.4473	11.88856	2.09	82.45	19.43	3.45
4	1	2	2	2	2.4266	2.4545	13.20251	1.14	91.39	15.23	4.21
5	1	2	2	2	2.4123	2.4545	13.71434	1.72	87.46	15.93	3.96
6	1	2	2	2	2.4223	2.4545	13.35903	1.32	90.16	16.10	4.42
7	1	3	3	3	2.3985	2.4505	15.88457	2.12	86.64	16.98	5.39
8	1	3	3	3	2.4101	2.4505	15.47808	1.65	89.34	16.45	5.17
9	1	3	3	3	2.4004	2.4505	15.81738	2.04	87.07	16.63	5.51
10	2	1	2	3	2.4054	2.4440	11.97081	1.58	86.79	20.65	5.35
11	2	1	2	3	2.3935	2.4440	12.40557	2.07	83.33	20.48	5.29
12	2	1	2	3	2.4015	2.4440	12.11022	1.74	85.65	20.30	5.41
13	2	2	3	1	2.3797	2.4639	14.96215	3.42	77.15	19.25	4.33
14	2	2	3	1	2.3925	2.4639	14.5064	2.90	80.00	20.48	4.52
15	2	2	3	1	2.3859	2.4639	14.73944	3.17	78.52	19.78	4.25
16	2	3	1	2	2.3472	2.5121	17.20741	6.57	61.85	18.90	5.11
17	2	3	1	2	2.3459	2.5121	17.25094	6.61	61.66	18.20	5.34
18	2	3	1	2	2.3333	2.5121	17.69547	7.12	59.79	18.90	5.25
19	3	1	3	2	2.3537	2.4505	14.59711	3.95	72.94	22.93	3.59
20	3	1	3	2	2.3451	2.4505	14.90989	4.30	71.15	23.80	3.72
21	3	1	3	2	2.3525	2.4505	14.64062	4.00	72.69	23.10	3.81
22	3	2	1	3	2.3377	2.4859	15.66875	5.96	61.95	30.98	3.96
23	3	2	1	3	2.3390	2.4859	15.62225	5.91	62.16	30.10	4.11
24	3	2	1	3	2.3539	2.4859	15.0818	5.31	64.80	30.63	3.83
25	3	3	2	1	2.3607	2.5020	16.81504	5.65	66.43	40.43	4.73
26	3	3	2	1	2.3766	2.5020	16.25477	5.01	69.18	40.95	4.65
27	3	3	2	1	2.3619	2.5020	16.77301	5.60	66.63	41.13	4.79

4. Discussions of test results

The results of aggregate and filler are within specified limits and according to “IS 2386” [22–24], are shown in Table 2. The test results of asphalt are also within the specified limits and according to IS specifications, as shown in Table 3. Based on sieve analysis results, 3-Aggregate gradations are plotted within the limits of “BC Grade-2” specifications [21].

Normalization was done considering the *Gmb*, *Gmm*, and Marshall stability values based on “Higher the better” criteria by using Equation-1. *VMA*, *Va*, *VFB* and Flow values are based on “Nominal is the best” criteria by using Equation-3. The set of original/ experimental values , i =

1-9 iterations and for K = 1-3 levels are listed in Table 6 are used for Normalization by going for, i = 1-9 iterations and for K = 1-3 levels.

Table 7 and Table 8 show all the Normalized sequences after the data processing using Equation-1 and Equation-3. The reference and the Normalized sequence are denoted as and respectively, in calculating the deviation sequences, and for i = 1-9, K =1-3.

Table 7

Normalization for Optimum Specific conditions at coarse gradation condition.

Trial Number	G_{mb}	G_{mm}	*VMA*	V_a	*VFB*	**Stability**	**Flow**
1	0.4772	0.0477	0.2166	0.4398	0.5291	0.1622	0.3960
2	0.5277	0.0477	0.1609	0.3900	0.4822	0.1419	0.4615
3	0.6737	0.0477	0.0000	0.2459	0.3389	0.1622	0.5869
4	1.0000	0.1547	0.4223	0.0000	0.0000	0.0000	0.3704
5	0.8466	0.1547	0.5868	0.1509	0.1489	0.0270	0.4416
6	0.9531	0.1547	0.4726	0.0461	0.0467	0.0338	0.3105
7	0.6981	0.0950	0.7157	0.2552	0.1801	0.0676	0.0342
8	0.8223	0.0950	0.8463	0.1328	0.0776	0.0473	0.0969
9	0.7186	0.0950	0.7373	0.2350	0.1635	0.0541	0.0000
10	0.7719	0.0000	0.0264	0.1152	0.1745	0.2095	0.0456
11	0.6445	0.0000	0.1662	0.2410	0.3054	0.2027	0.0627
12	0.7310	0.0000	0.0712	0.1555	0.2175	0.1959	0.0285
13	0.4969	0.2926	0.9878	0.5907	0.5396	0.1554	0.3362
14	0.6336	0.2926	0.8414	0.4567	0.4316	0.2027	0.2821
15	0.5637	0.2926	0.9163	0.5252	0.4876	0.1757	0.3590
16	0.1483	1.0000	0.2905	0.5948	0.8805	0.1419	0.1140
17	0.1351	1.0000	0.2765	0.5821	0.8733	0.1149	0.0484
18	0.0000	1.0000	0.1337	0.4522	0.8024	0.1419	0.0741
19	0.2183	0.0950	0.8705	0.7281	0.6990	0.2973	0.5470
20	0.1259	0.0950	0.9710	0.8191	0.7669	0.3311	0.5100
21	0.2055	0.0950	0.8845	0.7407	0.7086	0.3041	0.4843
22	0.0464	0.6150	0.7851	0.7508	0.8843	0.6081	0.4416
23	0.0602	0.6150	0.8000	0.7642	0.8925	0.5743	0.3989
24	0.2208	0.6150	0.9737	0.9202	0.9926	0.5946	0.4786
25	0.2938	0.8517	0.4166	0.8329	0.9460	0.9730	0.2222
26	0.4642	0.8517	0.5967	0.9974	0.8417	0.9932	0.2450
27	0.3066	0.8517	0.4302	0.8452	0.9384	1.0000	0.2051

Table 8

Normalization for Optimum Specific conditions at Fine gradation condition.

Trial Number	G_{mb}	G_{mm}	*VMA*	V_a	*VFB*	**Stability**	**Flow**
1	0.4772	0.0477	0.9068	0.9601	0.8520	0.1622	0.9205
2	0.5277	0.0477	0.8699	0.9134	0.7764	0.1419	0.9272
3	0.6737	0.0477	0.7633	0.7782	0.5457	0.1622	0.6358
4	1.0000	0.1547	0.9569	0.5474	0.0000	0.0000	0.8609
5	0.8466	0.1547	0.8479	0.6890	0.2398	0.0270	0.9735
6	0.9531	0.1547	0.9235	0.5907	0.0753	0.0338	0.7219
7	0.6981	0.0950	0.3857	0.7869	0.2900	0.0676	0.0795
8	0.8223	0.0950	0.4722	0.6720	0.1250	0.0473	0.2252
9	0.7186	0.0950	0.4000	0.7679	0.2633	0.0541	0.0000
10	0.7719	0.0000	0.7808	0.6555	0.2809	0.2095	0.1060
11	0.6445	0.0000	0.8734	0.7736	0.4917	0.2027	0.1457
12	0.7310	0.0000	0.8105	0.6933	0.3501	0.1959	0.0662
13	0.4969	0.2926	0.5821	0.8982	0.8688	0.1554	0.7815
14	0.6336	0.2926	0.6792	0.9760	0.6949	0.2027	0.6556
15	0.5637	0.2926	0.6296	0.9597	0.7852	0.1757	0.8344
16	0.1483	1.0000	0.1039	0.1338	0.1974	0.1419	0.2649
17	0.1351	1.0000	0.0947	0.1219	0.1859	0.1149	0.1126
18	0.0000	1.0000	0.0000	0.0000	0.0717	0.1419	0.1722
19	0.2183	0.0950	0.6599	0.7693	0.8745	0.2973	0.7285
20	0.1259	0.0950	0.5933	0.6839	0.7652	0.3311	0.8146
21	0.2055	0.0950	0.6506	0.7574	0.8590	0.3041	0.8742
22	0.0464	0.6150	0.4316	0.2802	0.2035	0.6081	0.9735
23	0.0602	0.6150	0.4415	0.2928	0.2168	0.5743	0.9272
24	0.2208	0.6150	0.5566	0.4392	0.3779	0.5946	0.8874
25	0.2938	0.8517	0.1875	0.3573	0.4768	0.9730	0.5166
26	0.4642	0.8517	0.3068	0.5117	0.6448	0.9932	0.5695
27	0.3066	0.8517	0.1965	0.3688	0.4890	1.0000	0.4768

Two conditions of gradation namely coarse gradation and Fine gradation based on the effect of voids in the HMA mix were considered. The deviation sequence is calculated using 5, 6, and 7 for the HMA mix. The distinguishing coefficient φ (range 0-1) can be substituted for the Grey relational coefficient in Equation -4. The value is adopted when all the performance measures have equal weightage. In this study, all performance measures considered are with equal weightage as shown in Table 9 and Table 10 for Grey relational coefficients of all nine combinations each with 3 trials. Grey relational grade was calculated by using Equation-8 for two conditions of both gradations and as listed in Table 9 and Table 10.

Table 9

GRC and GRG for Normalized Variables at Coarse gradation condition.

Grey Relational Coefficient (GRC) for Normalized Variables								**Grey Relational Grade (GRG)**
Trial Number	G_{mb}	G_{mm}	*VMA*	V_a	*VFB*	**Stability**	**Flow**	
1	0.4889	0.3443	0.3991	0.4741	0.5226	0.3737	0.8271	0.4900
2	0.5143	0.3443	0.3825	0.4528	0.4985	0.3682	0.8793	0.4914
3	0.6051	0.3443	0.3415	0.4008	0.4370	0.3737	1.0000	0.5003
4	1.0000	0.3717	0.4753	0.3351	0.3383	0.3333	0.8083	0.5231
5	0.7653	0.3717	0.5609	0.3725	0.3755	0.3394	0.8627	0.5212
6	0.9142	0.3717	0.4985	0.3457	0.3491	0.3410	0.7677	0.5126
7	0.6235	0.3559	0.6531	0.4038	0.3844	0.3491	0.6229	0.4847
8	0.7378	0.3559	0.7836	0.3676	0.3567	0.3442	0.6508	0.5138
9	0.6399	0.3559	0.6716	0.3973	0.3797	0.3458	0.6087	0.4855
10	0.6867	0.3333	0.3476	0.3629	0.3828	0.3874	0.6278	0.4469
11	0.5845	0.3333	0.3840	0.3992	0.4247	0.3854	0.6353	0.4495
12	0.6502	0.3333	0.3585	0.3738	0.3956	0.3834	0.6205	0.4451
13	0.4985	0.4141	1.0001	0.5527	0.5283	0.3719	0.7846	0.5929
14	0.5771	0.4141	0.7777	0.4817	0.4749	0.3854	0.7497	0.5515
15	0.5340	0.4141	0.8774	0.5156	0.5012	0.3776	0.8003	0.5743
16	0.3699	1.0000	0.4235	0.5552	0.8190	0.3682	0.6588	0.5992
17	0.3663	1.0000	0.4187	0.5475	0.8097	0.3610	0.6291	0.5903
18	0.3333	1.0000	0.3749	0.4797	0.7274	0.3682	0.6404	0.5605
19	0.3901	0.3559	0.8137	0.6511	0.6335	0.4157	0.9582	0.6026
20	0.3639	0.3559	0.9683	0.7382	0.6921	0.4277	0.9223	0.6383
21	0.3862	0.3559	0.8322	0.6620	0.6412	0.4181	0.8990	0.5992
22	0.3440	0.5650	0.7164	0.6709	0.8240	0.5606	0.8627	0.6491
23	0.3473	0.5650	0.7317	0.6831	0.8353	0.5401	0.8292	0.6474
24	0.3909	0.5650	0.9732	0.8669	1.0000	0.5522	0.8940	0.7489
25	0.4145	0.7712	0.4728	0.7534	0.9159	0.9487	0.7146	0.7130
26	0.4827	0.7712	0.5670	1.0000	0.7708	0.9867	0.7276	0.7580
27	0.4190	0.7712	0.4788	0.7676	0.9035	1.0000	0.7052	0.7207

Table 10
GRC and GRG for Normalized Variables at Fine gradation condition.

Grey Relational Coefficient (GRC) for Normalized Variables								**Grey Relational Grade (GRG)**
Trial Number	G_{mb}	G_{mm}	***VMA***	V_a	***VFB***	**Stability**	**Flow**	
1	0.4889	0.3443	0.9156	0.9706	0.9653	0.3737	0.9086	0.7096
2	0.5143	0.3443	0.8620	0.8932	0.8645	0.3682	0.9191	0.6808
3	0.6051	0.3443	0.7372	0.7260	0.6555	0.3737	0.6092	0.5787
4	1.0000	0.3717	0.9999	0.5500	0.4170	0.3333	0.8238	0.6423
5	0.7653	0.3717	0.8328	0.6461	0.4963	0.3394	1.0000	0.6359
6	0.9142	0.3717	0.9421	0.5762	0.4390	0.3410	0.6766	0.6087
7	0.6235	0.3559	0.4874	0.7348	0.5169	0.3491	0.3706	0.4912
8	0.7378	0.3559	0.5284	0.6328	0.4549	0.3442	0.4130	0.4953
9	0.6399	0.3559	0.4937	0.7157	0.5058	0.3458	0.3510	0.4868
10	0.6867	0.3333	0.7552	0.6205	0.5131	0.3874	0.3777	0.5248
11	0.5845	0.3333	0.8667	0.7213	0.6204	0.3854	0.3888	0.5572
12	0.6502	0.3333	0.7877	0.6496	0.5440	0.3834	0.3672	0.5308
13	0.4985	0.4141	0.5917	0.8708	0.9910	0.3719	0.7327	0.6387
14	0.5771	0.4141	0.6617	1.0000	0.7769	0.3854	0.6235	0.6341
15	0.5340	0.4141	0.6239	0.9698	0.8750	0.3776	0.7911	0.6551
16	0.3699	1.0000	0.3890	0.3835	0.4802	0.3682	0.4263	0.4882
17	0.3663	1.0000	0.3865	0.3802	0.4760	0.3610	0.3795	0.4785
18	0.3333	1.0000	0.3621	0.3493	0.4379	0.3682	0.3965	0.4639
19	0.3901	0.3559	0.6464	0.7171	1.0000	0.4157	0.6824	0.6011
20	0.3639	0.3559	0.5990	0.6420	0.8512	0.4277	0.7681	0.5726
21	0.3862	0.3559	0.6394	0.7057	0.9759	0.4181	0.8413	0.6175
22	0.3440	0.5650	0.5083	0.4296	0.4824	0.5606	1.0000	0.5557
23	0.3473	0.5650	0.5131	0.4341	0.4875	0.5401	0.9191	0.5437
24	0.3909	0.5650	0.5757	0.4940	0.5574	0.5522	0.8595	0.5707
25	0.4145	0.7712	0.4138	0.4585	0.6113	0.9487	0.5354	0.5934
26	0.4827	0.7712	0.4552	0.5302	0.7314	0.9867	0.5658	0.6462
27	0.4190	0.7712	0.4166	0.4632	0.6187	1.0000	0.5146	0.6005

The average of the Grey relational grade for every level of each individual factor is calculated as shown in Table 11 and Table 12. Since the Grey relational grades represent the level of correlation between the reference and Normalized sequence and it exhibits a stronger correlation with the reference sequence. Based on this existing study one can select a combination of the levels that provide the largest average response.

Table 11

Average Grey Relational Grade at Coarse gradation condition.

Level	Fiber (A)	Filler combination (B)	Binder (C)	Combined aggregate gradation (D)
1	0.5025	0.5182	0.5864	0.5991
2	0.5345	0.5912	0.5656	0.5719
3	0.6753	0.6029	0.5633	0.5412
Delta	0.1728	0.0847	0.0231	0.0579
Rank	1	2	4	3

Table 12

Average Grey Relational Grade at Fine gradation condition.

Level	Fiber (A)	Filler combination (B)	Binder (C)	Combined Aggregate gradation (D)
2	0.5524	0.6094	0.5933	0.5676
3	0.5890	0.5271	0.5635	0.5285
Delta	0.0397	0.0823	0.0300	0.0901
Rank	3	2	4	1

At Coarse gradation condition as shown in Table 11, combination A3B3C1D1 shows the largest value of the Average grey relation grade. It indicates that with Fiber 1%, Filler combination 2% cement- 0% lime, 5% of Binder and Combined aggregate gradation-1 is the optimal combination of HMA mix at coarse gradation condition. Considering the optimized combination of mix (A3B3C1D1) which were cast for determine the G_{mb}, G_{mm}, VMA, V_a, VFB, Stability and Flow were tested it was found that the results were within specifications [21].

Similarly, At Fine gradation condition as shown in Table 12, the combination A1B2C2D1 shows the largest value of the Average grey relation grade, for the factors A, B, C and D respectively. It indicates that with Fiber 0%, Filler combination 1% cement-1% lime, 5.5% Binder and combined aggregate gradation-1 is the optimal parameters combination of HMA mix at Fine gradation condition optimal combination mix. Results of G_{mb}, G_{mm}, VMA, V_a, VFB, Stability and Flow are within the specified limits [21].

4.1. Most significant factor

The Grey relational grade of both conditions was analyzed with Analysis of variance (ANOVA) General linear model adopted indicating the influence of HMA mix was considered for 95% confidence. From ANOVA, it is seen that for coarse gradation condition Fiber (72.9%) and Filler combination (18.2%) are having more significant effect on HMA mix. The Combined aggregate gradation and Binder are have less significant effect in this with as 7.25% and 1.64% respectively as seen in Table 13.

Table 13

ANOVA for GRG at Coarse gradation condition, using Adjusted SS for Tests.

Source	Degrees of Freedom	Seq SS	Adj SS	Adj MS	F-ratio	P-value	Contribution (%)
Fiber	2	0.152044	0.152044	0.076022	122.01	0.000	72.91
Filler combination	2	0.037956	0.037956	0.018978	30.46	0.000	18.20
Binder	2	0.003412	0.003412	0.001706	2.74	0.092	1.64
CAG	2	0.015118	0.015118	0.007559	12.13	0.000	7.25
Error	18	0.011216	0.011216	0.000623			
Total	26	0.219746					

From ANOVA for Fine gradation condition, combined aggregate gradation (53.15%) and Filler combination (34.37%) are having more significant effect on HMA mix. The Fiber and Binder are having less significance in this condition as 8.54% and 3.94% respectively as seen in Table14. The Main effects plots for GRG for both gradation conditions are shown in Figure 3 and Figure 4.

Table 14

ANOVA for GRG at Fine gradation condition, using Adjusted SS for Tests.

Source	Degrees of Freedom	Seq SS	Adj SS	Adj MS	F-ratio	P-value	Contribution (%)
Fiber	2	0.008811	0.008811	0.004405	5.54	0.013	8.54
Filler combination	2	0.035463	0.035463	0.017731	22.31	0.000	34.37
Binder	2	0.004062	0.004062	0.002031	2.56	0.105	3.94
CAG	2	0.054843	0.054843	0.027422	34.50	0.000	53.15
Error	18	0.014306	0.014306	0.000795			
Total	26	0.117484					

Table 15

Conformation test results of both gradation conditions.

Specifications	G_{mb}	G_{mm}	VMA	V_a	VFB	Stability	Flow
Coarse gradation	2.385	2.507	14.86	4.87	69.02	33.99	3.18
Fine gradation	2.418	2.504	13.28	3.43	74.17	24.89	3.87

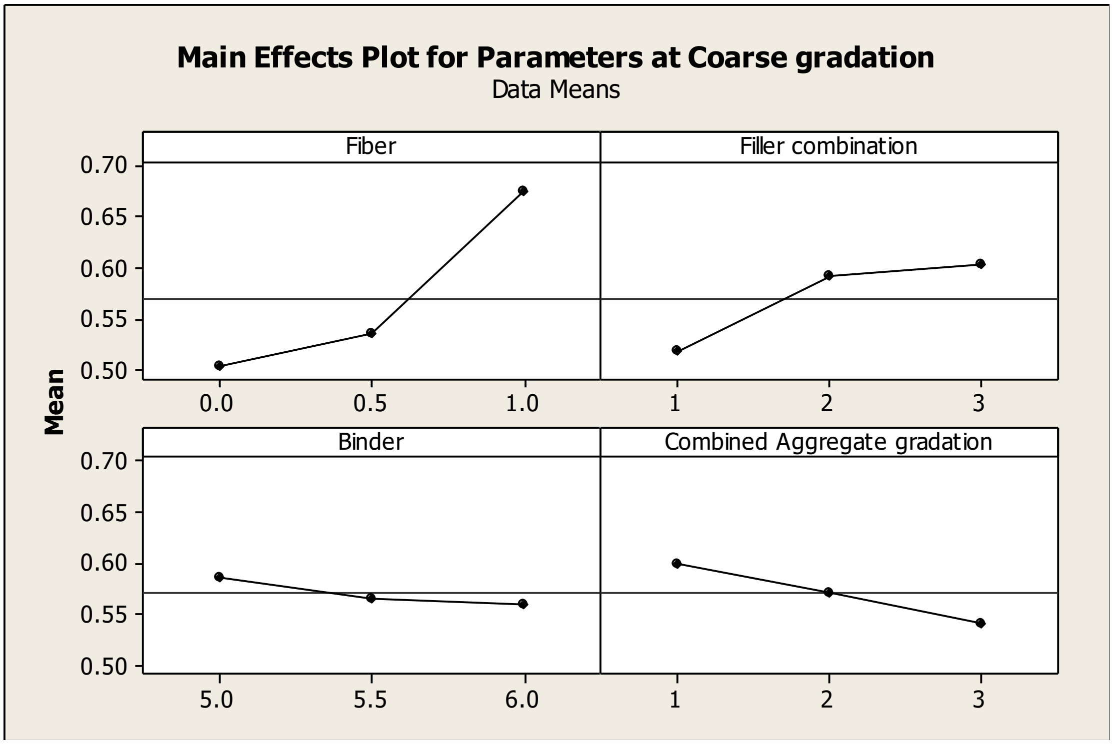

Fig. 3. Main effects plot for GRG at Coarse gradation condition.

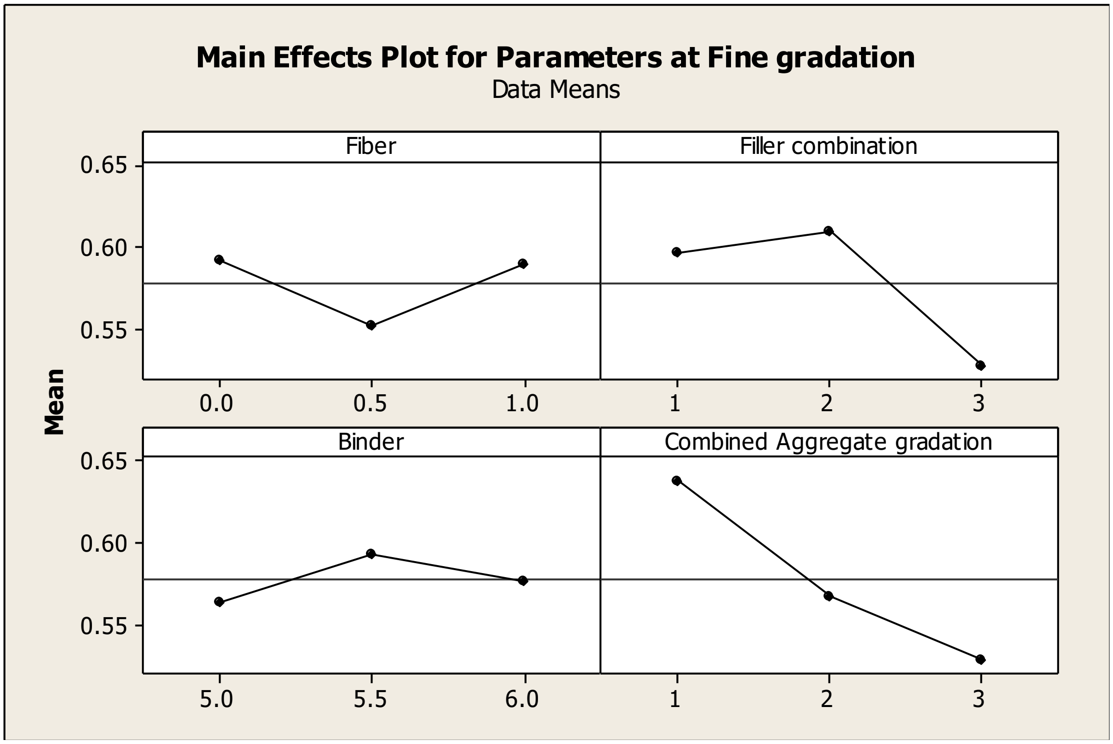

Fig. 4. Main effects plot for GRG at Fine gradation condition.

4.2. Conformation tests

The predicted Optimized combination A3B3C1D1 (Table 11) for Coarse gradation condition and A1B2C2D1 (Table-12) for Fine gradation condition are obtained from Grey relational Taguchi technique. The results of 3 samples were cast for the comparison test using Marshall Method of testing. And tests average values of performance measurements are shown in Table 15. Optimum Grey relational grade for coarse gradation and Fine condition were calculated using Equation-9 and values obtained are 0.7516 and 0.6800 respectively. The obtained results are within the specified limits. Hence Optimization by using Grey relational analysis based on Taguchi technique is recommended for HMA mix design, it deals with multiple number of parameters and performance measurements.

5. Conclusions

In this study to optimize the mix Grey relational analysis was carried out on an orthogonal array using the Taguchi technique for different combinations of fiber percent, filler combination, binder content, and aggregate gradation.

- From the Average Grey relational grade, it can be concluded that the largest values of Grey relational grade for 1% of Fiber, 2%-0% of Cement and Lime as Filler combination, 5% of Binder and Combined aggregate gradation-1 were found to be the most Optimized combination at Coarse gradation condition. Also larger values of Grey relation grade for the 0% of Fiber, 1%-1% filler combination, 5.5% Binder, and Combined aggregate gradation -1 was the most optimized option for Fine gradation condition.
- From the analysis, the stability is most influenced by polypropylene fiber. With the increase in fiber content, the stability increase. From the results, it is observed that VMA and Va are also increasing with fiber which helps in no bleeding condition as in case of Coarse gradation condition.
- The influence of the Filler combination of Cement and Lime (1%-1%) has a significant role in the performance of the mix for fine aggregate gradation with 0% fiber.
- In this study compared to the factors influencing the mix like Fiber, Filler combination, and combined aggregate gradation, the Binder has less influence on the performance of the HMA mix design.
- From the ANOVA technique, it is seen that the Fiber content and Filler combination have a significant contribution in the mix as seen in coarse graded conditions. Whereas in the case of Fine graded conditions the combined aggregate gradation and Filler combination has a significant contribution to the mix preparation.

Funding

This research received no external funding.

Conflicts of interest

The authors declare no conflict of interest.

References

[1] Arifuzzaman M. Advanced ANN Prediction of Moisture Damage in CNT Modified Asphalt Binder. J Soft Comput Civ Eng 2017;1:1–11. https://doi.org/10.22115/scce.2017.46317.

[2] Leiva-Villacorta F, Vargas-Nordcbeck A. Neural Network Based Model to Estimate Dynamic Modulus E* for Mixtures in Costa Rica. J Soft Comput Civ Eng 2019;3:1–15. https://doi.org/10.22115/SCCE.2019.188006.1110.

[3] Karanjule DB, Bhamare SS, Rao TH. Process Parameter Optimization for Minimizing Springback in Cold Drawing Process of Seamless Tubes Using Advanced Optimization Algorithms. J Soft Comput Civ Eng 2018;2:72–90. https://doi.org/10.22115/SCCE.2018.136009.1072.

[4] Mukhopadhyay A, Sahoo S. A Grey-Fuzzy Based Approach for the Optimization of Corrosion Resistance of Rebars Coated with Ternary Electroless Nickel Coatings. J Soft Comput Civ Eng 2022;6:107–27. https://doi.org/10.22115/SCCE.2022.326903.1401.

[5] Rezazadeh Eidgahee D, Jahangir H, Solatifar N, Fakharian P, Rezaeemanesh M. Data-driven estimation models of asphalt mixtures dynamic modulus using ANN, GP and combinatorial GMDH approaches. Neural Comput Appl 2022;34:17289–314. https://doi.org/10.1007/s00521-022-07382-3.

[6] Hu J, Ma T, Yin T, Zhou Y. Foamed warm mix asphalt mixture containing crumb rubber: Foaming optimization and performance evaluation. J Clean Prod 2022;333:130085. https://doi.org/10.1016/j.jclepro.2021.130085.

[7] Daneshvar MH, Saffarian M, Jahangir H, Sarmadi H. Damage identification of structural systems by modal strain energy and an optimization-based iterative regularization method. Eng Comput 2022:1–21. https://doi.org/10.1007/s00366-021-01567-5.

[8] Ren Z, Tan Y, Huang L, Yu H. Optimization of automatic extraction procedure for particles in asphalt mixture towards superior robustness and accuracy. Constr Build Mater 2022;342:128002. https://doi.org/10.1016/j.conbuildmat.2022.128002.

[9] Onyelowe KC, Rezazadeh Eidgahee D, Jahangir H, Aneke FI, Nwobia LI. Forecasting Shear Parameters, and Sensitivity and Error Analyses of Treated Subgrade Soil. Transp Infrastruct Geotechnol 2022. https://doi.org/10.1007/s40515-022-00225-7.

[10] Polo-Mendoza R, Martinez-Arguelles G, Peñabaena-Niebles R. A multi-objective optimization based on genetic algorithms for the sustainable design of Warm Mix Asphalt (WMA). Int J Pavement Eng 2022:1–21. https://doi.org/10.1080/10298436.2022.2074417.

[11] Ozbay E, Oztas A, Baykasoglu A, Ozbebek H. Investigating mix proportions of high strength self compacting concrete by using Taguchi method. Constr Build Mater 2009;23:694–702. https://doi.org/10.1016/j.conbuildmat.2008.02.014.

[12] Nirmala DB, Raviraj S. Experimental study of optimal self compacting concrete with spent foundry sand as partial replacement for M-sand using Taguchi approach. Sel Sci Pap - J Civ Eng 2016;11:119–30. https://doi.org/10.1515/sspjce-2016-0013.

[13] Abdullah WS, Obaidat MT, Abu-Sa'da NM. Influence of Aggregate Type and Gradation on Voids of Asphalt Concrete Pavements. J Mater Civ Eng 1998;10:76–85. https://doi.org/10.1061/(asce)0899-1561(1998)10:2(76).

[14] Shen S, Yu H. Analysis of Aggregate Gradation and Packing for Easy Estimation of Hot-Mix-Asphalt Voids in Mineral Aggregate. J Mater Civ Eng 2011;23:664–72. https://doi.org/10.1061/(asce)mt.1943-5533.0000224.

[15] Awuah-Offei K, Askari-Nasab H. Aggregate Cost Minimization in Hot-Mix Asphalt Design. J Mater Civ Eng 2011;23:554–61. https://doi.org/10.1061/(asce)mt.1943-5533.0000211.

[16] Rahman A, Ali SA, Adhikary SK, Hossain QS. Effect of fillers on bituminous paving mixes: An experimental study. J Eng Sci 2012;3:121–7.

[17] Sung Do H, Hee Mun P, Suk keun R. A study on engineering characteristics of asphalt concrete using filler with recycled waste lime. Waste Manag 2008;28:191–9. https://doi.org/10.1016/j.wasman.2006.11.011.

[18] Tapkin S. The effect of polypropylene fibers on asphalt performance. Build Environ 2008;43:1065–71. https://doi.org/10.1016/j.buildenv.2007.02.011.

[19] Tortum A, Çelik C, Cüneyt Aydin A. Determination of the optimum conditions for tire rubber in asphalt concrete. Build Environ 2005;40:1492–504. https://doi.org/10.1016/j.buildenv.2004.11.013.

[20] Tzeng CJ, Lin YH, Yang YK, Jeng MC. Optimization of turning operations with multiple performance characteristics using the Taguchi method and Grey relational analysis. J Mater Process Technol 2009;209:2753–9. https://doi.org/10.1016/j.jmatprotec.2008.06.046.

[21] Ministry of Road Transport and Highways (MoRTH). Specifications for road and bridge works, Indian Roads Congress, New Delhi, India (Fifth Revision). 2013.

[22] IS: 2386 (Part I) – 1963, Indian standard code of practice- Methods of test for aggregates for concrete particle size and shape, Bureau of Indian Standards, New Delhi, India (eleventh reprint august 1997). 1997.

[23] IS: 2386 (Part III) – 1963, Indian standard code of practice- Methods of test for aggregates for concrete specific gravity, density, voids, absorption and bulking, Bureau of Indian Standards, New Delhi, India (eighth reprint march 1997).

[24] IS: 2386 (Part IV) – 1963, Indian standard code of practice- Methods of test for aggregates for concrete mechanical properties, Bureau of Indian Standards, New Delhi, India (tenth reprint march 1997).

[25] IS: 1201 – 1978 To IS: 1220 – 1978, Indian standard code of practice - Methods for testing tar and bituminous materials, Bureau of Indian Standards, New Delhi, India (First Revision).

[26] American Society for Testing and Materials D1559-76, Standard test method for resistance to plastic flow of bituminous mixtures using Marshall apparatus.