Improving the Strength of Cold Mix Asphalt Concrete through Numerical Optimization

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Abstract
Compared to conventional hot-mix asphalt concrete (HMAC), the production and placement of cold mix asphalt concrete (CMAC) is a more environmentally sustainable alternative that offers significant reduction in energy use and greenhouse gas emissions. It has been widely used; however, its poor mechanical performance restricts its use to low traffic roads and temporary repair works. This limitation emphasises the need for performance enhancement to enable broader structural application, particularly in urban and high traffic roads. Opportunities exist to improve CMAC properties through the incorporation of suitable additives. Introduction of additives to the conventional bitumen mix requires systematic investigation and optimized design approaches capable of addressing complex mix behaviour. Conventional trial and error method are experimentally intensive, time consuming, and inadequate for capturing the nonlinear interactions among multiple constituents. This study uses the statically driven mix design optimization framework using Response Surface Methodology (RSM) for CMAC mix design optimization incorporating hydrated lime, silica fume, bitumen emulsion, and recycled PET (polyethylene terephthalate). A total of 83 different mixtures and 161 specimens were prepared and tested as per American Association of State Highway and Transportation Officials (AASHTO) standards for Marshall stability, flow, density and air-void content. The optimized job mix, comprising of 1.0% hydrated lime, 1.5% silica fume, 9.45% bitumen emulsion, and 0.35% recycled PET fibres (all percentages based on total dry weight of aggregate), achieved a Marshall stability of 7.36 kN. The results demonstrated that the optimized mix achieved mechanical performance comparable to that of HMAC. The incorporation of the mineral fillers like hydrated lime and silica fume improved the adhesion between emulsion and the aggregates, while PET fibres improved the tensile strength, bonding properties and resistance to deformation. These finding highlights the potential of using modified CMAC mixtures for high traffic roads. The developed optimization framework provides a practical decision-support tool for pavement engineers, enabling more systematic, efficient and sustainable CMAC mix design while reducing reliance on conventional trial-and-error approaches. RSM enabled the development of predictive models that captures both linear and nonlinear relationship, significantly reducing experimental effort while improving analytical precision. While the prediction model performs well within the calibrated range, further validation is required to assess long term durability, moisture resistance and field performance under traffic and field conditions.

Keywords: *Cold Mix Asphalt Concrete, Pavement, Sustainable Pavement, Response Surface Methodology, Modified Cold Mix Asphalt Concrete, Pavement Engineering PET Fibres, Fillers.*

1. INTRODUCTION

Cold mix asphalt concrete (CMAC) is a flexible paving material that is produced by mixing the crushed (cold) aggregate and unheated asphalt binder (emulsion), saving the cost of energy consumption and emissions of greenhouse gases during the heating process (up to 140-160C) like in case of conventional Hot Mix Asphalt Concrete (HMAC)) (Milad et al., 2022). CMAC was first used during World War I to reduce fuel usage. Early CMAC mixtures used petroleum cutbacks, but these were not safe and were later replaced with lower VOC asphalt emulsion by mid-century (Aschenbrener, 2024). The CMAC used today are either cationic or anionic emulsions (depending on aggregate type and chemical makeup, and climatic conditions) and polymer modified binders that help to increase the rut resistance of the mixture and reduce low-temperature cracking (Jain & Singh, 2021). Mix designs are developed to meet Marshall or

Superpave specifications, to ensure optimum void structure through proper aggregate gradation and emulsion content to ensure dimensional control, structural durability, and improve moisture susceptibility control (Meena, Rongmei Naga, et al., 2024).

Today, CMAC is used in wide range of applications from wearing courses for surface maintenance such as chip seals and slurry seals to full-depth cold-mix resurfacing in low-traffic pavements such as rural roads, and in private compounds (Chegenizadeh et al., 2022). In addition to enabling much faster repair (with minimal delay to the schedules due to weather conditions), CMAC allows the incorporation of larger percentages of reclaimed asphalt pavement (RAP) through on-site rejuvenation techniques (Meena, Naga, et al., 2024). These systems can also result in fewer virgin materials used and less construction waste generated. Because of its low production temperature, CMAC reduces the risk of burn, minimizing the exposure of workers to polycyclic aromatic hydrocarbons (PAHs) (Rao et al., 2023). It also lowers smog-producing emissions by up to 90 %, while reducing the capital and operational cost associated with plants and paving equipment.

However, CMAC has certain limitations. It has higher void content (usually 8-12 % as compared to 3-5 % for HMAC), and its early strength is relatively lower due to slower binder curing process (Osman et al., 2024). This makes CMAC susceptible to ravelling and moisture induced damage that occurs under heavy loads during its early service life. Although the use of polymer modified emulsions, amine additives and geosynthetic reinforcement can address these issues, but it increased the material, curing time, and traffic management costs by additional 20-30 % (Hafezzadeh et al., 2021). Storage stability also remains a challenge, because the emulsion separations and sedimentation can take place within days if the mixture is not properly prepared and stored. Due to inconsistent performance of CMAC and lack of sufficient long term field performance data on advanced formulations, their applications in in critical and heavy load pavement structures remains limited (Huang et al., 2020).

Therefore, this study aimed to improve the performance of CMAC by optimizing the proportions of hydrated lime, silica fume, bitumen emulsion and recycled PET fibres using Response Surface Methodology (RSM). Through a designed experiment and predictive modelling of Marshall stability, flow, density, and air-void content, the objectives are to (1) establish an optimal additive mix ratio, (2) compile and analyse performance data across varied formulations, (3) develop an RSM-based predictive model for mixture optimization.

2. COMPONENTS OF CMAC

CMAC consists primarily of coarse aggregates, fine aggregate and fillers materials along with binding materials such as Emulsion or Cutback bitumen. However, what distinguishes CMAC from conventional HMAC is the inclusion of water (IRC SP: 100-2014). Following are the components of CMAC:

2.1. Coarse Aggregate and Fine Aggregate

Coarse aggregate acts as the main skeleton of the asphalt mixture and contributes to its load-bearing capacity, while the fine aggregates fill voids in between the coarse aggregates and enhance workability. Both the aggregates ensure proper interlocking and resistance to traffic induced stresses. The aggregates are to be evaluated for gradation and other physical characteristics to ensure they met the necessary standards for use in cold mix design.

2.2. Bituminous Binders

In CMAC bitumen emulsion and cutback bitumen are usually used in the aggregate mixture to provide strength, cohesion and durability. The mixing is done without heating of bitumen unlike HMAC (IRC SP: 100-2014).

Bitumen emulsion is increasingly preferred over cutback bitumen due to its eco friendliness, ease of application, and lesser carbon dioxide (CO2) emission by eliminating aggregate and bitumen heating (Jain & Singh, 2020). In contrast, cutback bitumen emits harmful volatile compounds and requires longer curing times, making it less sustainable (Ling et al., 2013).

2.3. Filler Materials

Filler materials are fine particles that pass through a 75-micron sieve, typically including materials like rock dust, cement, lime fly ash, or silica fume. In CMAC, filler plays a crucial role despite being in small quantities, usually in the range up to 2% of the weight of dry aggregate as per MoRTH (2024) guidelines. Replacement of conventional fillers with mineral fillers are critical for binding enhancement, stability improvement, moisture resistance and durability

(Al-Hdabi et al., 2013). Filler fills the micro voids and improving the binder aggregate matrix.

2.4. PET Fibres

Studies show that incorporation of synthetic fibres in CMAC mix improves the tensile strength, flexibility, and crack resistance of the mix, contributing to better fatigue performance and longevity (Ferrotti et al., 2014).

3. RESPONSE SURFACE METHDOLOGY

Response Surface Methodology (RSM) is an effective statistical tool used to evaluate the effects of multiple variables. It establishes the relationship between factors (independent variables) and one or more response (dependent variables) using second-order regression models. It captures both linear and nonlinear (quadratic) interaction between factors and variables.

RSM significantly reduces the number of experimental trials needed, saving both time and resources, while still ensuring high prediction accuracy. Furthermore, analysis of variance (ANOVA) helps test the significance of each factor and its interaction (Hamzah et al., 2017; Bansal et al., 2016).

Among various RSM design, Central Composite Design (CCD) is one of the most widely adopted because it effectively models second-order responses and captures both linear and nonlinear (quadratic) interaction by including factorial, axial and centre points.

The relationship between the response and factors is represented by the second order (quadratic) polynomial equation:

$$\boldsymbol{Y} = \boldsymbol{\beta_0} + \sum_{j=1}^{k} \boldsymbol{\beta_j X_j} + \sum_{j=1}^{k} \boldsymbol{\beta_{jj} X_j}^2 + \sum_i \sum_{<j=2}^{k} \boldsymbol{\beta_{jj} X_i X_j} + \boldsymbol{e_i} \quad (1)$$

Where,

β_0 = Regression Coefficient

Y = Predicted Response

X_i and X_j = Factors

e_i= Random error

4. METHODOLOGY

4.1. Materials Selection

The performance and durability of CMAC depends on the proper selection of raw materials. The mix design process began with selecting appropriate aggregates, bituminous binders, fillers, and performance enhancing additives such as PET fibres as shown in Fig.1. Each component contributes significantly to ensuring the structural integrity and longevity of the pavement.

a. Coarse aggregates

For this study, granite coarse aggregate of size 20mm downgrade and fine aggregate (crusher dust) were locally sourced from Toorsa Crushing Plant, Phuentsholing, Bhutan. The aggregates were selected based their required physical quality in line with the standard specifications for effective interlocking and resistance to disintegration under traffic load and cost efficiency.

b. Bituminous Binders

For the study, a medium-setting cationic emulsion was used. The emulsions conform to all the standards of IS 8887. Research shows that cationic emulsions improve coating quality, enhance workability and increase resistance to moisture related issues, thereby leading to better performance (Ling et al., 2013). Additionally, this emulsion is locally produced in Pasakha, Phuentsholing, Bhutan, making it a convenient and sustainable choice for the project. For this study, bitumen emulsion was added in the range from 7% to 10% by weight of dry aggregate recommended in MoRTH (2013) guidelines.

c. Filler Materials

Silica fume was selected to improve the density, moisture resistance and durability of CMAC through its void-filling ability and enhance binder aggregate adhesion (Al-Zarjawi et al., 2020; Yao et al., 2013). Hydrated lime was introduced to improve adhesion, reduce moisture damage and delay bitumen aging to enhance the durability and service life of CMAC (Nazirizad et al., 2015).

Based on the literature, Silica fume and Lime of content 2% by weight of dry aggregates was used (Deb and Singh, 2021; Al-Hdabi et al.,2013; Buczynski and Iwanski, 2017; Thanaya et al.,2007).

d. PET Fibres:

To further enhance the mechanical properties of the CMAC, PET (polyethylene terephthalate) fibres were incorporated in the mix. The PET fibres used for this study were locally sourced from Clean Bhutan, Thimphu. The addition of PET fibres promotes sustainability by incorporating the recycled plastic waste. This practise aligns with environmentally friendly construction approaches. Based on prior studies, PET fibres of size 40 microns in diameter and length of 14mm was used for his study and in the percentage of 0.1 to 0.35 % by weight of dry aggregates was used (Deb & Singh, 2021).

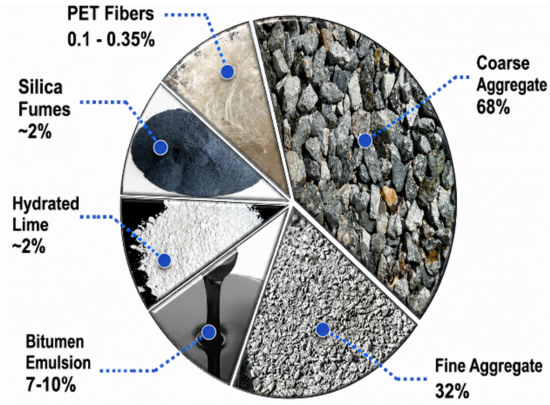

***Fig. 1:** Components of CMAC*

e. Material Testing

According to Indian Roads Congress (IRC: SP:100, 2014), understanding aggregate mineralogy and it effects on emulsion-based mixes is essential for ensuring durable and high performing asphalt pavements. The composition and interactions of aggregates with different emulsions, along with various quality tests of both aggregates and emulsion can determine their suitability for cold mix applications. Different aggregate properties influence mixed behaviour and must be considered during design. High quality raw materials, including aggregates, filler and binders, have a high impact on the pavement performance. This quality control measures ensure compliance with specifications and long-term pavement performance. Tabulated below is the list of Quality Test performed on aggregates: The outlook of the developed software is shown in Fig. 2 and Fig. 3. Fig. 4 shows the display of the result the user will get.

4.2. Aggregate Gradation and Blending

Aggregate gradation is essential for achieving a dense, well graded mix that provides strength, durability and workability in CMAC. A sieve analysis was conducted for coarse aggregate, fine aggregate and filler materials following IS 2386 standards and ensuring compliance with MORTH (2013) and IRC SP: 100 (2014)

Initial sieve analysis of course and fine aggregate samples from stockpile did not meet the required gradation set by the standard guidelines. To rectify this, aggregate blending was carried out using a trial and error method to achieve the required gradation for strength, workability and durability for flexible pavement. Through this process, the optimal blend ratio of 68 % coarse aggregate and 32% fine aggregate was determined confirming to the gradation requirements as shown in Fig.2. The resulting gradation curve from this blend ratio successfully met all specified limits across all sieve sizes as shown below in the

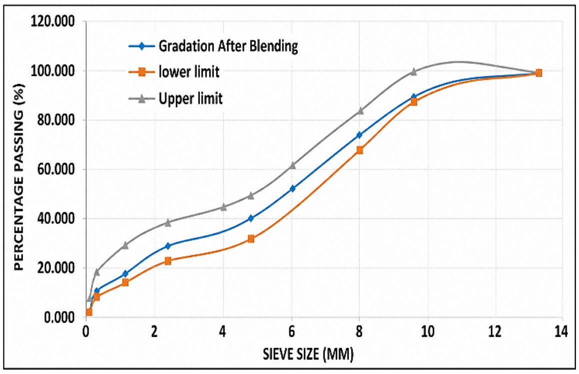

***Fig. 2:** Gradation Chart after aggregate blending*

4.3. Design Experiment with RSM

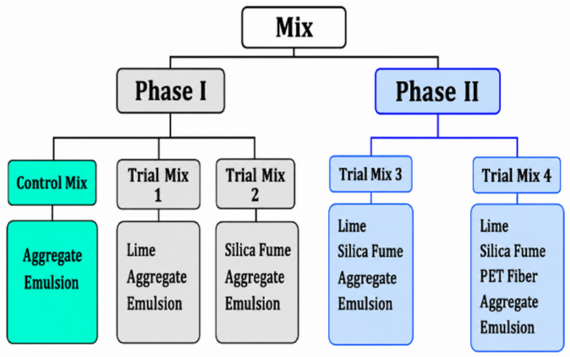

***Fig. 3:** Details of Phase Testing.*

RSM was used to design and optimize the CMAC mix. It was used to find the best mix of lime, silica fume, PET fibre and bitumen emulsion for improved strength, durability and workability. The selection of factors and their respective ranges for phase testing was based on preliminary investigation and a review of existing literature. As illustrated in Fig 3, the experimental design was divided into four trial mixes to systematically evaluate the individual and combined effects of the additives on CMAC performance.

A control mix was first prepared without additives, using only aggregates and bitumen emulsion to establish the baseline strength of CMAC. The control mix was used as a reference for comparison with subsequent trial mixes, to evaluate performance improvement after the incorporation of mineral fillers and PET fibres.

The experiment was performed in two phases. *Phase I* evaluated the individual effects of hydrated lime and silica fume with aggregate and bitumen emulsion to determine their optimum dosage. *Phase II* investigated the combined effects of hydrated lime, silica fume and recycled PET fibre to assess their combined effects on mechanical and volumetric properties of CMAC, to ultimately select the optimum mix design.

The Factors and Response variable considered in this study are presented in the *Table 1.*

Table 1: *Factor and Response Table*

Factors/Independent Variables	Responses/Dependent Variables
Aggregate	Marshall Stability
Bitumen	Marshall Flow
Lime	VFB
Silica Fume	Air Void
Pet Fibre	

The selected factors (aggregate, bitumen emulsion, hydrated lime, silica fume and recycled PET fibre content) were chosen because they significantly influence the mechanical, volumetric and durability of CMAC. The response variables (Marshall Stability, Marshall flow, void filled with bitumen (VFB) and air voids) were selected as standard MORTH(2013) performance indicators to evaluate strength, deformation behaviour, binder effectiveness and mix durability.

a. Experimental Runs

A total of 14 experimental runs for each trial mix

$$P = (0.05A + 0.1\,B + 0.5\,C) \times 0.7 \qquad (3)$$

1 & 2 and 20 and 30 experimental runs for trial mix 3 and 4 respectively were generated. The number of experimental runs in RSM was determined automatically by Central Composite Design (CCD) based on the number of independent factors. CCD generated an experimental matrix comprising factorial points, axial points and central points, with total numbers of run given by the following formula.

$$N = (2^k + 2k + 1) * r \qquad (2)$$

Where,

N = Number of experimental run
k = Number of factors
r = Number of replication factor

In each run, CMAC specimens were prepared by varying the contents of factors as per the design matrix. Number of specimens prepared for each trial mixes are presented in Table 2.

Table 2: *Numbers of Specimen*

Trial Mix	No. of Mix Ratios	Specimen (nos.)
Control Mix	5	5
Phase I		
Trial Mix 1	14	28
Trial Mix 2	14	28
Phase II		
Trial Mix 3	20	40
Trial Mix 4	30	60
Total	**83**	**161**

These specimens were tested according to MORTH (2013) standards using the Marshall method to record the measurement of responses. The experimental results were fed into the RSM model for analysis. RSM was then used to develop predictive models, evaluated the influence of individual factors, and optimized the mix for maximum Marshall Stability while ensuring that the other responses remained within acceptable limits. The predicted optimum mix was subsequently validated through laboratory testing to verify the variance between predicted and obtained values.

4.4. Laboratory Mixing and Testing

Laboratory mixing is a crucial step in the development of cold mix asphalt concrete (CMAC) designs. Unlike hot mix asphalt concrete (HMAC), CMAC involves mixing at lower temperatures, requiring additional considerations and parameters as discussed below. This study followed Modified Marshall method as per Indian Road Congress (IRC SP 100-2014) and the Ministry of Road Transport and Highways (MoRTH, 2013) guidelines, which are based on Asphalt Institute Manual Series 14 guidelines.

The main modification this study implemented is the elimination of the step requiring both soaked stability and wet stability tests for done to find the Optimum Total Liquid Content (OTLC). Instead, following Thanaya's (2007) recommendation, the study conducted only the soaked stability test for each Residual Bitumen Content (RBC) and determine the dry stability value at the Optimum Residual Bitumen Content (ORBC). This approach, as suggested by Thanaya (2007), simplified the design process while enhancing efficiency and cost-effectiveness.

- ***Sample Preparation:*** Aggregates and fillers (lime/Silica fume) were blended based on the optimal 68:32 coarse to fine ratio ensure dense grading and effective binder coating.
- ***Compaction Method:*** The Marshall compaction method was used, where 50 blows were applied to each side of the sample to achieve the required density, as outlined in IRC:SP:100-2014.

a. Cold Mix Design Procedure

The Ministry of Road Transport and Highways (MORTH) provide a systematic approach for designing bituminous cold mixes. The key steps followed for the study as listed below:

i. Determination of Initial residual bitumen content (IRBC) and Initial Emulsion Content (IEC)
ii. Determination of Optimum pre-wetting water content (OPWC)
iii. Determination of Residual Bitumen Content (RBC)
iv. Determination of Optimum Residual Bitumen Content (ORBC)
v. Determination of Initial Residual Bitumen Content (IRBC) and Initial Emulsion Content (IEC)

The initial step in designing a Cold Mix Asphalt (CMA) mixture involves determining the Initial Residual Bitumen Content (IRBC). IRBC is the amount of bitumen that remains in the asphalt after the initial mixing process. It is a crucial factor in determining the initial strength of an asphalt mixture. IRBC values was determined using an empirical formula (1) as per Asphalt Institute 1989:

Where,

P = Total binder requirement as a percentage by mass of the combined dry aggregates (%)

A = Percentage of dry aggregates greater than size 2.36 mm (%)

B =Percentage of dry aggregates passing sieve size 2.36 mm and retained on a 75-micron sieve (%)

C = Percentage of dry mineral filler passing a 75micron sieve (%)

Since CMA utilizes bitumen emulsions, which consist of bitumen, water, and emulsifiers, it's essential to convert the IRBC value into the corresponding amount of emulsion needed. This amount of emulsion is referred to as the Initial

$$IEC = \left(\frac{P}{X}\right) \times 100\% \qquad (4)$$

Emulsion Content (IEC). In other words, IEC represents the amount of emulsion needed to achieve the desired IRBC and was computed as:

Where,

P = Total binder requirements as a percentage by mass of the combined dry aggregates (%)

X = Percentage of bitumen content in emulsion (%)

These IEC values were further used to estimate the optimum pre-wetting water content (OPWC).

Determination of Optimum Pre-Wetting Water Content (OPWC) with Coating Test

The coating test was performed to find the Optimum Pre-Wetting Water Content (OPWC) by blending dry aggregates and filler with varying water contents, followed by mixing with the calculated IEC value and mixed thoroughly for about 2 to 3 minutes. The goal was to achieve a uniform and workable mix with at least 50% surface coating. For this study, the OPWC was found to be 2% by weight of dry aggregate.

Variation of Residual Bitumen Content (RBC) with soaked stability test

To evaluate the effect of Residual Bitumen Content (RBC) on CMAC stability, RBC was varied between 7% and 10% as per MoRTH (2013) guidelines, with 1 % increments. Specimens were prepared with 2 % OPWC and compacted with 50 Marshall blows on each side, then cured in mould for 24 hours, oven cured for at 40°C for 24 hours, followed by room temperature curing for 24 hours.

After curing, samples underwent 48 hours capillary soaking, followed by Marshall-Soaked Stability test at room temperature. This test helped assess mix performance in saturated conditions. The results were used to identify Optimum Residual Bitumen Content (ORBC).

Determination of Optimum Residual Bitumen Content (ORBC)

The Optimum Residual Bitumen Content (ORBC) was identified by evaluating Soaked stability, air voids, dry density and flow values across various RBC values. The goal was to achieve maximum Marshall stability while meeting all CMAC design standards specified by MORTH (2013, 5th Revision) and IRC SP:100-2014 as mentioned in Table 3.

***Table 3**:Specification Table for CMAC*

Properties	**Standards** (IRC SP :100-2014 & MoRTH 2013)
Marshall-Soaked Stability (KN)	2.2
Flow (mm)	2 to 8
Air Voids (%)	6 to 10

For Control mix, the ORBC was identified by plotting performance parameters (air voids, dry density, stability, flow) against varying RBC levels to visually identify the optimum point. Literature recommends that if either soaked stability or air voids fail to meet the required criteria, the compaction level should be increased to achieve the necessary specifications (Thanaya, 2007). For Trail Mix 1, 2, 3 & 4, ORBC was determined using numerical optimization employing Response Surface Methodology (RSM) analysis.

5. RESULTS AND DISCUSSION

Control mix obtained the Marshall stability of 3.2 kN which is slightly greater than the minimum required specified by MoRTH (2013) of 2.2 kN, but comparatively less for high traffic application. This served as the baseline for subsequent experimental trials. The detailed experimental results are presented in the Table 4.

***Table 4** : Control Mix Data Sheet*

Properties	**Residual Emulsion Content**
Maximum Stability	7.20%
Maximum Dry Density	7.70%
% Air Voids	7.20%
Optimum Residual Emulsion Content	**7.37%**
Flow for Optimum Residual Emulsion content is **3.2 mm**	

5.1. Analysis of Response

a. Trial Mix 1

The response surface and contour plots in Fig.4 and Fig.5. show that Marshall Stability increase with increasing lime and bitumen emulsion contents up to an optimum range. The M arshall Stability is highest ~6.0 kN when it contains 1.2–1.4% lime and 8.6–8.8% emulsion. This improvement can be attributed to the enhanced adhesion between aggregates and bitumen emulsion provided by hydrated lime. Beyond this range, Marshall stability gradually decreases because excessive lime increases mixture stiffness or insufficient emulsion reduces aggregate binding.

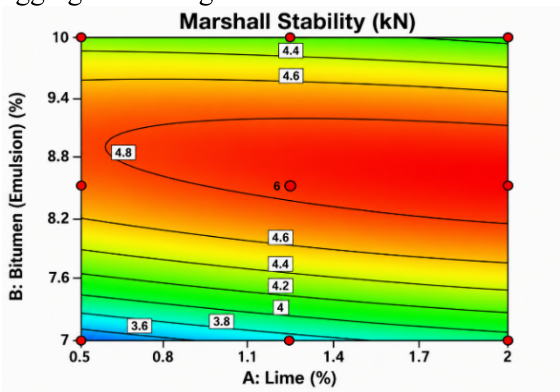

***Fig. 4**: Contour plot of Marshall Stability vs Lime & Bitumen.*

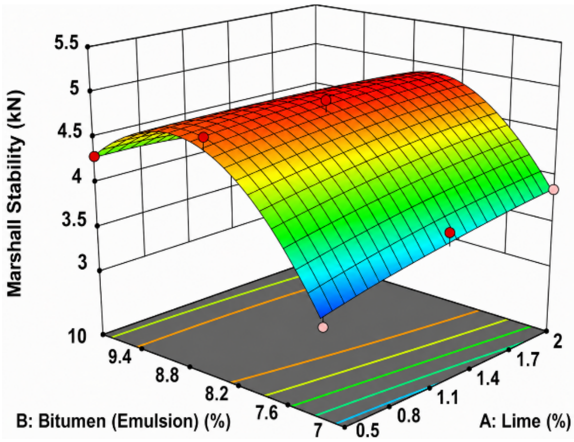

***Fig. 5:** 3D surface plots of Marshall Stability vs Lime & Bitumen.*

b. Trial Mix 2

For Trial Mix 2, from the Fig.6 and Fig.7, Marshall Stability peaks at ~4.9 kN at around 1.8% silica fume and 9.6% emulsion. Silica fume acted as micro-filler by filling voids and strengthening the asphalt, thereby improving the load bearing capacity of the mixture. However, Stability decreases when silica fume content fall below 0.6% or exceed 1.8%, indicating that insufficient filler failed to improve the matrix while excessive filler increased stiffness and reduced workability leading to poor compaction. This plot helps in identify the optimal values of the factors.

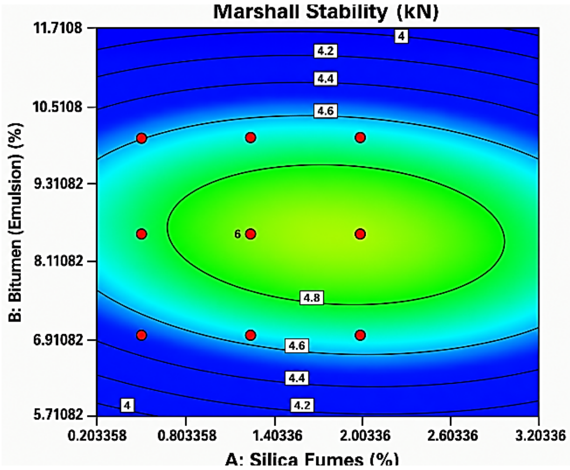

Fig. 6: Contour plot of Marshall Stability vs Silica Fumes & Bitumen

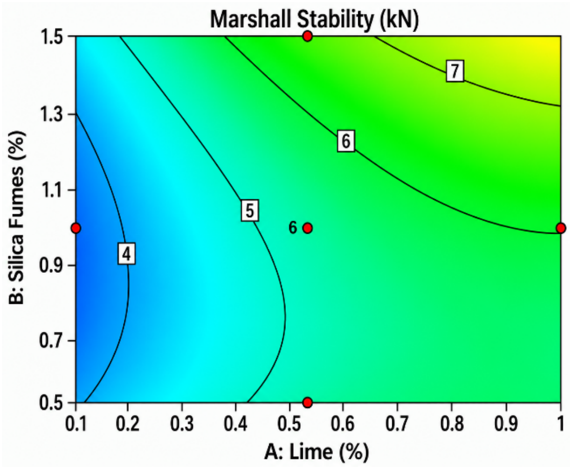

Fig. 8: Contour plot of Marshall Stability vs Silica Fumes & Lime

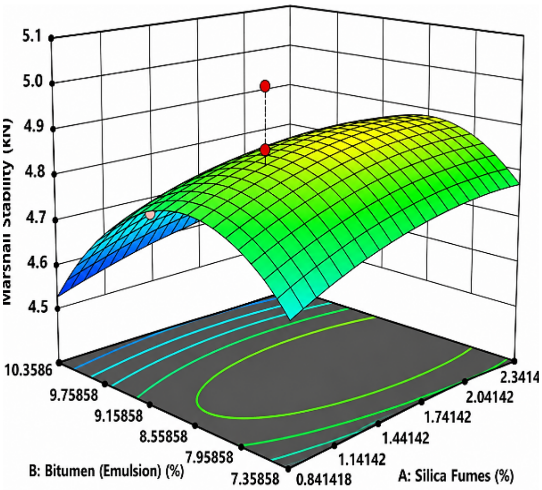

Fig.7: 3D surface plots of Marshall Stability vs Silica Fumes & Bitumen.

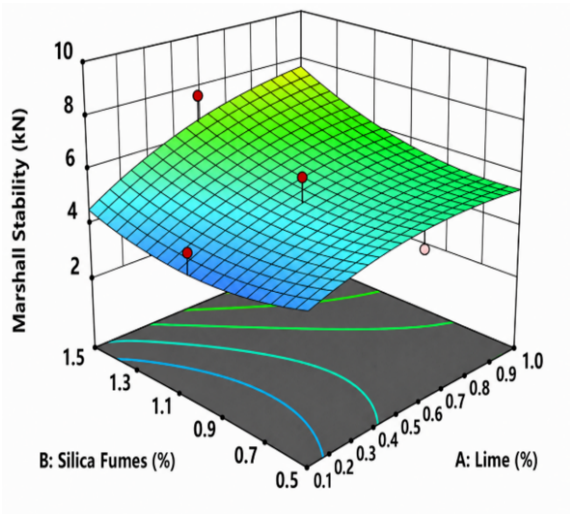

Fig. 9: 3D surface plots of Marshall Stability vs Silica Fumes & Lime.

c. Trial Mix 3

For Trial Mix 3, the response surface indicated in Fig.8 and 9, highest Marshall Stability occurred when lime ranges from 0.5 to 0.6 %, bitumen emulsion is within 8.8 to 9.0 % and silica fume between 1.0 to 1.2 %, together with balanced lime levels. Within these combination range, hydrated lime improved aggregate-bitumen adhesion, silica fume filled the micro-voids and sufficient emulsion provided effective coating of the aggregates. The combined action of these materials produced a dense and well bonded mixture, resulting in maximum stability.

d. Trial Mix 4

From the Fig.10 and Fig.11, Marshall Stability reaches ~7 kN when the mixture contained about 0.5% lime, 0.8% silica fume, 0.2% PET fibre, and 8.8–9.0% emulsion. This balanced combination of silica fume, lime and PET fibres enhances bonding, density, and strength. If any of these factors decreases or increases beyond their optimal range, stability decreases because of poor fibre dispersion, excessive stiffness or inadequate binder coating.

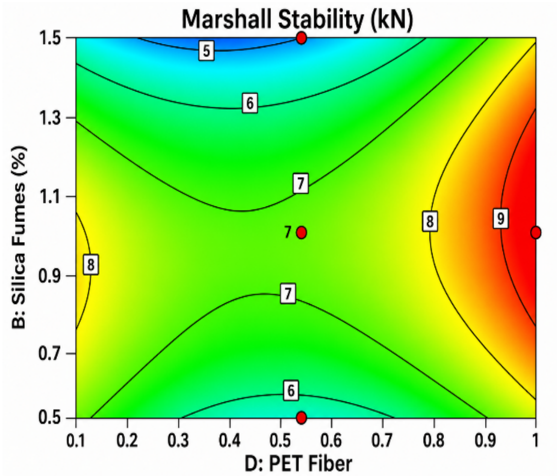

***Fig 10**: Contour plot of Marshall Stability vs Silica Fumes & PET Fibre*

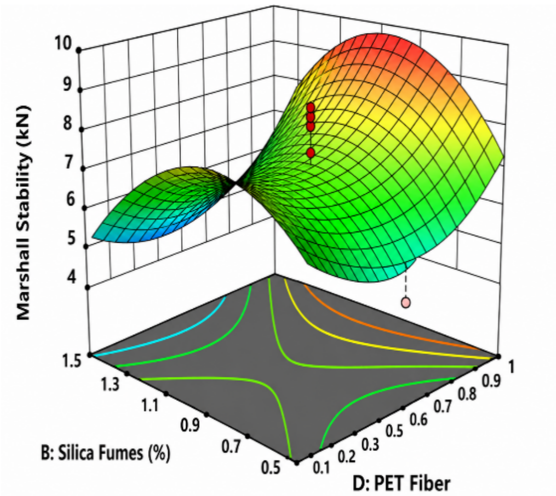

***Fig. 11:** 3D surface plots of Marshall Stability vs Silica Fumes & PET Fibre*

5.2. Statistical Analysis of response

The ANOVA results indicate that the developed models for Marshall Stability in Trials Mixes 1 to 4 are statistically significant, with high *F-values* (71.88, 4.58, 4.70 and 2.95) and very low *P-value*, suggesting that the likelihood of these results occurring due to random noise is extremely low (0.01%). Further analysis confirms that all inputs factors Lime, Silica Fume, PET Fibre and Bitumen Emulsion have significant effects on Marshall Stability (*P<0.05*). Furthermore, the nonsignificant Lack of Fit (LOF) test shows that the developed quadratic regression model is adequate to represent the experimental data and could reliably predict Marshal Stability for Optimization of CMAC,

5.3. Regression Model Interpretation

The final regression models, based on the significant influencing factors, are represented by the following second order (quadratic) polynomial equations. Thess equations defines the relationship between the independent variables and Marshall stability.

a. Trial Mix 1

$$Marshall\ Stability\ (kN) = -26.06663 + 1.53098A + 6.84556B - 0.055948A^2 - 0.380654B^2 - 0.151111AB$$

Here, A and B are the represent the percentage of Lime and Bitumen respectively used in CMAC.

The regression model from Trial Mix 1 indicates that both lime and bitumen emulsion positively influence Marshall Stability up to an optimum level, with bitumen emulsion having significant effect due to higher positive coefficient. The negative coefficients indicate that the increase in Marshall stability continues only up to optimum level after which it decreases due to increased stiffness and reduced aggregate interlocking

b. Trial Mix 2

$$Marshall\ Stability\ (kN) = -2.40278 + 0.444444A + 1.62111B - 0.08A^2 - 0.093333B^2 - 0.017778AB$$

Here, A and B are the percentage of Silica Fume and Bitumen respectively used in CMAC.

The regression model for Trial mix 2 shows that both silica fume and bitumen emulsion improve Marshall stability up to optimum range. The negative quadratic coefficients confirm the input of additives beyond the optimum range will likely reduce the Marshall Stability.

c. **Trial Mix 3**

The regression model for Trial mix 3 shows that lime exhibits the most significant positive effect on Marshall Stability due to higher coefficient, while emulsion also contribute positively. The positive interaction between lime and silica fume (AB) indicates that both contributes to improve the mixture. The negative interaction between lime and bitumen (AC) suggests that excessive quantities of these materials reduce stability while interaction between silica fume and bitumen (BC) has only minor effect.

$$Marshall\ Stability\ (kN) = -9.08493 + 15.92501A - 2.89092B + 2.52652C - 2.39098A^2 + 2.77778B^2 - 0.096744C^2 + 1.64276AB - 1.44675AC - 0.263052BC$$

Here, A, B and C are the percentage of Lime, Silica Fume and Bitumen, respectively used in CMAC.

d. Trial Mix 4

$$Marshall\ Stability\ (kN) = -2.77449 - 15.60586A + 12.84570B + 2.86891C - 29.21204D + 8.24581A^2 - 7.62111B^2 - 0.268189C^2 - 5.51080D^2 + 2.33021AB + 0.726881AC - 1.30557AD + 0.188819BC - 4.83989BD + 3.97719CD$$

Here, A, B, C and D represent the percentage of Lime, Silica Fume, Bitumen and PET Fibre used in CMAC.

The regression model for Trial mix 3 shows that silica fume and bitumen emulsion (BC) positively improve Marshall stability, whereas excessive lime and PET fibre (AD) reduces stability. The positive interaction between lime and silica fume (AB) indicates their complimentary effect in strengthening the CMAC. Similarly, positive interaction between bitumen emulsion and PET fibre (CD) shows that adequate binder improves fibre dispersion and reinforcement. Negative interaction between silica fume and PET fibre (BD) suggests that excessive amount of both materials reduce mixture workability and compaction and thus reduces Marshall Stability.

The developed regression models demonstrated good predictive capability and accurately represented the relationship between mix variables and Marshall stability. This regression models also provide a practical mathematical tool for predicting Marshall Stability and optimizing the composition of CMAC.

5.4. Optimization of the Trial Mixes

An optimization test was conducted to find the optimal amounts of lime, silica fume, PET Fibre and bitumen emulsion. The goal for this mix was to ensure high stability, better consolidation and less voids. To determine the optimal mix, second-order polynomial models was used within the set parameters range as shown in Table 5.

A validation test was conducted by preparing two specimens for each trial mix under room temperature. The experimental results closely matched the RSM model predictions, confirming the model's accuracy as shown in Fig.12.

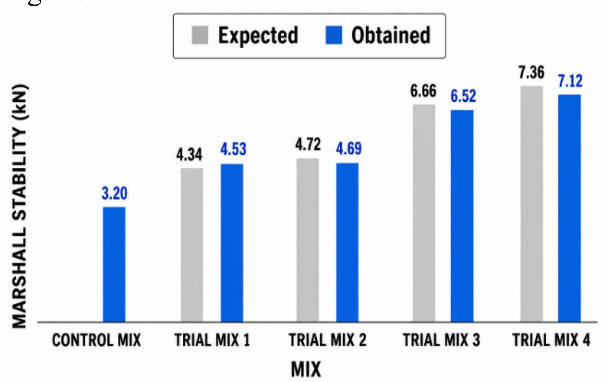

***Fig 12**: RSM Model Predictability: Experimental vs Predicted Marshall Stability*

6. CONCLUSION

The study went on to prove the successful application of Response Surface Methodology (RSM) with Central Composite Design (CCD) for optimizing cold mix asphalt concrete (CMAC) containing hydrated lime, silica fume and recycled PET fibres. The results showed that composite utilization of the materials will improve the mechanical characteristics and the overall quality of CMAC using aggregate–binder interaction, decreasing voids, and enhancing the matrix of the pavement material. In addition to material optimization, the application of statistical optimization to sustainable material engineering highlights the promise of synergizing the design of materials and exploring novel pavement system structures for a more systematic, efficient, and evidence-based pavement mix design. Effective and practical predictive framework was developed to serve as decision support tool for the engineers to minimize conventional trail-and-error approach for design and to improve design efficiency. Also, the use of recycled and industrial by-products will help make more environmentally friendly build-up of pavements and create an approach that can be used in making future additional pavements and applications in sustainable pavement engineering in the framework of CMAC.

Table 5: Optimum Value of CMAC Mix Parameters

Variables	Phase 1		Phase 2	
	Trial Mix 1	**Trial Mix 2**	**Trail Mix 3**	**Trial Mix 4**
Lime (%)	0.50	0.00	1.00	1.00
Silica Fume (%)	0.00	0.5	1.50	1.03
Emulsion (%)	9.97	9.30	9.45	9.36
PET Fibre (%)	0.00	0.00	0.00	0.31
Model prediction				
Marshall Stability (kN)	**4.34**	**4.72**	**6.66**	**7.36**
Marshall Flow (mm)	4.42	4.89	2.86	3.07
Dry Bulk Density (g/cm^3)	2.17	2.18	2.19	2.17
Air Voids (%)	6.79	7.73	8.24	9.20
Laboratory Experiment				
Marshall Stability (kN)	**4.53**	**4.69**	**6.52**	**7.12**
Marshall Flow (mm)	4.51	4.32	2.75	2.89
Dry Bulk Density (g/cm^3)	2.21	2.01	2.25	2.15
Air Voids (%)	6.80	7.65	8.34	8.95

7. LIMITATIONS AND RECOMMENDATION

A cost benefit analysis of the optimized mix was beyond the scope of this study. Future studies should incorporate a cost benefit analysis to evaluate the economic feasibility of optimized CMAC along with its engineering performance to support its practical implementation.

Future research should validate the developed RSM model through field trials under actual traffic and environmental conditions to assess its applicability beyond laboratory testing. Additional studies are recommended to evaluate effects of curing temperature, heavy compaction (75 blows) and accelerated aging simulations to assess long-term durability of mixes with recycled PET fibres. Field trials with in-situ monitoring would validate lab-optimized designs under real traffic and climate, while microstructural analysis (e.g., SEM or image analysis) could reveal how silica fume and fibres bond and disperse within the matrix. Furthermore, comparative studies with other sustainable additives (bio-binders, crumb rubber, nanomaterials) together with cost benefit analysis would help identify the most cost-effective and high-performing solutions.

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