Choudhary *et al.*
Beni-Suef Univ J Basic Appl Sci (2022) 11:127
https://doi.org/10.1186/s43088-022-00302-3

Beni-Suef University Journal of Basic and Applied Sciences

RESEARCH

Open Access

Mechanical evaluation of recycled aggregate mixes and its application in reclaimed asphalt pavement (RAP) stretch

Lokesh Choudhary[1*], Shubham Bansal[2], Megha Kalra[3] and Lokesh Dagar[4]

Abstract

Background: The depletion of natural resources has led to the need of looking out for alternatives of primary construction materials. The use of reclaimed asphalt pavement (RAP) has become a common practice as it reduces economic burden and saves natural resources and energy. This study is based on partial replacement of fresh natural aggregate with reclaimed aggregate. The project is divided into two phases; first one discusses the mechanical viability of replacing 10%, 20%, 30%, 40%, 50% and 60% of fresh aggregates with reclaimed aggregates. The second phase involves the study conducted on a 9.8 KM dense bituminous macadam (DBM) layer, constructed using the most optimum mix from the first phase of study. Finally, a cost analysis of the pavement was conducted to assess its economic viability.

Results: In the light of MORTH guidelines, laboratory results showed improvement in the Marshall parameters till 30% replacement of fresh aggregates. Eventually, the DBM layer was constructed using the mix design having 30% replaced fresh aggregates. It showed satisfactory performance after short-term duration without any evidence of rutting or fatigue cracking on surface. Testing of core samples from road stretch proved the negligible degradation with ageing.

Conclusion: The DBM constructed using reclaimed aggregate showed a saving of 15% in the total cost.

Keywords: Reclaimed asphalt pavement, Recycled aggregate, Marshall method, Stability-flow analysis, Volumetric analysis, Dense bituminous macadam

1 Background

During the reconstruction and resurfacing of an existing asphalt road, the top layer of the older pavement is removed and discarded. This discarded material consisting of asphalt and aggregates obtained from removing or processing of a pavement is known as reclaimed asphalt pavement (RAP) (Fig. 1) [1]. If the RAP is separated and segregated properly, it consists of good quality, well-graded aggregated covered by asphalt. Hence, RAP can be used along with the virgin materials, thereby reducing the demand of fresh raw material. This may also lead to a better waste disposal alternative of the old pavement waste. The present work analyses the reuse of RAP, by replacing the fresh aggregate. However, employing RAP in new construction is a recent technique and needs to be investigated thoroughly. Some studies state that the hot mix recycling is a popular technique in which RAP material can be mixed with new material [2]. They evaluated the performance of asphalt with RAP and rejuvenating agent. They also recommended that for faster performance evaluation, Accelerated Pavement Testing Facility (APTF) should be used. Further, some studies revealed that the performance of the pavement constructed with 30% RAP

*Correspondence: lokesh.anmol@gmail.com

[1] Department of Civil and Environmental Engineering, The NorthCap University, Gurugram, Haryana 122017, India
Full list of author information is available at the end of the article

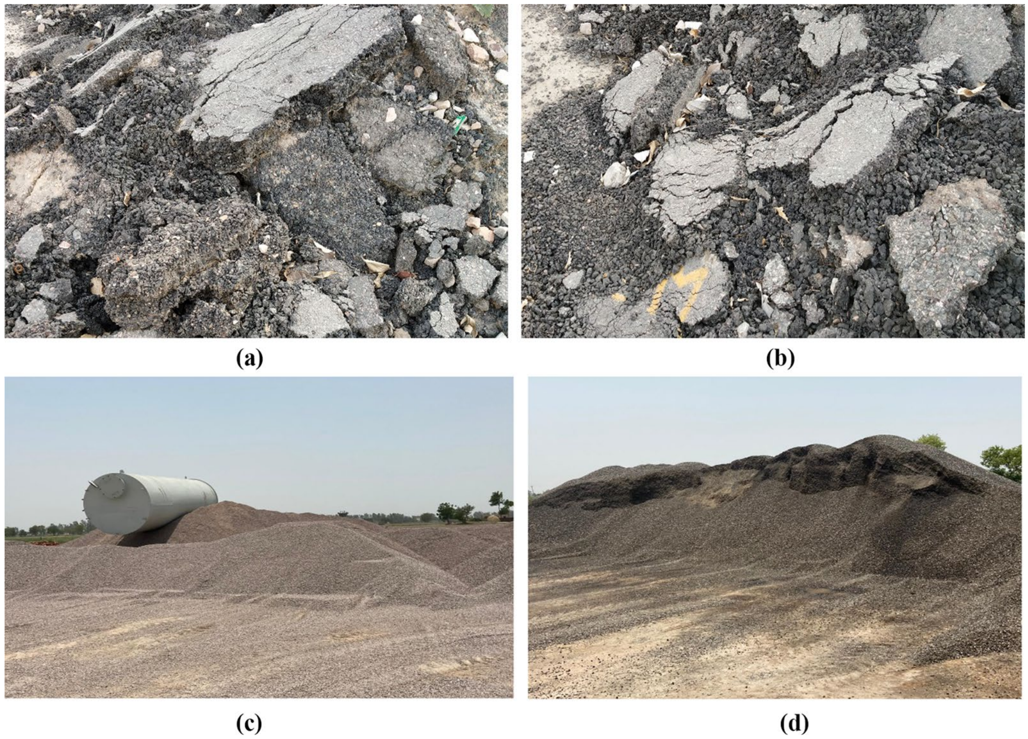

Fig. 1 a–d Milling of Narwana-Tohana road surface (MDR-112) and extraction of RAP aggregates

content is similar to the performance of conventional pavements [3]. Also, to avoid any adverse effects, many agencies limit the RAP to 30% [4]. This could further be verified from study conducted on the use of RAP and recycled concrete aggregates (RCA) in dense bituminous macadam (DBM) [5–7]. In other recent studies, the gradation of RAP was adjusted with the help of RCA, and the RAP bitumen was modified with bitumen of low viscosity, i.e. VG10 and VG30. As per the laboratory investigations carried out, 70:30 and 60:40 proportions were found optimum for VG30 bitumen or VG10 bitumen and RAP [8]. Tarsi et al. [9] and Thakur and Han [10] reviewed various published studies to understand the challenges around use of high quantity of RAP aggregates. They also studied the incorporation of binder-coated recycled aggregate in design of mixes. The environmental and economic viability of using RAP was also deliberated, and they concluded that its usage could lead to a huge cost saving. The use of RAP is gaining prominence due to reduction of construction cost. A decrease of 54% of the cost has been reported by the authors with improvement in resistance to rutting [11]. The parameters like Marshall stability, flow, bulk density, etc., showed an improvement due to better inter-molecular bonding between the binder-coated aggregates and bitumen [12–16]. Also, the stability value and strength results showed better results for mixtures using RAP as a partial replacement by making it more impermeable [17].

The developed nations have been utilising RAP material and have laid guidelines for the same. However, till recent years India did not stress on the use of recycled pavement material due to the lack of technology. But with the growing issues of waste disposal, shortage of landfills and lack of natural resources, the researchers in India are focussing on incorporating RAP and developing a suitable methodology for its optimum benefits. This research work determines the amount of RAP that can be used along with virgin aggregates through laboratory investigations and the results obtained are used in the field on a real-time project and its cost implications are also calculated.

2 Materials

The raw material required for laboratory and field investigations was procured from different sites. Recycled aggregates were collected by milling the bituminous layer of Narwana-Tohana Road (MDR-112), Jind, Haryana, as shown in Fig. 1. To maintain the homogeneity, self-prepared sampling pattern was followed according to which samples were collected from the collecting dump at regular interval of 30 min and the samples were mixed and a batch of 10 ft. × 10 ft. was prepared. Virgin aggregates were taken from the Khanak Mines of Tosham District, Bhiwani, Haryana, and samples of equal volume were collected from the collecting dump at a height of every 3 ft. to form a batch of 10 ft. × 10 ft. Virgin Bitumen of Grade VG30 was procured from Panipat Refinery, Haryana.

3 Methods

The methodology of experimental programme is presented in Fig. 2. After procurement of materials, the physical tests of virgin and RAP aggregate as well as bitumen were carried out as per the standard procedures. Parameters of tested materials were found to be lying within the prescribed limit as per IS 73 and MORTH guidelines [18] as shown in Tables 1 and 2.

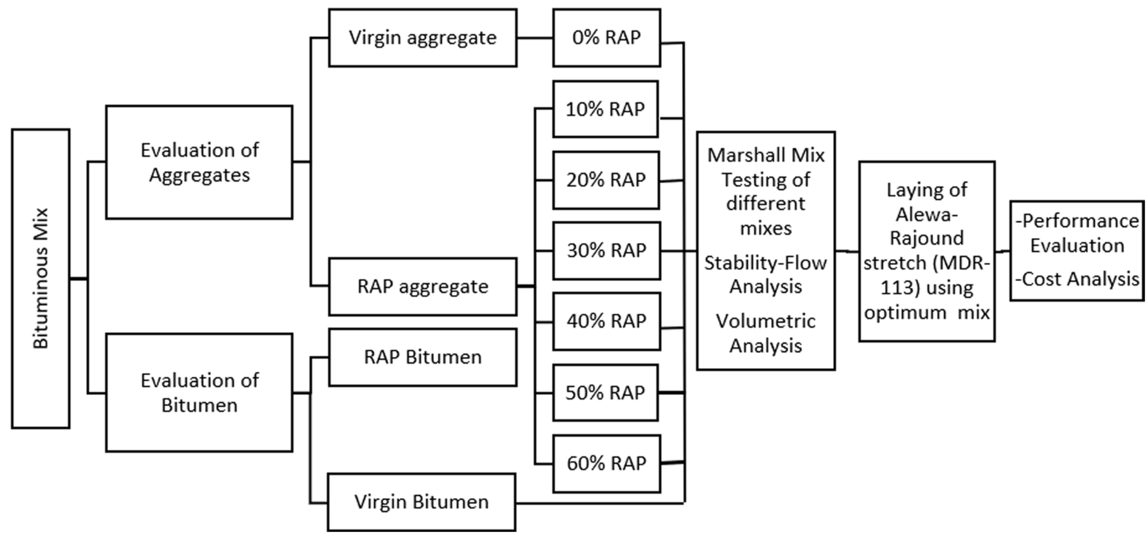

Fig. 2 Flowchart depicting methodology

Table 1 Properties of Virgin and Recycled aggregate

Property	Code of standards	Virgin aggregate	Recycled aggregate	Permissible values (MORTH specifications [18])
Impact value (%)	IS 2386 (Part IV)	19.30	20.20	Max 27%
Crushing value (%)	IS 2386 (Part IV)	22.85	24.38	Max 30%
Stripping value	IS 6241	98.00	97.00	Min. 95
Specific gravity	IS 2386 (Part II)	2.63	2.62	2.5–3.0
Water absorption value (%)	IS 2386 (Part IV)	0.65	0.63	Max 2%
Abrasion value (%)	IS 2386 (Part IV)	24.80	15.80	Max 30%

Table 2 Properties of virgin and RAP bitumen

Property	Code of standards	Virgin bitumen	Requirements as per IS:73 for virgin bitumen	RAP bitumen	MORTH [18] requirements for RAP bitumen
Penetration value (1/10 mm)	IS 1203	54	Min. 45	19	Min. 15
Flash Point (°C)	IS 1209	308	Min. 220	–	–
Solubility (%)	IS 1216	99.25	Min. 99.0	99.10	Min. 99.0
Softening Point (°C)	IS 1205	51	Min. 47	–	–
Specific Gravity	IS 1202	1.03	–	1.02	1.01–1.06

After physical testing, Marshall mix design procedure was followed to evaluate the Marshall parameters of dense bituminous macadam (Grade II) mix prepared with various proportions of recycled aggregate (0–60%). Proportioning of aggregate for different mixes is shown in Table 3 which was done using Rothfutch method. All the proportions are found to be lying within the prescribed limit as per MORTH as shown in Fig. 3. The DBM (Grade-II) mix samples were prepared for above-mentioned percentage replacement of virgin aggregates with recycled aggregates (three specimens for each mix) and bitumen content ranging from 4 to 6% by total weight of mix. The prepared Marshall specimens (Fig. 4) were tested at Mananda Test House, Dera Bassi, Mohali, Punjab, using digital Marshall Testing Machine at standard conditions. Stability and flow values were observed, and volumetric parameters were evaluated. The optimum mix found by laboratory investigations has been used for widening and strengthening of Alewa-Rajound road (MDR-113) in Jind District, Haryana (from RD 0.00 to 9.80 KM making total length of 9.8 KM of the stretch) in order to investigate the field performance of the mix.

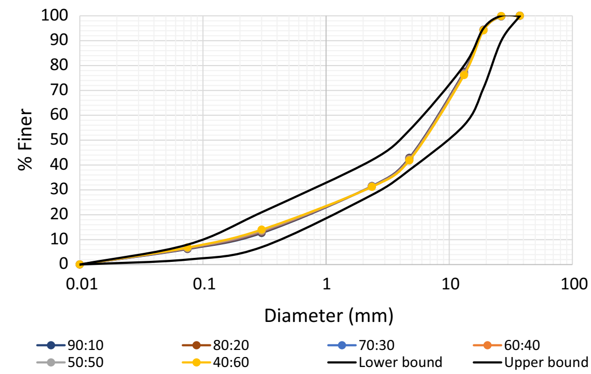

Fig. 3 Gradation curve for different percentages of mix

4 Results

4.1 Marshall stability

Variation of Marshall stability value of mixes with binder content is shown in Fig. 5a. Marshall stability value of mix having fresh aggregate only increased with the addition of binder content upto 5% and then decreased. Stability value of mixes having different proportions of recycled aggregate also increased with binder content upto 5% and then decreased. It has been observed that the stability curves of mixes having reclaimed aggregate are lower as compared to fresh aggregate mixes. Maximum stability value for each composition of mix is reiterated in Fig. 5b.

4.2 Density

Variation of density of mixes with binder content is shown in Fig. 5c. Density of mix having fresh aggregate increases gradually with increase in addition of binder content upto 5.5% and beyond that it starts decreasing. A similar trend was seen in mixes having fresh aggregates replaced with recycled aggregates. Variation of maximum unit weight with percentage replacement of fresh aggregate is also shown in Fig. 5d.

4.3 Air voids

Variation of air voids of mixes with binder content is shown in Fig. 5e. Air voids of mixes having fresh aggregate as well as specific proportion of reclaimed aggregate are found to be decreasing with increase in addition of binder content. It is also observed that air voids decrease with increase in percentage replacement of fresh aggregate with reclaimed aggregate.

4.4 Flow value

Variation of flow value of mixes with binder content is shown in Fig. 5f. Flow value of mixes having fresh aggregate as well as specific proportion of recycled aggregate is

Table 3 Gradation of DBM (Grade II) mix with different percentages of RAP aggregate

Sieve size (mm)	Virgin aggregates (% finer)	RAP aggregates (% finer)	MORT&H requirements	Graded mix of different proportions (% finer)					
				90:10	80:20	70:30	60:40	50:50	40:60
37.50	100	100	100	100	100	100	100	100	100
26.50	99.70	100	90–100	99.73	99.76	99.79	99.82	99.85	99.88
19.00	94.40	94.00	71–95	94.36	94.32	94.28	94.24	94.2	94.16
13.20	77.70	75.10	56–80	77.44	77.18	76.92	76.66	76.4	76.14
4.75	43.10	41.00	38–54	42.89	42.68	42.47	42.26	42.05	41.84
2.36	31.60	31.00	28–42	31.54	31.48	31.42	31.36	31.3	31.24
0.30	12.40	15.10	7–21	12.67	12.94	13.21	13.48	13.75	14.02
0.075	6.10	7.30	2–8	6.22	6.34	6.46	6.58	6.7	6.82

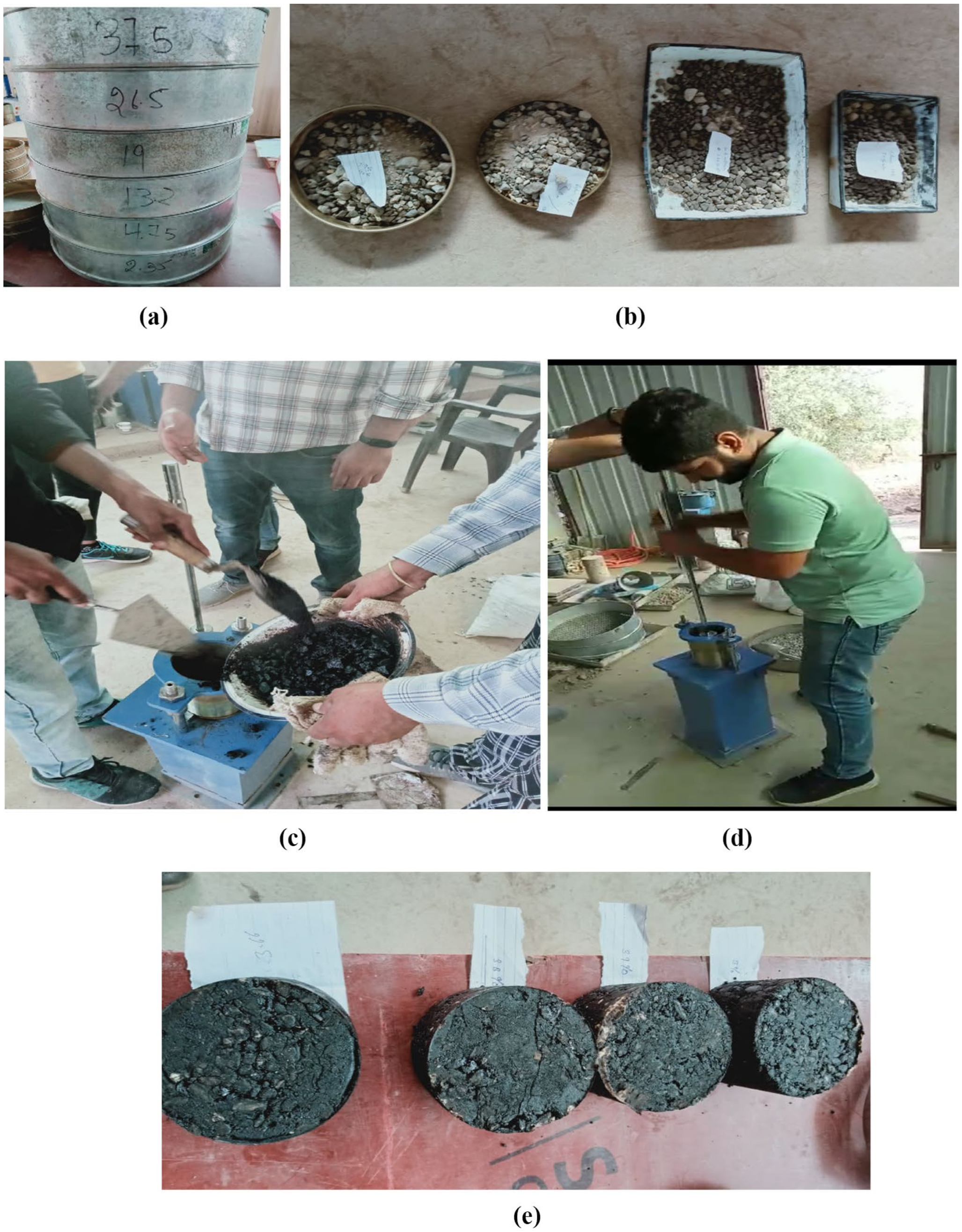

Fig. 4 **a**–**e** Graded samples for different percentages of mix

found to be increasing with increase in addition of binder content. Irregular variation of flow value with increase in percentage replacement has been seen in the plot.

5 Discussion

The variation in Marshall stability values shown in Fig. 5b gives us a clear picture of the trend followed by stability values among the virgin mix and other mixes prepared with replacement. Stability value seen from 10 to 20% was almost similar, but it increased marginally with increase in replacement percentage from 20 to 30% and then decreased upto 60% replacement of aggregate. It can be inferred from this that 30% replacement of fresh aggregate results in most optimum mix with respect to Marshall stability values. The trend shown in Fig. 5d reflects that unit weight of the mix increases

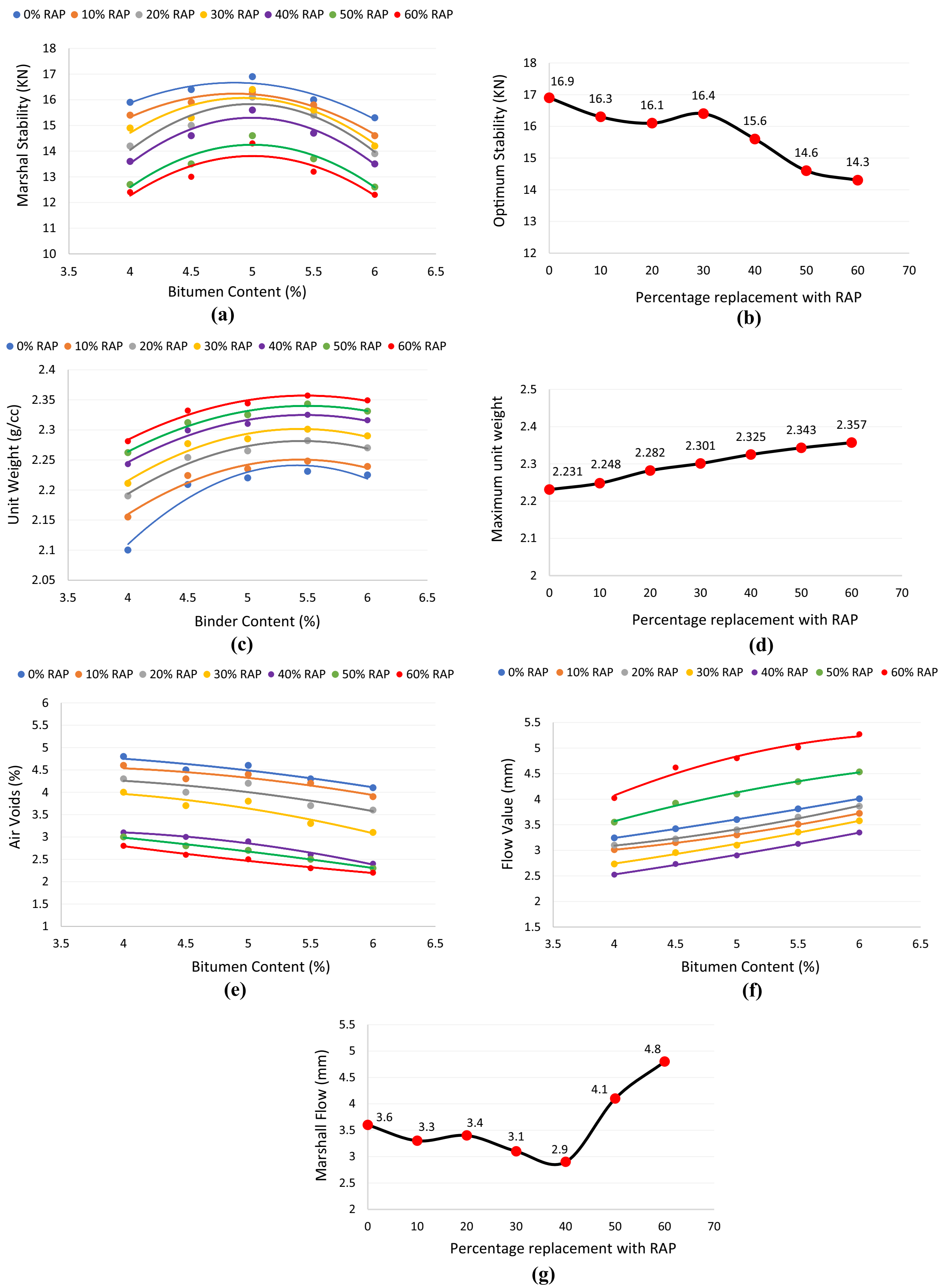

Fig. 5 **a** Marshall stability versus bitumen content for different mixes. **b** Variation of optimum stability values for different mixes. **c** Unit weight versus bitumen content for different mixes. **d** Variation of optimum stability values for different mixes. **e** Air voids versus bitumen content for different mixes. **f** Flow value versus bitumen content for different mixes. **g** Variation of Marshall flow values for different mixes

continuously with increase in percentage replacement of fresh aggregate due to increased unit weight of recycled aggregates. This is due to intrusion of binder into micro-pore structure of aggregates and coating on the exterior surface in recycled aggregates. Air voids in mixes shown in Fig. 5e having more than 30% replacement of fresh aggregate with reclaimed aggregate are found to have less than 4% air voids irrespective of binder content and hence follow MORTH criteria of maximum air voids. The variation shown in Fig. 5g such as increase in flow value with increase in percentage replacement till 20%, then decrease till 40% replacement and an abrupt increase beyond 40% infers that only % replacement till 40% shows a flow value within 2–4 mm as per MORTH specifications [18] with 40% being the maximum amount of replacement with desired results.

Based on the results obtained by replacing fresh aggregate with reclaimed aggregate in proportion ranging from 10 to 60%, an attempt has been made to define the optimum percentage of RAP aggregate replacement. Optimum stability has been observed at 30% replacement, while unit weight has been found increasing till 60% replacement. Air voids have been found within desirable criteria above 30% replacement, while flow value up to 40% replacement has been found within MORTH limits. Adopting the optimality criteria of maximum stability & unit weight and ensuring the flow value & air voids within prescribed MORTH limits, mix having 30% replacement of fresh aggregate with recycled aggregate can be concluded as the optimum mix.

Fig. 6 Surface prepared for DBM work

6 Field investigation

The optimum replacement percentage obtained by laboratory investigations was further considered to construct a road stretch and evaluate its performance (Fig. 6).

6.1 Project details

The case stretch was named as 'Special Repair by providing widening and strengthening of road using Reclaimed bituminous material' extending from RD 0.00 to 9.80 km (widening from 5.5 m width to 7.00 m) on Alewa-Rajound road (MDR-113) of Jind District, Haryana. The total length of the road constructed was 9.8 km with a completion duration of 9 months. A typical road cross section designed for construction is shown in Fig. 7.

6.2 Gradation and mix design

The gradation of virgin aggregates and reclaimed aggregates in ratio of 70:30 is presented in Table 4. Also, the

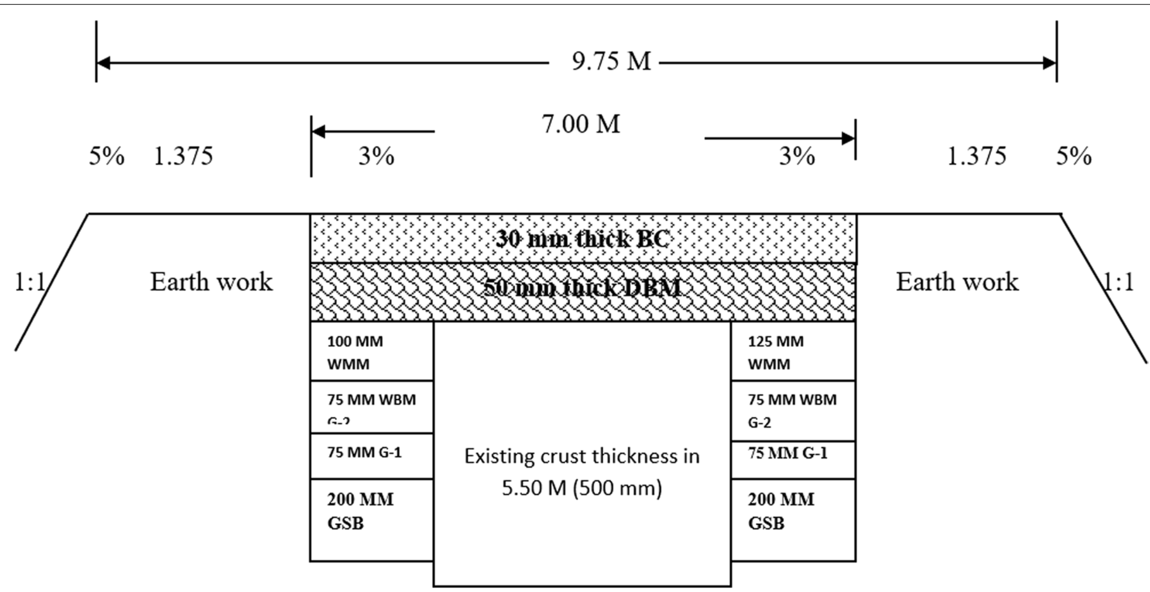

Fig. 7 Cross section of Alewa-Rajound Road

Table 4 Gradation of fresh and reclaimed aggregates for DBM

Sieve size (mm)	Virgin Agg. (% passing)			RAP Agg. (% passing)	MORT&H requirements	Results
	20 mm	10 mm	Stone dust			70:30
37.5	100	100	100	100	100	100
26.5	100	100	100	100	90–100	100
19.0	80.8	100	100	95.8	71–95	94.71
13.2	28.1	99.1	100	81.1	56–80	78.80
4.75	0.9	10.5	96.4	38.2	38–54	38.27
2.36	0.8	3.2	80.1	24.1	28–42	28.19
0.30	0.5	1.1	32.1	3.9	7–21	9.56
0.075	0.3	0.7	10.9	1.3	2–8	3.34

Table 5 Marshall test parameters for final design mix for 50-mm thick DBM layer

Bitumen content	Unit wt. (gm/cc)	Marshall stability (KN)	Marshall flow (mm)	% Air void
4.5%	2.351	14.9	3.2	4.3

Marshall stability parameters of the final mix design used in construction of stretch are as tabulated and shown in Table 5.

6.3 Performance evaluation

To assess the quality and performance of DBM work with 30% reclaimed aggregate material, core of samples was taken using core cutter from three different locations, namely location A, B and C, at RD 2.620 km, RD 3.550 km and RD 5.430 km, respectively, after the period of month since the inception of traffic. Bitumen content was found out using bitumen extractor and bulk density using specific gravity apparatus. Figure 8a–f depicts the core cutting, collection of samples and general view of the road section for visual assessment.

As shown in Table 6, average bulk density of core samples obtained from the stretch was found to be marginally less than the initial Marshall samples due to ageing of mix. Bitumen content was found to be nearly same as that of original mix. These results conclude that not much degradation of mix has taken place due to ageing.

Visual inspection survey has confirmed that the surface of road is compact and bonded. Also, there was no evidence of any kind of longitudinal cracks, rutting or settlement in the pavement surface.

6.4 Cost analysis

The partial use of RAP aggregates for new DBM road construction or maintenance/widening of existing roads can be seen as an opportunity to identify and prioritise cost saving in the projects. A detailed cost analysis of the Alewa-Rajound stretch laid with the optimum mix with 30% replacement of virgin aggregates with RAP aggregates for the purpose of research led to a cost saving of 14.91% owing to a total saving of around Rs 40.07 lacs. For conducting the cost analysis, cost of cold milling of existing bituminous road, labour, machinery, fresh material and contractor's profit has been considered as presented in Tables 7 and 8. For comparison, roadwork without RAP aggregate has been considered as compacted DBM laid 50 mm thick in one layer by hot mix plant and paver finisher as per clause no. 507 and 113.3 of MORTH specifications [18] for road and bridge works (5th Revision) (Table 9).

7 Conclusions

1. Stability value increases marginally with increase in replacement percentage upto 30% and then decreases upto 60% replacement of aggregate. This behaviour is seen as a result of lesser interlayer bonding between RAP aggregates and virgin bitumen beyond the optimum percentage and can be inferred as an adverse effect of excess replacement of RAP with fresh aggregates.
2. Density value increases continuously with increase in replacement percentage of fresh aggregate due to a higher unit weight of RAP aggregates in comparison to fresh aggregates
3. Air voids decrease with increase in percentage replacement of fresh aggregate with recycled aggregate owing to existing higher degree of saturation in RAP aggregates, thereby reducing air voids in the inter-particular space.
4. It is observed that flow value increases with increase in percentage replacement till 20% and then decreases till 40% replacement. In the mixes having higher percentage of recycled aggregate (greater than

Fig. 8 a–f Core cutting, sample collection and general visual inspection of the road stretch

Table 6 Bitumen and bulk density of field-collected samples from different locations

Location	Bitumen content (%)		Bulk density (g/cc)	
	Obtained	Required	Obtained	Required
A	4.65	4.5	2.341	2.351
B	4.48		2.315	
C	4.72		2.353	

40%) flow value increases abruptly and exceeds the allowable maximum limit of 4 mm as per MORTH specifications.

5. Adopting the optimality criteria of maximum stability & unit weight and ensuring the flow value & air voids within prescribed MORTH limits, mix having 30% replacement of fresh aggregate with recycled aggregate is obtained as the optimum mix.
6. Stretch constructed with 30% replacement of fresh aggregate with recycled aggregate is seen in satisfactory condition after short-term duration without any evidence of rutting or fatigue cracking on surface. Testing of core samples has concluded that not much degradation of mix has taken place due to ageing.
7. Stretch constructed with 30% replacement of fresh aggregate with recycled aggregate resulted in total cost reduction of 14.91% leading to a saving of Rs. 4,08, 940 per KM of the stretch.

Table 7 Cost analysis of DBM with RAP aggregates

Analysis for recycling of Bituminous pavement by Milling (DBM) (below 80 mm)

S. no.	Description of items	Unit	Qty	Rate	Amount
	MORT&H specification				
	Recycling—of Bituminous Pavement with Central recycling Plant				
	Recycling pavement by cold milling of existing bituminous layers, planning the surface after cold milling, reclaiming excavated material to the extent of 30% to the required quantity, hauling and stockpiling the reclaimed material near the central recycling plant after carrying out necessary checks and evaluation, adding fresh material including mixing				
	Unit = cum				
	Taking output-120 cum (276 Tonne)				
(A)	Labour				
	Mate	Day	0.48	585.00	280.80
	Mazdoor skilled	Day	2.00	585.00	1170.00
	Mazdoor	Day	10.00	585.00	5850.00
	(A) Total				7300.80
(B)	Machinery				
1	Mechanical broom @ 1250 sqm hour	Hour	1.28	310.50	397.44
2	Air compressor 250cfm	Hour	1.28	337.50	432.00
3	Bitumen pressure distributor @1750sqm per hour	Hour	0.91	934.20	850.12
4	Hot mix plant 100-120TPH producing an average of 75 tonne per hour	Hour	3.00	15,075.45	45,226.35
5	Electric generator set 250 KVA	Hour	3.00	1350.00	4050.00
6	Front end loader 1.00 cum bucket capacity	Hour	3.00	702.00	2106.00
7	Tipper 5.5 cum capacity	Hour	18.00	270/2	2430
8	Smooth wheeled roller 8–10 tonne	Hour	3.00 × 0.65*	400.95	781.85
9	Vibratory roller 8 tonne	Hour	3.00 × 0.65*	1341.90	2616.71
10	Smooth wheeled tandem roller 6–8 tonne	Hour	3.00 × 0.65*	400.95	781.85
	(B) Total				59672.32
(C)	Material				
I	Bitumen				
	A bitumen content is 4.5% by weight of mix. For reclaimed material, fresh bitumen will be required to the extent of 60% of normal requirement				
	In a mix of 276 tonne, 82.8 tonne is reclaimed and balance 193.2 tonne is fresh mix				
	Bitumen VG-30 required for reclaimed mix of 82.8 tonne @ 60 per cent = 82.8 × 0.60 × 0.04 5 = 2.24	Tonne	2.24	53,983.00	120,921.92
	Bitumen VG-30 required for fresh mix of 193.2 tonnes = 193.2 × 0.045 = 8.69	Tonne	8.69	53,983.00	469,112.27
II	Aggregates				
	Percentage of mix requiring fresh aggregates—70%				
	Weight of fresh mix = 276 × 0.70 = 19.2 tonne				
	Weight of fresh aggregate in the mix = 193.2 × 0.96 = 185.47 tonne				
	Taking average density of 1.6 tonne/cum, total volume of Aggregate = 115.92 cum				
	Size-wise requirement of fresh aggregates				
	37.5–25 mm @ 23%	cum	26.66	856.13	22,824.43
	25–10 mm @ 15%	cum	17.39	856.13	14,888.10
	10–5 mm @ 20%	cum	23.18	856.13	19,845.09
	Below 5 mm @ 42%	cum	48.69	776.13	37,789.77
	(C) Total				685381.58
	(A+B+C)				752354.70
(D)	5% over charges @ % on (a + b + c)				37,617.74
	(D) Total				789972.44
(E)	10% contractor's profit@ % on (a + b + d) on Rs	104,590.86			10459.09
	Cost for 120 cum of DBM = (a + b + c + d + e) = Grand Total			G. Total	800432

Table 7 (continued)

Analysis for recycling of Bituminous pavement by Milling (DBM) (below 80 mm)					
S. no.	**Description of items**	**Unit**	**Qty**	**Rate**	**Amount**
	Rate per sqm = (a + b + c + d + e)/120				6670.26
	Say Rs.		6670.30	/- P.cum	
(F)	Cost of reclaimed DBM per km	23,34,605	Per km		

Table 8 Cost Analysis of DBM without RAP aggregates

Description	Quantity	Unit	Rate (in Rs.)	Amount (in Rs.)
Unit = /sqm	Taking output = 195 cum or 450 tonnes			
(a) Material (Grading—I)	20.25 Tonne	= 429.75 MT = 1.6 tonne/cum = 268.60 cum	53,983	1,093,155.75
(i) Bitumen VG-30 4.5% of mixed wt				
(ii) Aggregate Wt. of aggregate Taking density of aggregate Volume of aggregate Grading-II (40 mm nominal size)	450—20.25			
25-10 mm 30%	80.58 cum		856.13	68,986.96
10-5 mm 28%	75.21 cum		856.13	64,389.54
5 mm and below 42%	112.81 cum		776.13	87,555.23
(A)				1314087.47
(b) Labour Laying 60-mm-thick dense bituminous macadam (HSR 24.32) av. Lead 1				
Km. 1	450	tonne	101.4	45,630
Add ceiling premium 370% for Rs				168,831
(B)				214461.00
Total (A + B)				1528548.47
Rate/cum	1528548.47/195			7838.70
Cost of DBM without reclaimed material				2743545.00

Table 9 Comparison of the cost

Per km cost of DBM (in Rs)		Per km saving (in Rs)	Total saving in the project (length of road = 9.8 km)
With RAP	**Without RAP**		
23,34,605	27,43,545	4,08,940	40,07,612

Abbreviations

RAP: Reclaimed Asphalt Pavement; MORTH: Ministry of Road Transport and Highways; DBM: Dense Bituminous Macadam; APTF: Accelerated Pavement Testing Facility; RCA: Recycled Concrete Aggregate; VG: Viscosity Grade; MDR: Major District Road; IS: Indian Standard; KM: Kilometre; RD: Reduced Distance.

Acknowledgements

The authors acknowledged the facilities provided by Department of Civil and Environmental Engineering, The NorthCap University, Gurugram for this research work.

Author contributions

LC and LD were involved in the experimental analysis, and SB and MK were involved in the data interpretation. All authors have read and approved the manuscript.

Funding

No funding was received for carrying out this research.

Availability of data and materials
The datasets generated and analysed during the current study are not publicly available as it is a part of an ongoing research, but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
The individuals depicted in the photos have provided their written informed consent for the photos to be included in the article.

Competing interests
Authors do not have any competing interests.

Author details
[1]Department of Civil and Environmental Engineering, The NorthCap University, Gurugram, Haryana 122017, India. [2]Department of Civil Engineering, Thapar Institute of Engineering and Technology, Patiala, Punjab 147004, India. [3]Department of Civil Engineering, Jamia Milia Islamia, New Delhi 110025, India. [4]Public Works (Buildings and Roads) Department, Rohtak, Haryana 124001, India.

Received: 2 January 2022 Accepted: 15 September 2022
Published online: 01 October 2022

References
1. Misra AK, Kalra M, Bansal S (2017) Influence of polymer treatment on strength and water absorption capacity of recycled aggregate concrete. Int J Sustain Build Technol Urban Dev 8(2):81–91. https://doi.org/10.12972/susb.20170008
2. Pradyumna TA, Mittal A, Jain PK (2013) Characterization of reclaimed asphalt pavement (RAP) for use in bituminous road construction. Procedia Soc Behav Sci 104:1149–1157. https://doi.org/10.1016/j.sbspro.2013.11.211
3. Xiao F, Amirkhanian SN (2009) Laboratory investigation of moisture damage in rubberised asphalt mixtures containing reclaimed asphalt pavement. Int J Pavement Eng 10(5):319–328. https://doi.org/10.1080/10298430802169432
4. Tao M, Mallick RB (2009) Effects of warm-mix asphalt additives on workability and mechanical properties of reclaimed asphalt pavement material. Transp Res Rec 2126(1):151–160. https://doi.org/10.3141/2126-18
5. Mhlongo SM, Abiola OS, Ndambuki JM, Kupolati WK (2014) Use of recycled asphalt materials for sustainable construction and rehabilitation of Roads. In: International Conference on Biological, Civil and Environmental Engineering (BCEE-2014), Dubai, UAE. https://doi.org/10.15242/iicbe.c0314157
6. Tambake SO, Kumar DN, Manjunath KR (2014) Laboratory investigation on hot mix asphalt using reclaimed asphalt pavement (RAP) for bituminous concrete mix. Int J Res Eng Technol 3(6):245–249. https://doi.org/10.15623/ijret.2014.0306045
7. Bansal S, Misra AK, Chopra T, Bajpai P (2018) Laboratory analysis of Marshall parameters of dense bituminous macadam mix using waste materials. Int J Environ Technol Manag 21(3/4):190–201. https://doi.org/10.1504/IJETM.2018.097918
8. Purohit S, Panda M, Chattaraj U (2021) Use of reclaimed asphalt pavement and recycled concrete aggregate for bituminous paving mixes: a simple approach. J Mater Civ Eng 33(1):04020395. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003480
9. Tarsi G, Tataranni P, Sangiorgi C (2020) The challenges of using reclaimed asphalt pavement for new asphalt mixtures: a review. Materials 13(18):4052. https://doi.org/10.3390/ma13184052
10. Thakur JK, Han J (2015) Recent development of recycled asphalt pavement (RAP) bases treated for roadway applications. Transp Infrastruct Geotech 2:68–86. https://doi.org/10.1007/s40515-015-0018-7
11. Chopra K, Kumar A, Mallick RB, Veeraragavan A (2012) Investigations on laboratory performance of bituminous mixes with reclaimed asphalt pavement materials—a step towards sustainable road infrastructure in India. J Indian Road Congress 73(3):339–352
12. Bansal S, Misra AK, Bajpai P (2017) Evaluation of modified bituminous concrete mix developed using rubber and plastic waste material. Int J Sustain Built Environ 6(2):442–448. https://doi.org/10.1016/j.ijsbe.2017.07.009
13. MdBasir MF, Mackolil J, Mahanthesh B, Nisar KS, Muhammad T, Anuar NS, Bachok N (2021) Stability and statistical analysis on melting heat transfer in a hybrid nanofluid with thermal radiation effect. J Process Mech Eng 235(6):1–12. https://doi.org/10.1177/09544089211033161
14. Lund LA, Omar Z, Dero S, Chu Y, Khan I, Nisar KS (2021) Temporal stability analysis of magnetized hybrid nanofluid propagating through an unsteady shrinking sheet: partial slip conditions. Comput Mater Continua 66(2):1963–1975. https://doi.org/10.32604/cmc.2020.011976
15. Khan U, Zaib A, Khan I, Nisar KS (2020) Dual solutions of nanomaterial flow comprising titanium alloy (Ti_6Al_4V) suspended in Williamson fluid through a thin moving needle with nonlinear thermal radiation: stability scrutinization. Sci Rep 10:20933. https://doi.org/10.1038/s41598-020-77996-x
16. Singh B, Nisar KS (2020) Thermal instability of magnetohydrodynamic couple stress nanofluid in rotating porous medium. Numer Methods Partial Differ Equ 2020:1–14. https://doi.org/10.1002/num.22614
17. Sharma U, Giri HK, Khatri A (2018) Use of recycled asphalt material for sustainable road construction. Indian Highways 46(9):29–36
18. Ministry of Road Transport and Highways (2013) Specification for road and bridge works. In: Indian Roads Congress—5th Revision, New Delhi, India. https://skmobi.files.wordpress.com/2017/04/morth-specifications-for-road-bridge-works-5th-revision-by-sk.pdf

Publisher's Note