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RESEARCH ARTICLE

Performance of bituminous paving mixtures containing recycled concrete aggregate, fly ash and rice husk ash: A probabilistic approach

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Abstract – Due to the rapid increase in construction activities, the depletion of natural resources is accelerating. Extensive research has focused on finding alternative materials to conserve resources and minimize costs. This study explores the utilization of recycled concrete aggregate (RCA) as a substitute for coarse aggregate, along with waste materials like fly ash (FA) and rice husk ash (RHA) as fillers in bituminous paving mixtures. The aim is to address environmental concerns and waste disposal issues. The research evaluates the performance of different filler types in non-conventional bituminous mixtures using VG 30 grade bitumen as a binder, specifically for lower bituminous layers. A typical bitumen concentration of 5% by weight of dense bituminous macadam (DBM) mixtures is chosen based on existing literature. The study assesses various performance characteristics, including Marshall parameters, indirect tensile strength, and moisture susceptibility. A probabilistic approach is employed to determine the most suitable distribution model, focusing on retained stability (RS) as a measure of moisture susceptibility. For this, fifteen distribution functions were considered with three Goodness-of-fit (GOF) tests. To identify the best suitable function, 50 numbers of samples were prepared to find RS with two types of fillers and two types of coarse aggregate. Experimental results indicate that mixtures with natural aggregate exhibit slightly superior performance, but those with RCA meet all the requirements specified in relevant Indian codes and specifications. The probability analysis confirms that the Burr distribution best fits the experimental data, particularly for moisture susceptibility characteristics.

Keywords – RCA, Probabilistic approach, Fly ash, Rice husk ash, Retained stability.

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BACKGROUND

Over the past few decades, the rapid pace of modernization has led to a significant increase in demolition activities and new construction projects. Consequently, this has generated substantial amounts of construction and demolition waste (C&D), posing significant challenges for both society and the environment, particularly when it is disposed of in landfills. However, an alternative approach involves processing and transforming these waste materials into recycled concrete aggregates (RCA), as shown in Figure 1 (Giri *et al.,* 2021). This shift towards reutilization holds the potential to yield remarkable advantages for society. Offering substitute sources of construction aggregates can effectively reduce reliance on finite natural resources. Moreover, this recycling and repurposing of construction waste contributes to the conservation of our precious natural resources and promotes the principles of sustainable development. Currently, in many instances, conventional bituminous pavement mixes make use of crusher dust, cement, and lime as fillers (MoRTH, 2013). However, numerous investigations have been conducted to explore the utilization of waste materials like recycled fine aggregate dust, glass powder, brick powder, sludge ash, waste marble dust, and coal powder waste, alongside conventional fillers, for formulating hot mix asphalt (Mistry *et al.*, 2019). In the contemporary landscape, a substantial volume of waste is generated from sources such as thermal power plants and the agricultural industry in India. Notable examples include fly ash (FA) and rice husk ash (RHA) (Mistry *et al.*, 2016). Although RHA has gained popularity as an alternative material in concrete applications, limited research has been dedicated to exploring its potential as a filler in bituminous mixes. To address this gap, an experimental study was undertaken to investigate the performance of RHA and FA as substitute filler materials in bituminous blends. These blends incorporated both RCA and NA. The study involved the application of the Marshall mix design process with a consistent bitumen content, followed by a comprehensive assessment of the mechanical properties of the formulated mixes.

Further, real-life problems contain uncertainties in counteracting engineering problems. It is required to predetermine an appropriate probabilistic model that is capable of providing the quantification of such uncertainties arising during construction (Ang and Tang, 2007; Conte, 2001, Melchers, 1999). The probabilistic technique is one of the best statistical approaches to identify this random variable at the desired accuracy level.

The probability of failure is a function of the load (P) and resistance (R) effect of the structure, where P and R are random variables.

If R - P is defined as the safety margin, then Pr (R - P > 0) represented through the shaded area in Figure 2 shows the probability of failure.

The quantification of the safety margin of the structure influenced by the probability distribution of R, is affected by various considering factors. The randomness involved makes the problem quite tricky. The tensile strength ratio is taken as the typical parameter to direct the probability distribution of R.

Hence, in the present study attempts to investigate the potential of utilizing RCA and waste materials, specifically fly ash and rice husk ash, as fillers in dense bituminous macadam mixtures (DBM). To establish a benchmark, conventional natural aggregates were also employed in preparing the bituminous specimens. While a study by Showkat and Singh (2022) focused on survival analysis for moisture damage in asphalt mixtures, their analysis solely centred on tensile strength ratio (TSR). Traditionally, the TSR test has been widely employed as the primary criterion to evaluate the susceptibility of bituminous mixtures to moisture-induced damage. Nonetheless, it is also crucial to consider retained stability test (RS) as a significant measure of moisture susceptibility, particularly under extremely high-temperature testing conditions in compression mode. Consequently, this research aims to quantify the moisture susceptibility using a probabilistic approach, specifically by assessing retained stability, for dense bituminous mixtures that incorporate RCA, RHA, and FA.

Figure 1 Recycled concrete aggregates

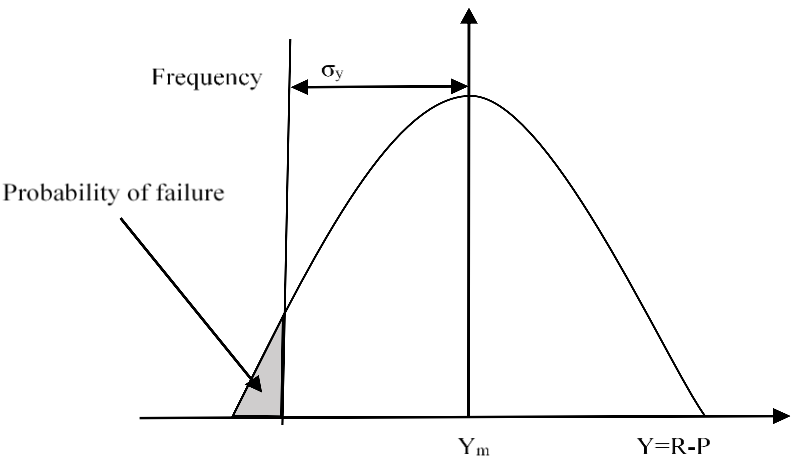


Figure 2 Probability of failure concept

LABORATORY INVESTIGATION

The experimental examination includes a study on the influence of coarse aggregate, bitumen and filler type on the performances of DBM mixtures. In this study, four combinations of mixtures comprising two different types of aggregates (NA and RCA), and two types of fillers (rice husk ash and fly ash) were considered, each mix being made with VG 30 bitumen. These four distinct bituminous mixtures considered in this study were represented as NFA, NRHA, RFA and RRHA. The first letter of the notation represents the coarse aggregate fraction (N- NA and R-RCA) whereas; the succeeding letters represent the filler type (i.e. FA- fly ash and RHA- rice husk ash). The gradation of aggregates of the bituminous mixture considered as per MoRTH (2013) is shown in Figure 4, in which the middle points of the specification ranges concerning a particular sieve size were considered for the preparation of bituminous samples in the present study. The physical properties of all materials used (except FA and RHA) are presented in Tables 1 and 2. The specific gravity for fly ash and rice husk ash was observed in the laboratory to be 2.1 and 1.95 respectively.

MATERIALS

For each category of the mixture, the performance characteristics in the form of Marshall parameters, indirect tensile strength and moisture-induced damage characteristics represented in the form of RS as well as TSR were carried out. The details of the experimental program have been shown in Figure 3 in the form of a flowchart. The Marshall test according to ASTM D1559 is an affordable procedure still being followed in many countries as well as in India for the design of bituminous mixtures. A similar procedure was also considered in the present investigation to prepare different bituminous mixtures with different ingredient materials as mentioned earlier at 5% bitumen content for further performance studies, as the same concentration is generally observed to be more or less optimum in DBM bituminous mixtures. Only one bitumen concentration has been chosen in this study to make a comparative study of bituminous mixtures prepared to enable proper assessment of the influence of the use of waste materials in flexible paving mixes at a preliminary level.

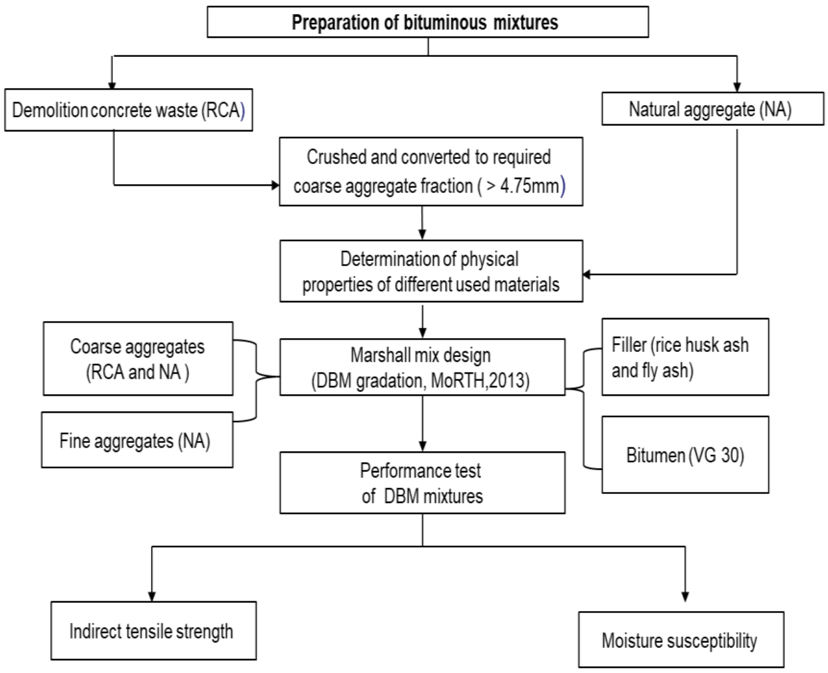


Figure 3 Flow chart of experimental methodology

Table 1. Physical properties of RCA and NA used

Properties	IS Specification	Properties		Recommended value (MoRTH, 2013)
		NA	RCA	
Impact value (%)	(IS 2386-PIV, 1963)	15	26	<30
Crushing strength (%)		14	28	<30
Los-Angeles abrasion (%)		21	31	<40
Flakiness index (%)	(IS 2386-PI, 1963)	21	22	<30
Elongation index (%)		22	24	
Water absorption (%)	(IS 2386-PIII, 1963)	0.28	5.1	<2
Specific gravity		2.68	2.38	—
Stripping (%)	(IS 6241, 1971)	1.5	4.7	<5

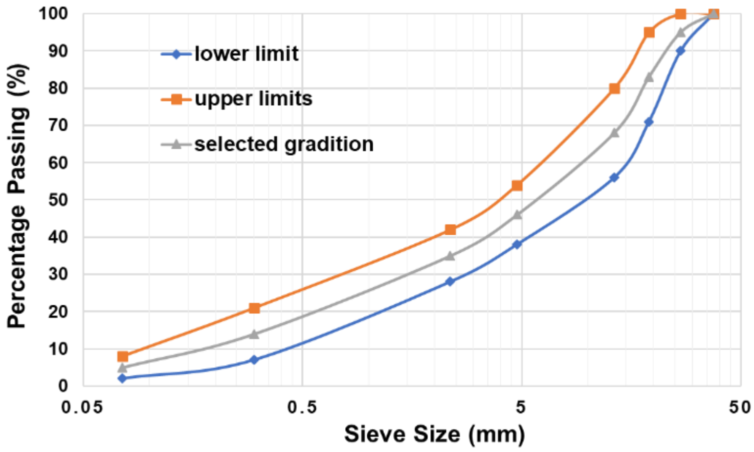


Figure 4 Gradation curve for DBM mixture

Table 2. Physical properties of bitumen used

Properties	IS Specification	Test Observations	Suggested value (IS 73, 2013)
Specific gravity	(IS 1202, 1978)	1.01	> 0.99
Penetration (0.1 mm)	(IS 1203, 1978)	69	> 50
Ductility (cm)	(IS 1205, 1978)	87	> 75
Softening point (°C)		49	> 47
Absolute viscosity (Poise)	(IS 1206-PII, 1978; IS 1206-PIII, 1978)	2645	2400-3600
Kinematic viscosity (cSt)		427	> 350

Tests Performed

Indirect Tensile Strength (ITS) test

The ITS test is taken up in this study according to ASTM D6931, for quantifying the tensile strength characteristics of different HMA mixtures. The ITS test for a specific mixture type was conducted at three different test temperatures such as 15°C, 25°C and 35°C. The normal Marshall specimens were positioned in between two loading strips (Figure 5) under a compressive load in a vertical plane, resulting in a relatively uniform stress perpendicular to the applied loading plane to cause failure of the specimen (Moghaddam et al., 2014). The ITS value was determined according to Eq. (1) given below. In this equation P is the maximum failure load (N), H is the thickness of the test specimen (mm) and D represents the diameter of the specimen (mm).

$$\text{ITS} = \frac{2000 \times P}{\pi \times D \times H} \qquad \text{Eq.(1)}$$

Moisture susceptibility characteristics

Moisture-induced damage in the bituminous mixture is a major reason for distress in bituminous pavements. The moisture susceptibility or resistance to moisture-induced damage of bituminous mixtures is important to realize the ability of adequate bonding between bituminous binder and aggregate in the presence of moisture and temperature (Lee et al., 2012). To assess the resistance of bituminous mixtures to moisture, a parameter called tensile strength ratio (TSR) is generally used as per AASHTO T283 (2014), and the TSR value is calculated using Eq. (2).

$$\text{TSR} = \frac{\text{ITS of conditioned specimen}}{\text{ITS of unconditioned specimen}} \times 100 \qquad \text{Eq.(2)}$$

Another way to indirectly assess the resistance to moisture-induced damage of bituminous mixture is by retained stability test (RS) as per a specified procedure according to ASTM D1075 (2011). The RS value is determined using Eq. (3).

$$\text{RS} = \frac{\text{Stability of conditioned specimens}}{\text{Stability of unconditTioned specimens}} \times 100 \qquad \text{Eq.(3)}$$

Figure 5 ITS test setup

OUTCOME AND INTERPRETATION

MARSHALL CHARACTERISTICS

In Table 3, the Marshall test results were presented and it was found that the mixture made with RCA offers a higher Marshall stability value, but the unit weight was seen to be more for the bituminous mixture than that containing NA as coarse fraction. The higher stability value in the RCA mixture may be because of the rough surface texture resulting in a good bonding between the aggregates in the presence of bitumen. The mixture with RCA has a lower unit weight compared to the mixture prepared with conventional aggregate, which may be due to the presence of cement paste over its surface, as well as its low specific gravity as compared to NA. The mixtures prepared with fly ash as filler material offered improved Marshall parameters as compared to rice husk ash.

It was observed from Table 3 that, all the bituminous mixtures fulfil the required Marshall criteria according to MoRTH specifications (2013), each prepared with a bitumen content of 5%.

INDIRECT TENSILE STRENGTH

The ITS with test temperature for various samples are presented in Figure 6. From the figure, it is observed that the samples made with natural aggregate as coarse aggregate and fly ash as a filler offer superior performance both at lower and higher test temperatures as compared with other combinations. However, the mixture made with RCA and fly ash resulted in nearly similar values. From this ITS observation, it is also observed that fly ash offered better results as compared with RHA as a filler material.

Table 3. Marshall parameters for different bituminous mixtures

Mix	Marshall Stability (kN)	Flow value (mm)	Unit Weight (gm/cc)	Air voids (%)	VMA (%)	VFB (%)
NFA	13.1	3.35	2.483	4.7	16.8	68.6
NRHA	11.9	3.45	2.472	4.9	16.5	66.8
RFA	16.3	3.1	2.337	4.2	15.7	71
RRHA	15.3	3.25	2.328	4.5	15.5	69.7

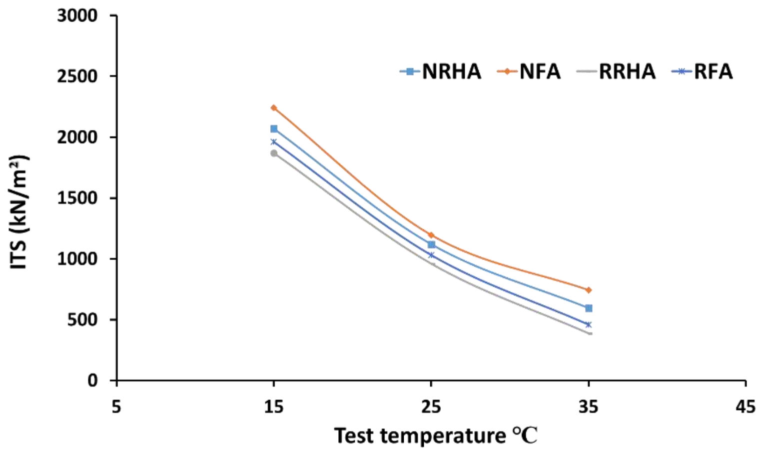


Figure 6 ITS test at various test

MOISTURE SUSCEPTIBILITY CHARACTERISTICS

The results of moisture susceptibility characteristics in terms of TSR for conventional and non-conventional bituminous mixtures are given in Figure 7. It is understood that specimens with NA as coarse aggregates result in higher TSR as compared with samples prepared with RCA. On the other hand, the RCA specimens offered less TSR value as compared with the NA mixture, though both satisfy the minimum value of TSR value according to MoRTH (2013) (TSR value > 80%).

Similarly, in the retained stability test, the mixture compacted with NA and fly ash as filler offers better results as compared with specimens containing RCA or rice husk ash as presented in Figure 8. From Figures 7 and 8, it is generally observed that fly ash offers better moisture-induced damage as compared with rice husk ash as filler material, though rice husk ash satisfies the required moisture susceptibility criteria according to Indian specifications. Based on this RS result of RCA, a further 50 numbers of samples were prepared and the statistical analysis using a probabilistic approach.

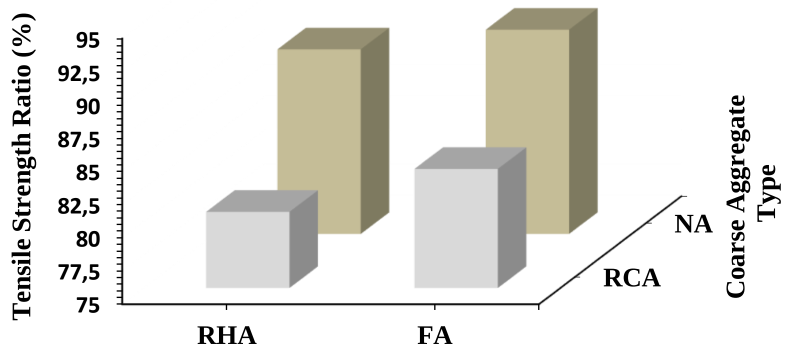


Figure 7 TSR values for DBM mix

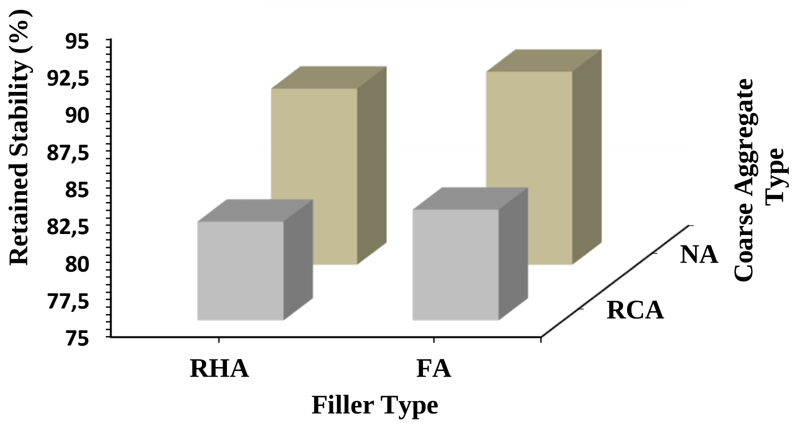


Figure 8 RS values for DBM mix

Table 4. Statistical parameters of RS data

Statistic	RHA	FA
Sample size	50	50
Mean	81.64	82.44
Variance	0.27	0.59
Standard deviation	0.52	0.77
Coefficient of variation	0.01	0.01
Standard error	0.07	0.11
Skewness	1.25	-0.46
Excess kurtosis	5.71	-0.03

VARIABILITY IN RETAINED STABILITY

As moisture-induced damage is an important parameter to characterize a bituminous mixture, in the present investigation a probability analysis was done to confirm the utility of the waste materials in bituminous pavement construction. For this purpose, fifty numbers of specimens were considered, and corresponding RS results adopting the above-mentioned procedure were noted as shown in Table 4. It is found that, the mean values for RHA and FA as filler in the bituminous mixture containing RCA as a coarse fraction were found to be 81.64 and 82.44, respectively. The other statistical parameters are presented in the same table. Statistical analysis is conducted to identify the variabilities of the observed data with the proposed probability distributions. The analysis was done for fifteen selected probability distribution functions taken in the analysis by considering the statistical parameters as represented in Table 5. The best-fit distribution is formed on the recognition basis by Goodness of Fit (GOF) test results by Kolmogorov-Smirnov (K-S), Kolmogorov-Smirnov-Lilliefors (K-S-L) and Anderson-Darling (A-D) at 5% of significance level by rejecting the remaining. The K-S and K-S-L investigations can explain the difference between the observed cumulative distribution function and the hypothesized cumulative distribution function (Benjamin et al., 1970; Hakim et al., 2021). The A-D test is nothing but the modified K-S distribution function. The critical number rests on the size of a sample, and the significance level, and the best-suited fit deliberates as the lower its rank, the higher the statistic of a function [5]. The GOF test results for RHA and FA samples are presented in Table 6. From Table 6 representing the GOF test, it can be noted that the Burr (4P) distribution was found to be most appropriate among all other distributions with a minimum rank for both RHA and FA samples as filler material that can best suit the experimental test results. The Burr distribution is a continuous probability distribution that is often utilized in reliability analysis and survival analysis. It is a flexible distribution that can model a wide range of shapes, including unimodal, U-shaped, and skewed distributions (Lilliefors, 1967).

Table. 5. Parameters for the probability distribution functions

	Distributions	Parameters RHA	Parameters FA
1	Burr	k=0.56407 α=401.78 β=81.418	k=3.5197 α=144.7 β=83.404
2	Burr (4P)	k=0.6637 α=36.655 β=7.8786 γ=73.586	k=53.476 α=6.9308 β=8.4931 γ=77.97
3	Erlang	m=23901 β=0.00342	m=11118 β=0.00741
4	Erlang (3P)	m=60 β=0.06517 γ=77.736	m=521 β=0.03462 γ=64.398
5	Exponential	λ=0.01225	λ=0.01213
6	Exponential (2P)	λ=0.73127 γ=80.272	λ=0.55072 γ=80.627
7	Gamma	α=23902.0 β=0.00342	α=11119.0 β=0.00741
8	Gamma (3P)	α=53.443 β=0.06904 γ=77.948	α=506.92 β=0.03492 γ=64.734
9	Gumbel Max	σ=0.41173 μ=81.402	σ=0.60961 μ=82.091

10	Kumaraswamy	α_1=2.8966 α_2=835.66 a=80.108 b=97.499	α_1=4.8762 α_2=9.3614 a=79.033 b=84.994
11	Log-Gamma	α=4.6672E+5 β=9.4324E-6	α=2.1549E+5 β=2.0475E-5
12	Logistic	σ=0.29114 μ=81.64	σ=0.43106 μ=82.443
13	Lognormal	σ=0.00638 μ=4.4023	σ=0.00941 μ=4.4121
14	Lognormal (3P)	σ=0.13834 μ=1.288 γ=77.979	σ=0.02272 μ=3.5339 γ=48.186
15	Normal	σ=0.52807 μ=81.64	σ=0.78186 μ=82.443

Table. 6. GOF test for RS data of the specimen

	Distribution	RHA				FA			
		K-S and K-S-L		A-D		K-S and K-S-L		A-D	
		Statistic	Rank	Statistic	Rank	Statistic	Rank	Statistic	Rank
1	Burr	0.06931	2	0.25951	2	0.07839	2	0.20763	2
2	Burr (4P)	0.06878	1	0.25594	1	0.07673	1	0.23964	1
3	Erlang	0.1046	8	0.97989	10	0.11563	10	0.51859	8
4	Erlang (3P)	0.09131	4	0.72668	6	0.12102	11	0.58185	11
5	Exponential	0.62591	15	23.13	15	0.62393	15	22.97	15
6	Exponential (2P)	0.37027	14	10.854	14	0.30944	14	7.8749	14
7	Gamma	0.10596	10	0.98783	11	0.1131	7	0.50439	5
8	Gamma (3P)	0.09494	5	0.70428	5	0.12207	12	0.59129	12
9	Gumbel Max	0.11636	12	0.84101	7	0.18232	13	2.6963	13
10	Kumaraswamy	0.13301	13	1.4875	13	0.08216	3	0.26323	3
11	Log-Gamma	0.10494	9	0.96781	9	0.11397	9	0.51493	6
12	Logistic	0.09023	3	0.62914	3	0.11239	6	0.55172	10
13	Lognormal	0.10359	7	0.93324	8	0.11375	8	0.51586	7
14	Lognormal (3P)	0.09907	6	0.67989	4	0.11153	4	0.52505	9
15	Normal	0.10662	11	0.99614	12	0.11184	5	0.48896	4

The focus of this study revolved around analysing the retained stability (RS) as the primary distress parameter. The Burr distribution was selected for the analysis and the probability density function (PDF) and cumulative distribution function (CDF) of the Burr distribution were considered using equations (4) and (5) respectively. These equations involve the parameters of μ (shape), σ (scale), γ (location) and Ø (Laplace integral).

Probability density function

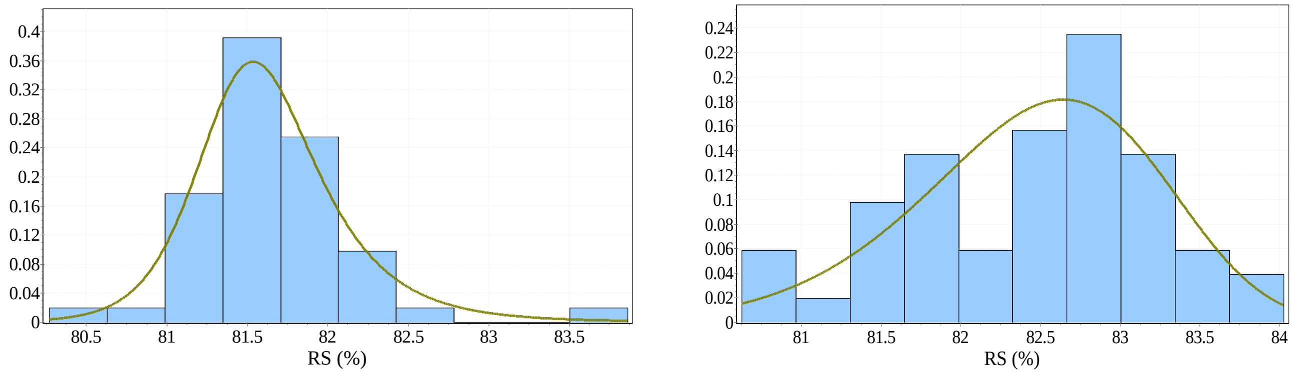
$$f(x) = \frac{\alpha k \left(\frac{x-y}{\beta}\right)^{\alpha-1}}{\beta(1+\left(\frac{x-y}{\beta}\right)^{\alpha})^{k+1}} \quad \text{Eq. (4)}$$

Cumulative distribution function

$$F(x) = 1 - (1+ \left(\frac{x-y}{\beta}\right)^{\alpha})^{-k} \quad \text{Eq. (5)}$$

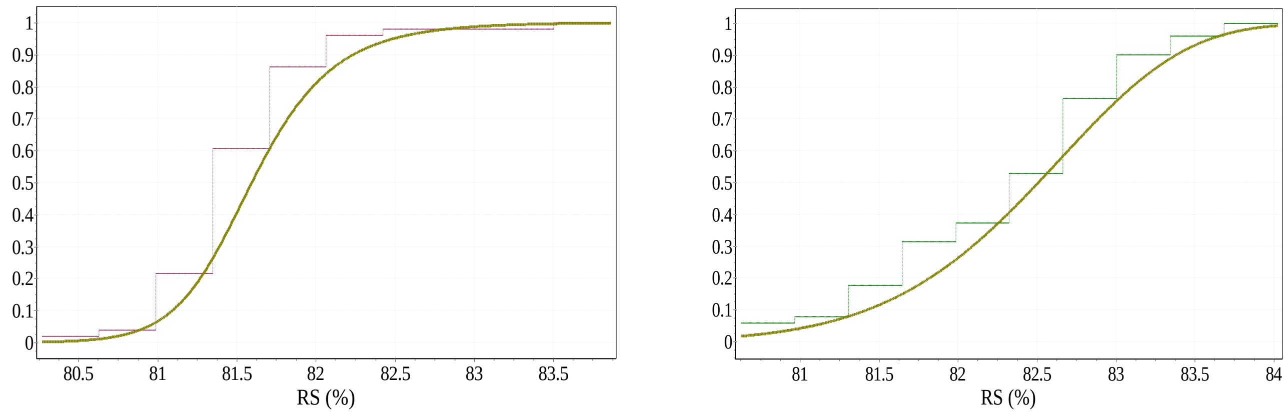
$$\gamma < x < +\infty$$

By using Eq. (4) and (5), the PDF and CDF for RHA and FA were represented in Figures 9 and 10 respective



(a) RHA (b) FA

Figure 9. Probability distribution function plots for (a) RHA and (b) FA

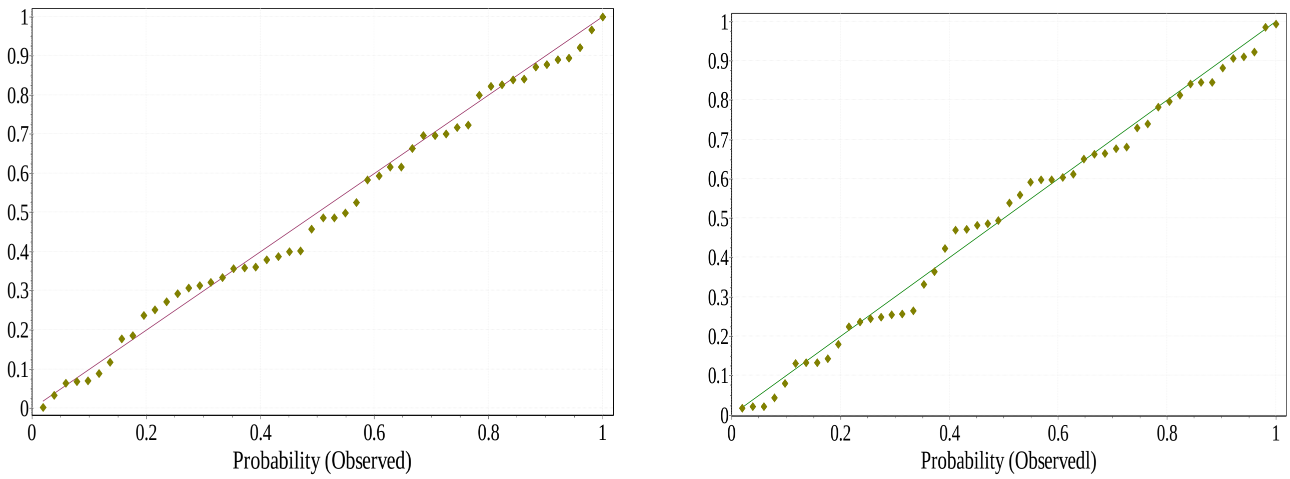


(a) RHA (b) FA

Figure 10 Cumulative distribution function plots for (a) RHA and (b) FA

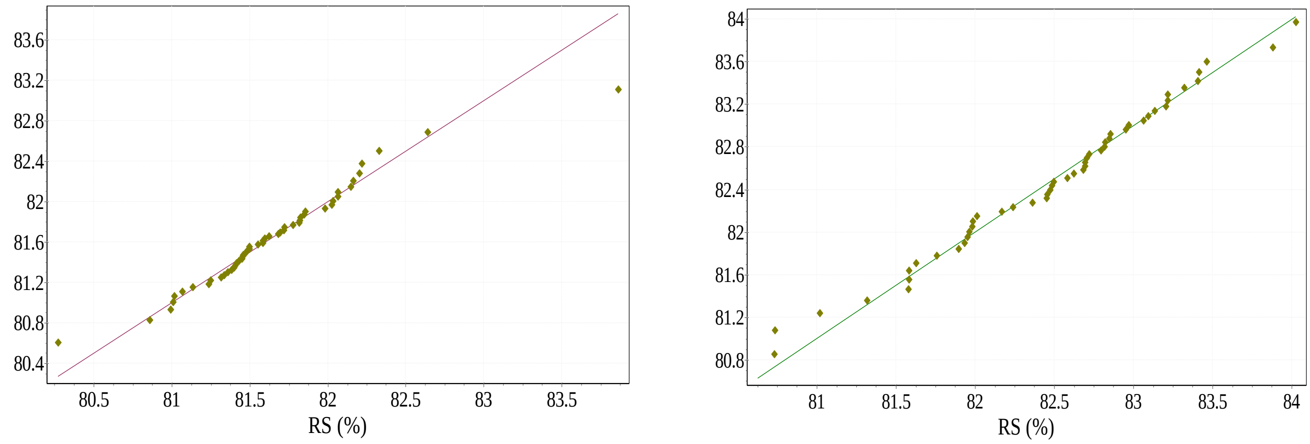
A P-P plot is the probability-probability plot that represents the detected values of CDF drawn against the fitted CDF values, whereas the quantile-quantile as Q-Q plot is a graph that indicates the observed data drawn against the fitted distribution quantiles.

Figures 11 and 12 represent the plots for RHA and FA respectively, drawn at a linear line of 45° indicating that burr distribution predicts the variability of RS taken with significant accuracy both at the centre and at the tail.



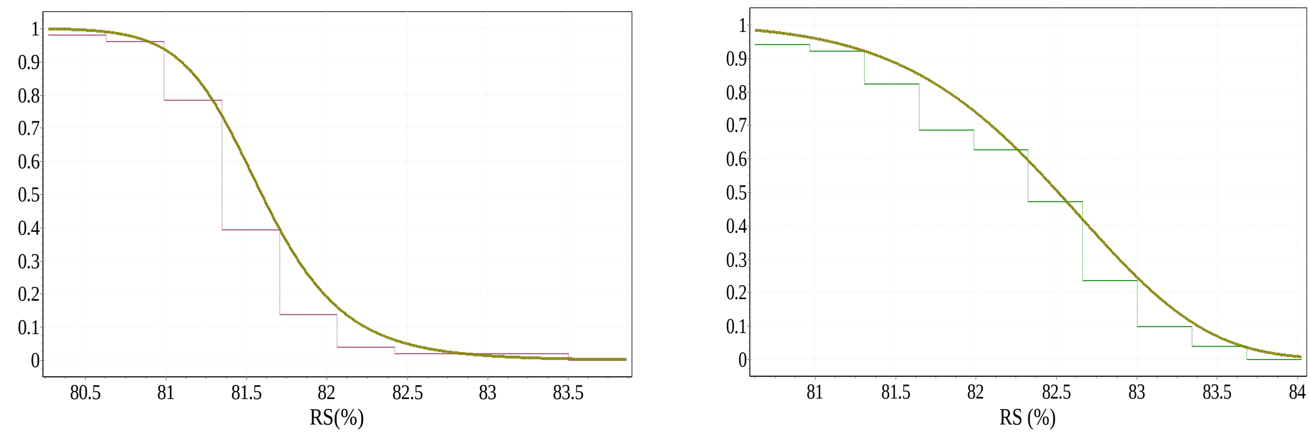
(a) P-P plot (b) Q-Q Plots

Figure 11 Normality plot for RHA



(a) P-P plot (b) Q-Q Plots

Figure 12 Normality plot for FA

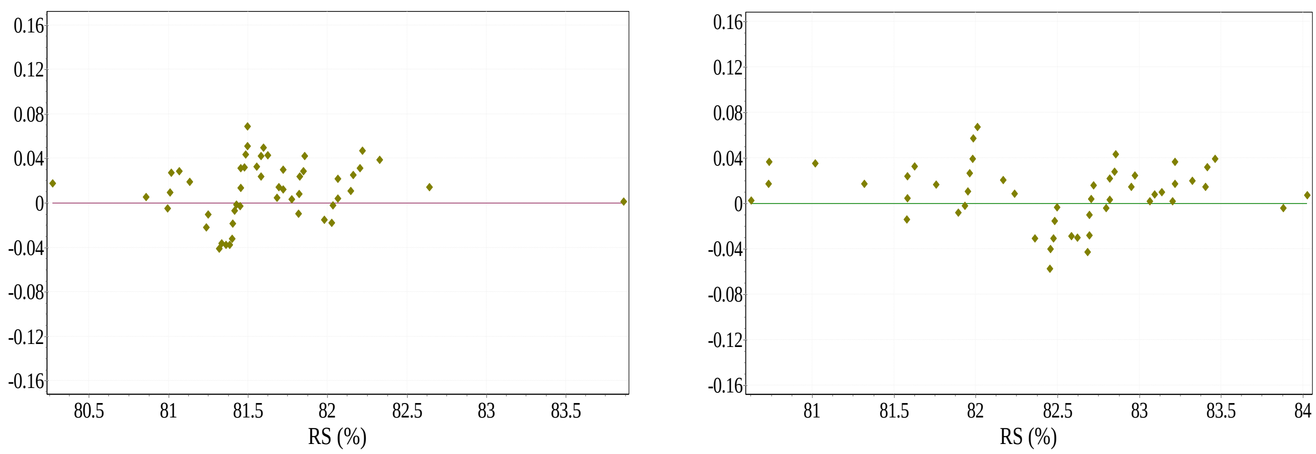


(a) RHA (b) FA

Figure 13 Survival plot for RHA and FA

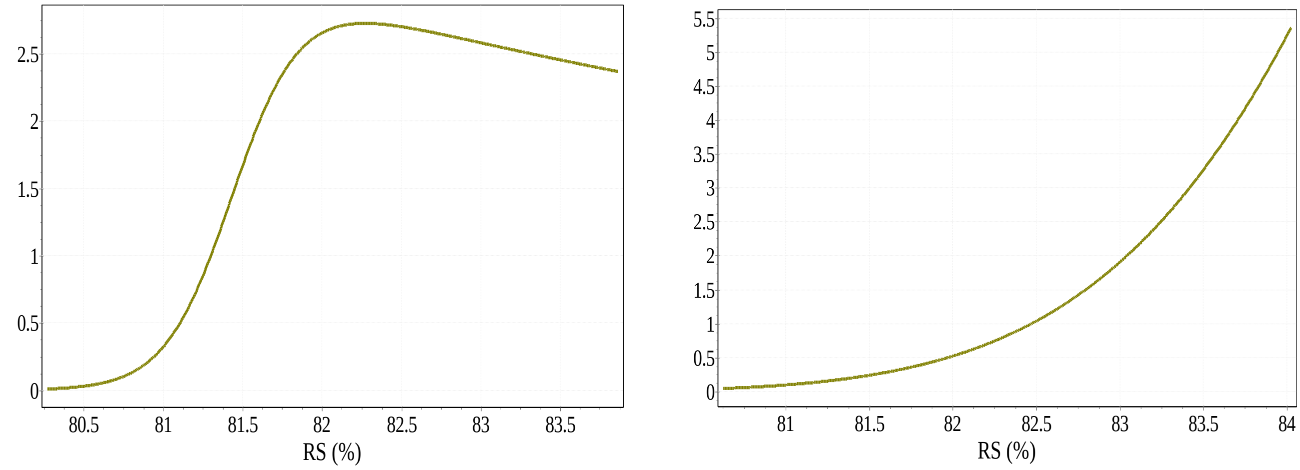
The survival function shown in Figure 13, is a plot to describe the investigational values with a function of chances as expressed in Eq (6).

$$S(x) = P(X > x) = 1 - F(x) \qquad \text{Eq. (6)}$$



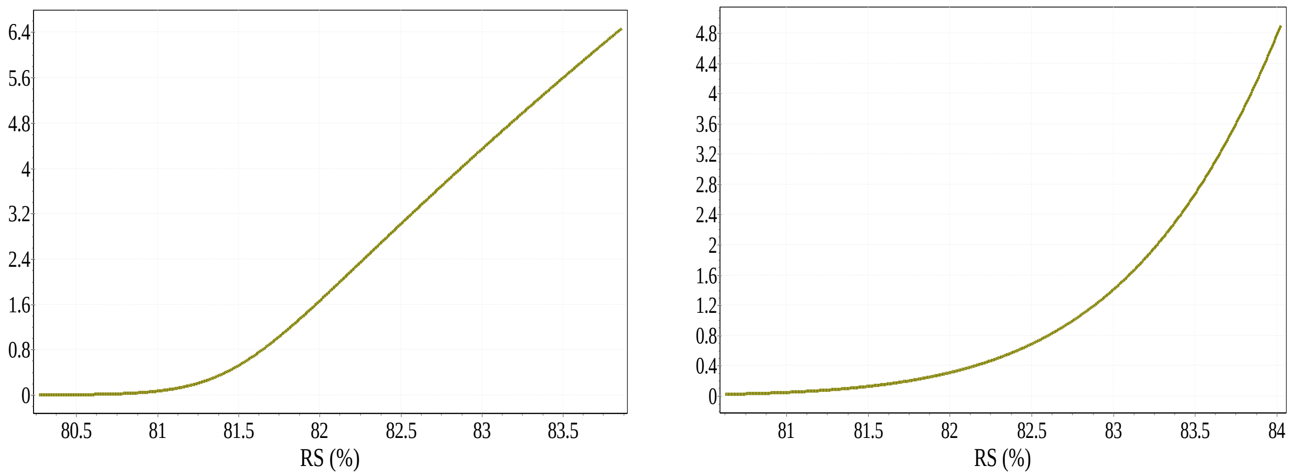
(a)RHA (b) FA

Figure 14 Probability difference plot with Burr distribution



(a) RHA (b) FA

Figure 15 Hazard function plot with burr distribution



(a) RHA (b) FA

Figure 16 Cumulative hazard function drawn with burr distribution

Figure 14 shows the probability difference plot that depicts the variance of observed CDF and the fitted CDF value with burr function was less than 0.06 for both RHA and FA samples. In reliability analysis, the two significant parameters used as the hazard function and cumulative hazard function were also drawn for RHA and FA samples, as presented in Figures 15 and 16. The hazard plot shows the tendency in the failure rate as a function of strength. The burr hazard rate is usually an increasing followed by a decreasing function and can be offered a zero approach for a large value of x [28]. Also, it can be seen that the shape of the hazard function highly believes in the data and the selected function of probability. The distribution is developed to represent the RS values of the bituminous mixture concerning the shape of the hazard function effectively. However, this way is not visible in Figure 15 as this figure was drawn for a variety of x within the limit of the experimental data.

CONCLUSION

The current investigation encompassed both experimental work and probabilistic analysis of four distinct formulations of dense bituminous macadam mixtures. These compositions featured two different types of coarse aggregates: natural aggregate and recycled concrete aggregate. In addition, two waste materials, fly ash and rice husk ash, were integrated into the mixtures as a filler. The outcomes of the experimental phase highlighted that the DBM mixture, formulated with 5% bitumen content and utilizing fly ash and rice husk ash, met the criteria set by Indian standards as outlined in the Marshall test. Assessing their resistance to moisture-induced deterioration, it was observed that the DBM mixture containing NA exhibited superior performance in terms of retained stability when compared to the mixture incorporating RCA. However, it's noteworthy that both mixtures fulfilled the minimum requirements stipulated in the relevant specifications. These empirical findings were subsequently reinforced by a statistical probabilistic analysis. The investigation into probability distributions revealed that the

burr distribution yielded the most favourable results in terms of the Goodness of Fit test, with both types of mixtures highlighting the lowest ranks concerning RS values.
In light of the combined insights from the experimental and statistical phases, it can be inferred that waste materials, whether employed as fillers or aggregates, hold significant promise as viable substitutes for traditional components in bituminous pavement construction. This substitution not only offers economic advantages, particularly in areas proximate to the available waste materials but also contributes to the conservation of dwindling natural resources, potentially repurposing them for other critical applications.

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