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Development and Evaluation of Sustainable Bituminous Paver Blocks

Padmakumar Radhakrishnan [1,2] and Vignesh Dhurai [1,2,*]

[1] Department of Civil Engineering, College of Engineering Trivandrum, Thiruvananthapuram 695016, Kerala, India
[2] CET Campus, APJ Abdul Kalam Technological University, Thiruvananthapuram 695016, Kerala, India
* Correspondence: dvignesh005@gmail.com

Abstract: Most road surfaces globally are constructed using bituminous materials. The construction of new roads and the maintenance of existing ones demand a huge amount of virgin natural aggregates. Depletion of resources that takes place during the construction of the road has an impact on cost and also on the environment. Hence, there is a need to reduce virgin aggregate use for bituminous pavement construction. This can be achieved by utilizing sustainable materials such as marble waste and reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA)-type road construction. This research work is focused on sustainable development goal (SDG) 12, exclusively on the target number 12.5 which describes the recycling and reuse of materials. However, no investigations were seen to be reported on the integrated utilization of sustainable materials and RAP in bituminous paver blocks. The bituminous mixes were evaluated based on strength and compared with the control mix in this study. Bituminous paver blocks were then cast using sustainable materials and tested in the laboratory to assess the performance of the blocks through a compression test, Cantabro loss test, and wheel rut test. The test results gave satisfactory values; hence, these bituminous blocks can be used for service maintenance of the pavement structures. The study indicates that using sustainable material along with RAP in blocks can provide an eco-friendly, easily maintainable pavement system which makes it a key approach to SDG 9 as well, in terms of innovative infrastructure solutions.

Keywords: bituminous blocks; sustainable development; sustainable material; recycle; innovative road unit; rut test; field simulation test

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1. Introduction

Road infrastructure plays a vital role in all aspects of developing countries. A significant component of road infrastructure are the pavement structures that are constructed using either bituminous material or cement concrete. The majority of pavement structures in developing countries such as India are made with bituminous material as the main constituent. India's road network was named the world's largest in 2019, with 5.9 million kilometers of road. The total road length of the country has inflated considerably from 0.3 million km [1]. An increase in the road length results in rising demand for materials for construction and for regular maintenance. The use of excellent quality conventional materials in road construction is turning out to be increasingly expensive in developing countries because of scarcity and demand for virgin materials. One of the major aspects that affect sustainability in construction is material consumption [2]. Along with the rising demand for construction materials, developing countries are also facing certain issues such as waste disposal (an environmental concern) and also challenges during utility service maintenance work on pavements, as it requires various types of machinery and techniques to be implemented and also more resources based on the condition of work. The sustainable development goals (SDG) were framed by the United Nations (UN) in the year 2015 to guide global communities toward sustainable development [3]. A total of 17 SDGs with 169 targets covering the aspects of ending poverty, zero hunger, good health for all, quality education opportunities for all, gender equality, sustainable water management, clean energy for everyone, sustainable economic growth with decent work culture, industry innovation by building resilient infrastructure, reduced inequalities, safe sustainable cities, sustainable consumption and production in terms of recycling and reuse, climate action, protect life below water and on land, peace, justice for all, and partnership for the goals [4]. This research work is focused on covering a part of the targets which come under SDG 9 and 12. Various works in the literature reviewed that come under the category of SDG 9 and 12 are discussed below.

Many researchers are trying to find out possible ways to improve the use of waste materials in pavements and thus to reduce the use of virgin materials, as well as to implement new techniques for road construction and maintenance works. Recycling of asphalt pavement creates a cycle of reusing materials that optimizes the utilization of natural resources. Recycling in pavement construction majorly relates to the use of RAP [5,6] and has a few challenges [7]. A variety of materials have been employed in place of conventional materials such as RAP [8–10], quarry debris [11], marble waste [12–15], mining wastes [16], rice husk ash [17], and other materials [18–22]. A few research attempts have been made, such as the utilization of locally available materials and waste materials in the pavement structure [23] and quarry wastes along with RAP [24]. RAP has been intensively investigated as the most popular material, and different studies using RAP are prescribed in Table 1. RAP could be a useful alternative to virgin materials as it reduces the requirement for virgin aggregate [25,26]. Some findings suggest that the asphalt mixes with RAP with a high proportion [21,27], even 50 to 100% replacement ratio, and thus provided better performance [28]; 50% RAP substitution in base course performed better compared with conventional hot mix asphalt mixtures, as they minimized the environmental impacts through the reduction of energy consumption, improved the mechanical properties and durability, and also enhanced the stripping resistance [29]. Increasing RAP content reduces the density of the specimen, and the moisture damage decreases significantly with an increase in RAP content. Similarly, the performance of specimens related to rutting characteristics is also significant. Fatigue behaviour was found to be low for all mixes for up to 30% RAP content [30]. No negative effect was seen on the test specimen when RAP is mixed with the high modulus mixture, even for high proportions [31]. In some studies, recycled concrete aggregate is also used as an ingredient for the construction of road pavement [32], and for sustainable development by using construction and demolition waste [33].

Table 1. Different studies using RAP.

RAP Studies	Ref. Literature
Mechanical behavior	[19,34–37]
Construction (recycling)	[38,39]
Structural performance	[19,20,25,40,41]
Serviceability conditions	[19,20,42]

From the literature reviewed, it was also found that the largest natural stone produced in the world is marble, accounting for 50% of the world's natural stone produce [43]. Marble dust is usually dumped on riverbeds and possesses a serious environmental concern [44]. To reduce the disposal issues related to this waste generated, they are reclaimed to produce appropriate alternative materials for highway construction [24]. Reuse of waste generated in the construction of roads is one of the possible solutions to reduce the use of virgin material [45]. Some studies have found that other materials such as marble can serve as an alternate material for virgin material [46]; for example, marble dust is used as filler in asphalt pavement construction [12,23,47], marble chips [48], and wastes from marble quarries as aggregates in pavement construction [11,49]. From the literature, it was observed that the use of virgin material for road construction and maintenance works can be reduced by utilizing sustainable materials such as RAP, marble wastes, etc. and the proportion of these materials may vary depending on the purpose.

This study is mainly focused on an innovative technique for the rapid maintenance of pavement structure by developing bituminous blocks, and is not limited to the re-use of existing road material such as reclaimed asphalt but also utilizes a waste material, i.e., marble dust. In developing countries, pavement structures are not maintained properly during service maintenance works such as water supply and electrical services, as well as structural maintenance work such as rectifying distresses including potholes in pavement structures. The trenches created for service maintenance works are normally filled manually and the roads are resurfaced using either concrete or chipping material for faster execution. During maintenance work, the prevailing surface materials are wasted, owing to poor workmanship. Proper measures taken to reclaim and reuse the existing pavement, instead of using it as a filling material, as an ingredient for bituminous pavement works can save considerable amounts of virgin material. Present maintenance works do not provide a better solution, thus evolving an idea of developing a bituminous block for achieving better results in the maintenance works, which relates to SDG 9 on innovative solutions for infrastructure. In the earlier days, bituminous blocks were being used in road pavement construction in isolated places across the world, such as Georgia and Canada. Bituminous blocks have the benefits of a wide application range and easy recycling, and less time is required for curing. Some studies have been done to evaluate the bituminous blocks' performance [50]. Zhang et al. conducted a study to compare the mechanical characteristics of the precast hot-mix asphalt block with the precast mortar block, and based on the research result, it can be concluded that the precast HMA paver block has good resistance to deformation and rutting at par with conventional paver blocks, and for different climatic conditions and environments, the precast bituminous blocks should be designed to meet the desired gradation and requirement [50]. Abdelgalil et al. conducted a study on the influence of block thickness on the performance of asphalt blocks, and observed that with a decrease in block thickness of the asphalt block, the static load resistance also decreases [51].

From the extensive literature study, it was analyzed that few studies have been carried out on paver blocks made of conventional HMA. No studies were found to have been carried out on bituminous paver blocks cast using sustainable materials. This paper focuses on the development of modular bituminous blocks for pavement construction and maintenance in countries. In this study, the mechanical properties of the HMA mix using conventional and sustainable materials are evaluated, and then the optimum mixes are used for casting the HMA paver blocks. The ultimate objective of this work is to develop bituminous concrete paver blocks, using two sustainable materials, namely RAP and marble dust waste in the conventional hot-mix asphalt (HMA-bituminous concrete of grade 2 mix) to reduce the use of virgin materials and to provide a sustainable solution to the service maintenance works. By the above-mentioned objectives, a part of the sustainable development goals framed by the UN such as SDG 12 and SDG 9 can be achieved. The structure of this article comprises different sections. Section 2 describes the materials used in this research. In Section 3, the methodology followed in this research is discussed. Detailed discussions about the results from the laboratory test are discussed in Section 4. Finally, in Section 5, the summary of the findings is presented.

2. Materials

The study made use of the following materials: Bitumen, coarse and fine aggregate, and sustainable materials, namely, RAP and Marble.

2.1. Bitumen

The bitumen was subjected to various tests as per Indian Standards to determine its properties, including specific gravity [52], penetration [53], softening point [54], and ductility [55] as specified in the specifications. The type of binder used has an effect on the properties of bituminous mixes. In the paver block, VG 30 (viscosity-graded) bitumen was used, with the properties listed in Table 2 below.

Table 2. Properties of Bitumen.

Name of the Test	Obtained Result	Standards
Specific gravity test on bitumen (IS:1202)	1	0.99 minimum
Penetration test on bitumen (IS:1203)	67	50–70
Softening point test on bitumen (IS:1205)	52 °C	40–52 °C
Ductility test on bitumen (IS:1208)	77 cm	75cm minimum

2.2. Aggregate

The aggregate of sizes 12 mm and 6 mm and filler material were used in the bituminous mix. Table 3 shows the aggregate gradation based on the sieve analysis as per IS 2386:1963 (part 1). The selection of aggregates for the study is based on the MoRTH (Ministry of Road Transport and Highways, India) [56] specifications. For the bituminous concrete mix of grade 2, the normal aggregate sizes are 12 mm and 6 mm, and filler material is used. The aggregate type is charnockite, which was commonly used for road construction at the regional level. For the mix design, the specific gravity of all aggregate sizes was determined as per IS 2386:1963 (part 3), and the specific gravity values for 12 mm, 6 mm, and filler material were 2.67, 2.68, and 2.60, respectively, indicating that all values are within the specified limit. The specific gravity of aggregates is used in the calculation of the stability value of the mix.

Table 3. Aggregate Gradation (%).

Aggregate Nominal Size	Sieve Size (mm)									
	19	**13.2**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
12 mm	100	51.33	2.67	0	0	0	0	0	0	0
6 mm	100	100	92.58	14.04	0	0	0	0	0	0
Filler	100	100	100	100	88.30	68.1	55.82	37.62	24.63	9.03
Marble	100	100	100	93.75	81.25	65.63	48.44	25	15.63	6.25

2.3. Sustainable Materials

The sustainable materials used in this study are marble waste (fine and coarse) and RAP, the marble waste being bought from the rock mines and RAP was collected from the service road of the Karikkakom area of the Kanyakumari-Kochi NH 66 bypass road, Thiruvananthapuram, Kerala, India. RAP and marble waste were crushed to produce aggregates of a smaller size than 19mm using a jaw crusher for the incorporation of materials in the bituminous mixes; marble waste was made finer using a roller crusher. The utilization of RAP and marble waste in the bituminous mixes will achieve a part of sustainable development goal 12 and target number 12.5 in the way of recycling and reuse of materials.

3. Methodology

3.1. Design of HMA

The bituminous concrete of grade 2 mix was selected for the HMA mix as per the MoRTH specification for roads and bridge works in India [56]. The gradation was obtained by the trial-and-error method and was compared to the required specification, for the above-selected materials. The proportion of mix for the control specimen was fixed as 20, 30, and 50 percent of 12 mm, 6 mm, and filler material, respectively. Figure 1 shows the gradation of materials used in the bituminous mixes, and all values are within the specified limit. The upper limit and lower limit of the gradation were selected from the bituminous concrete mix of grade 2 as per specification [56].

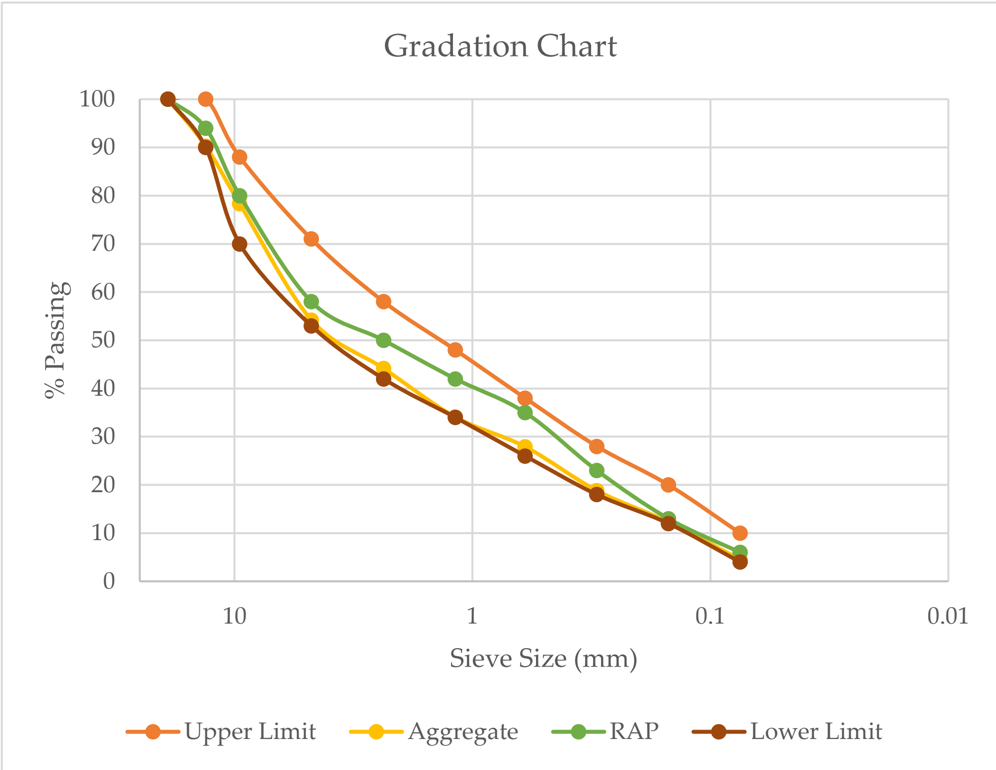

Figure 1. Gradation values of materials.

3.2. Specimen Preparation

In this study, two sets of the bituminous mix were used for casting the bituminous blocks, i.e., control mix and sustainable mix; for the sustainable mix, RAP and marble waste were integrated. The control mix proportioning with varying binder content is shown in Table 4. The bituminous specimens using RAP material were prepared by changing the percentage of RAP content, using the optimum binder content obtained for the control mix by the Marshall stability test. Eight mixes were prepared using sustainable material with varying RAP percentages and varying marble waste percentages in the RAP-incorporated control specimen as a replacement for filler material. The proportion of RAP in the bituminous mix was changed by 10%, 20%, 30%, and 40%. Marble waste was also used as a replacement for fines in the bituminous mix, in order to reduce the use of virgin materials. As per the literature study, marble waste can be used as a replacement for fines by about 100% [57]. The percentage of replacement of fines in the sustainable bituminous mix used for the present study was 25%, 50%, 75%, and 100%. In the marble mix, 30% of RAP was used, which denotes the optimum RAP content based on the laboratory test results. The sustainable bituminous mix proportioning adopted in this study is shown in Table 5.

Table 4. Control Mix Proportion.

Material (Grams)	Mix 1	Mix 2	Mix 3	Mix 4
12 mm aggregate	240	240	240	240
6 mm aggregate	360	360	360	360
Filler	600	600	600	600
Binder Content	54	60	66	72
Binder %	4.5	5	5.5	6

Table 5. Sustainable Mix Proportion.

Material (Grams)	RAP Mix				Marble Mix			
	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12
12mm aggregate	216	192	168	144	168	168	168	168
6mm aggregate	324	288	252	216	252	252	252	252
Filler	540	480	420	360	315	210	105	0
RAP	120	240	360	480	360	360	360	360
RAP %	10	20	30	40	30	30	30	30
Bitumen in RAP	5	10	15	20	15	15	15	15
Virgin bitumen	61	56	51	46	51	51	51	51
Marble	0	0	0	0	105	210	315	420
Marble %	0	0	0	0	25	50	75	100

3.3. Preparation of Bituminous Blocks

The optimum mixes obtained based on the previously discussed test results were used for the preparation of the bituminous blocks. These mixes included mix 3, mix 7, and mix 12, and the size of the bituminous block is 150 mm × 150 mm × 55 mm. Specimen thickness of the bituminous block is adopted based on the average thickness of the bituminous concrete layer in practice [58]. The procedure adopted for bituminous block manufacturing is similar to the Marshall specimen-casting technique, but the compaction is done using hydraulic compression instead of the drop-hammer compaction used for the casting of the Marshall specimen.

Initially, the ingredients are weighed, and the overall weight of the mix is fixed, based on the size of the compacted bituminous block. Then, the materials are mixed and heated up to the required temperature according to the specification, and compaction is done. Based on the trial-and-error method, the hydraulic load is given for the casting of blocks to achieve the desired density and thickness of the modular bituminous block. According to the standard specification in India, the equivalent standard axle load passing over the bituminous pavements is about 8 Ton [56], i.e., per dual wheel assembly, the load would be 4 Ton. For producing the bituminous blocks, a hydraulic loading of 90kN was applied which is more than the standard axle load as per the specifications. The schematic process of the bituminous block compaction and compacted bituminous block is shown in Figure 2.

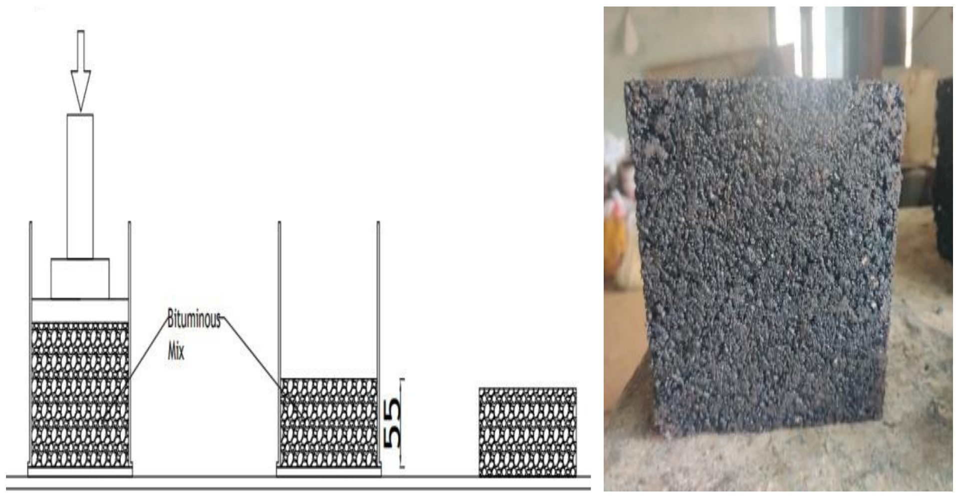

Figure 2. Bituminous block.

3.4. Test on Bituminous Blocks

In this study, the novel bituminous blocks are evaluated for their load-bearing capacity, rutting resistance, and loss of material due to abrasion and impact. In addition to the above-mentioned tests, a field simulation was carried out to evaluate the performance of bituminous blocks. The rut depth of the bituminous block is assessed by placing four specimens in the wheel rut tester mold, which is a unique approach used in this study. 158 block specimens were manufactured for conducting the performance evaluation. Conventional tests were done on an average of 3 samples for each test and an average of 16 samples was used for the rut test and field simulation test. The performance of the bituminous block when loaded over the edge and center of the block was tested using the wheel rut tester. The wheel rut testing of the bituminous block and the loaded area are shown in Figure 3. The placement of the bituminous block in the wheel rut test reflects the real scenario of bituminous block construction. The load-bearing capacity of the block was tested by using a compression strength-testing machine, and the procedure adopted was the same as per the testing of modular blocks [59]. The load observed at the failure of the bituminous block is recorded as the load-bearing capacity. The wear and tear of paver blocks is generally studied through conventional abrasion tests using an abrasive charge such as sand. These tests are not applicable or reliable in the case of the viscoelastic mix. Hence, a study on the performance of blocks subjected to abrasion and impact was done, based on the principles of the Cantabro loss test [60], with an aim to subject the blocks to an extreme amount of abrasion and impact.

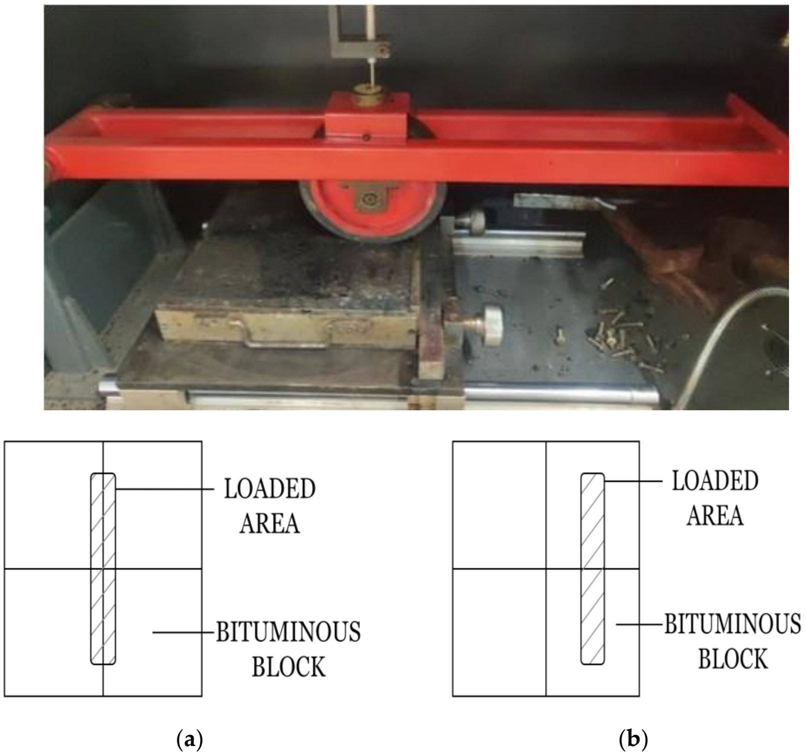

Figure 3. Wheel rut tester and loaded area (hatched area) (**a**) over the joint; (**b**) over the center.

3.5. Field Simulation Test

While the wheel rut tester evaluates the rut resistance of a bituminous block, the study has a limitation in that the role of underlying layers is not considered, as the slab is placed inside a steel mold. The field simulation test was conducted to evaluate the performance of the bituminous block by simulating a realistic scenario of bituminous block pavement subjected to repeated wheel loads in the field. A laboratory setup was fabricated using mild steel and acrylic sheet, to perform a field simulation test. From the field simulation test, the surface deformation and the rut depth of the bituminous blocks are measured by applying dynamic loading over the surface. The method of loading for the field simulation test was identical to the wheel rut test. In the setup, pavement layers were constructed, i.e., subgrade, subbase, base course, and blocks. The total material quantity for each pavement layer was determined by using the compacted density required. The material used for the subgrade is red soil and the thickness is 300 mm. The granular subbase layer was constructed using a combination of crushed stones, and the thickness is 150 mm. Wet mix macadam was constructed as the base course and the thickness is 250 mm. Bituminous blocks of thickness 55 mm are placed over the base course. The layer thickness of the pavement structure was calculated based on the California bearing ratio of the material. Loading was done by means of a hydraulically loaded pneumatic wheel. A loading set-up fabricated for another study in the laboratory was used for this purpose. The deformation of the surface was measured by using linear variable differential transducers (LVDT).

4. Results and Discussion

4.1. Marshall Stability

The binder content selected for the control specimen bituminous mix was 4.5%, 5%, 5.5%, and 6%, and the optimum binder content was determined by the Marshall stability test as described earlier. The average value of bitumen (binder) content giving maximum stability, maximum bulk density, and 4% air voids of the bituminous mix is the optimum binder content. Based on the test results, the following graphical plots are made: (a) stability vs. bitumen content, (b) bulk density vs. bitumen content, (c) air void vs. bitumen content, and (d) flow value vs. bitumen content. The graphical plots for the control specimen are shown in Figure 4. The optimum binder content and maximum stability value of the mix are, respectively, 5.5% and 12.42 kN. The stability value of the bituminous mix having a binder content of 6% decreased by 13% due to an increase in asphalt content. As the asphalt content increases, the flow value of the bituminous mix also increases and the percentage of air void decreases because of the voids filled by asphalt and an increase in adhesion between the particles.

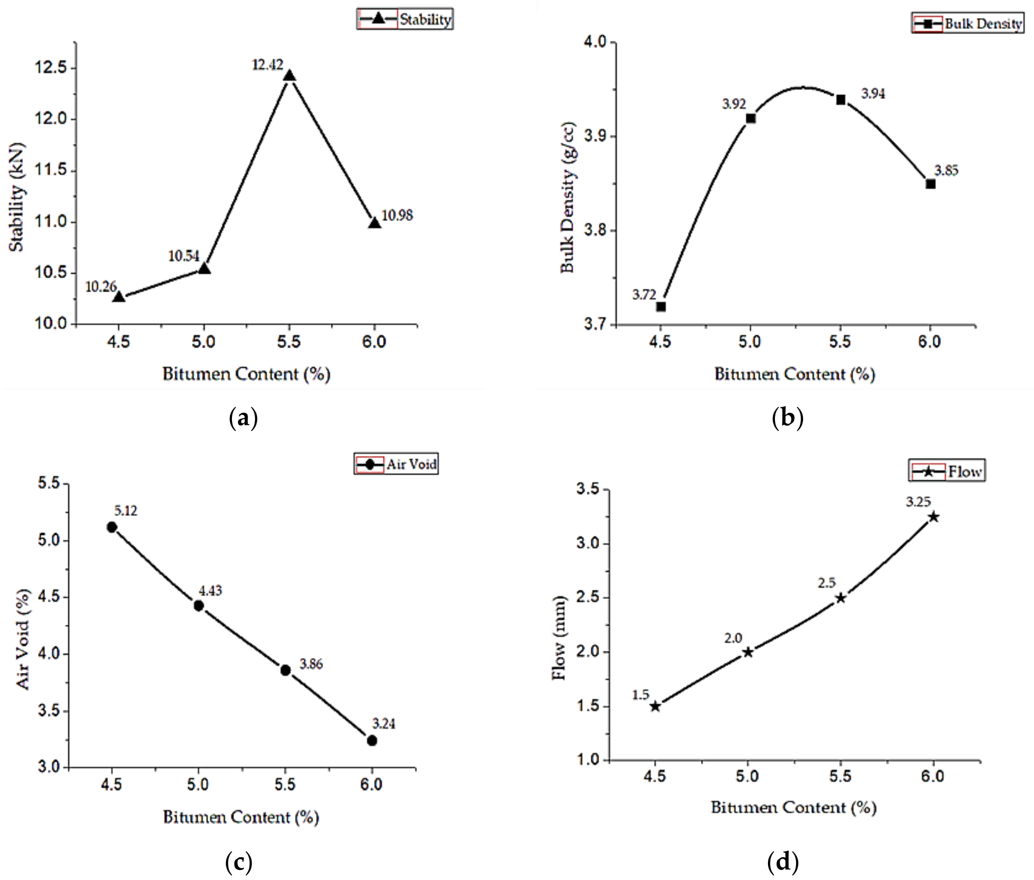

Figure 4. Graphical plots of control specimen (**a**) stability vs. bitumen content; (**b**) bulk density vs. bitumen content; (**c**) air void vs. bitumen content; (**d**) flow vs. bitumen content.

The sustainable mix using RAP was prepared using the optimum control mix, i.e., mix 3, by varying the percentage of RAP content. The optimum sustainable RAP mix is obtained by the Marshall stability test. The maximum stability value of 12.13 kN was observed for mix 7. Then, the inclusion of sustainable material in the bituminous mixes (mixes 9, 10, 11, 12) was evaluated using the Marshall stability test. The stability value of the bituminous mix containing marble waste increases as the waste content increases. The stability value is 10.41 kN for 25% replacement of marble in control + RAP mix, and it increases for 50%, 75%, and 100% replacement to 10.91 kN, 11.46 kN, and 12.09 kN, respectively. The stability value of mix 12 is 16% more than mix 9. The Marshall stability value for the fines replaced by marble specimens is shown in Table 6. The stability value of mix 9 is less than the control mix because the increase in fine material will increase the surface area and cause difficulty in binding, and reduce the voids too. The stability value for all the mixes is more than the specified value of 9kN. A comparison of stability values of the sustainable bituminous mixes is shown in Table 6.

Table 6. Marshall Test Results for Sustainable Mixes.

Parameter	RAP Mix				Marble Mix			
	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12
Stability (kN)	9.81	11.45	12.13	10.52	10.41	10.91	11.46	12.09

4.2. Evaluation of Bituminous Blocks

The modular paver blocks (concrete) are generally tested for load-bearing capacity using the compression-testing machine. There is no standard test or code specification available for assessing the performance of the modular bituminous paver blocks. In this study, the performance of the modular blocks was assessed by finding load-bearing capacity using the compressive strength-testing machine. The load sustained by the bituminous block for the three optimum mixes mix 3, mix 7, and mix 12 during the test are presented in Figure 5. The test results show that all the bituminous blocks sustained a load higher than the standard load of 80 kN. For the control mix (mix 3), RAP mix (mix 7), and marble mix (mix 12), the load-bearing capacity is higher than the standard load. The addition of marble waste thus increases the load-carrying capability of the bituminous block.

(**a**) (**b**)

Figure 5. Block specimen (**a**) before testing; (**b**) after testing, showing loss of material marked by red circles.

Corners of the specimen disintegrate more (red circles) in comparison with the central portion of the specimen, as shown in Figure 5 during the Cantabro loss test. While it is a matter of concern, it may be noted here that the specimen is allowed to cyclically fall from a height of 700 mm and hit the bottom of the abrasion testing cylinder. In addition, damage to the edges and corners is high as there is no adjacent block to transfer the loads, whereas, in reality, the effect would be minimal as there would be adjacent blocks in contact and bonding with the tested block. In this study, the principle of the Cantabro loss test method was used to perform a relative comparison between the blocks made out of the conventional mix and the sustainable mixes; the intention was only to rigorously test the vulnerability of each test specimen (damage to the edges and corners, and material loss), and hence, instead of Marshall cylindrical specimens, the blocks were tested as such. Cantabro loss test values (indicative only) for the square bituminous blocks are shown in Figure 6.

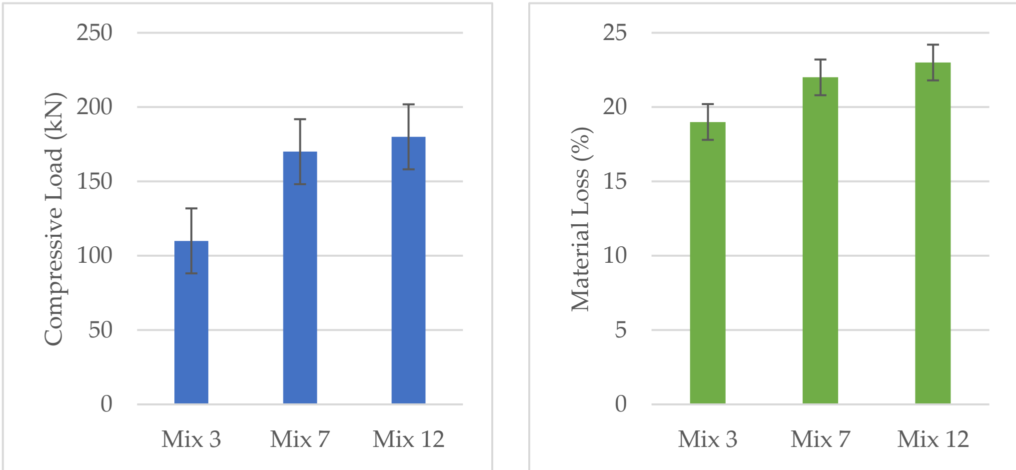

Figure 6. Results of compression and material loss based on the principle of Cantabro test.

The rut depth on the bituminous block is determined from the wheel rut test under a controlled temperature of about 60 °C. The rut depth values were measured for the bituminous blocks at two places, i.e., over the center of the bituminous block and over the joint of the bituminous blocks. The rut depth values for the bituminous block specimen are presented in Table 7. Compared to the results of the control specimen (4.15 mm), the bituminous block specimens using sustainable materials showed a better performance in rutting. Based on the test result, it can be inferred that the bituminous block specimens using marble dust showed better rut resistance. The rut resistance offered by the specimens with RAP and specimens with marble dust as fines is about 55% and 73% more, respectively.

Table 7. Average Rut Depth (mm).

Type	Position	Notation	Rut Depth	Standard Deviation
Control Mix	Joint	CMJ	4.15	1.46
Control Mix	Center	CMC	3.82	0.94
RAP Mix	Joint	RMJ	1.86	0.43
RAP Mix	Center	RMC	1.58	0.47
Marble Mix	Joint	MMJ	1.08	0.32
Marble Mix	Center	MMC	0.77	0.18

4.3. Field Simulation Test

The pavement layer construction with bituminous blocks is shown in Figure 7. The field simulation test was performed to measure the deformation under dynamic loading. A rolling load was applied through a loaded pneumatic tyre of a special set-up on the joints and center of blocks of the bituminous block pavement (by changing the laying pattern). The deformation of the bituminous block was measured using linear variable differential transducers (LVDT). The LVDTs are placed on the pavement on blocks adjacent to the wheel path. The position of the LVDT and loading path is shown in Figure 6. After the loading process, the rut depth, i.e., deformation along the wheel path, was measured using a steel rule. The deformation of the bituminous block by joint loading and center loading of the control mix after loading are shown in Figure 8. The rutting deformation values of the modular bituminous block for the control mix and sustainable mix using RAP and marble are shown in Table 8.

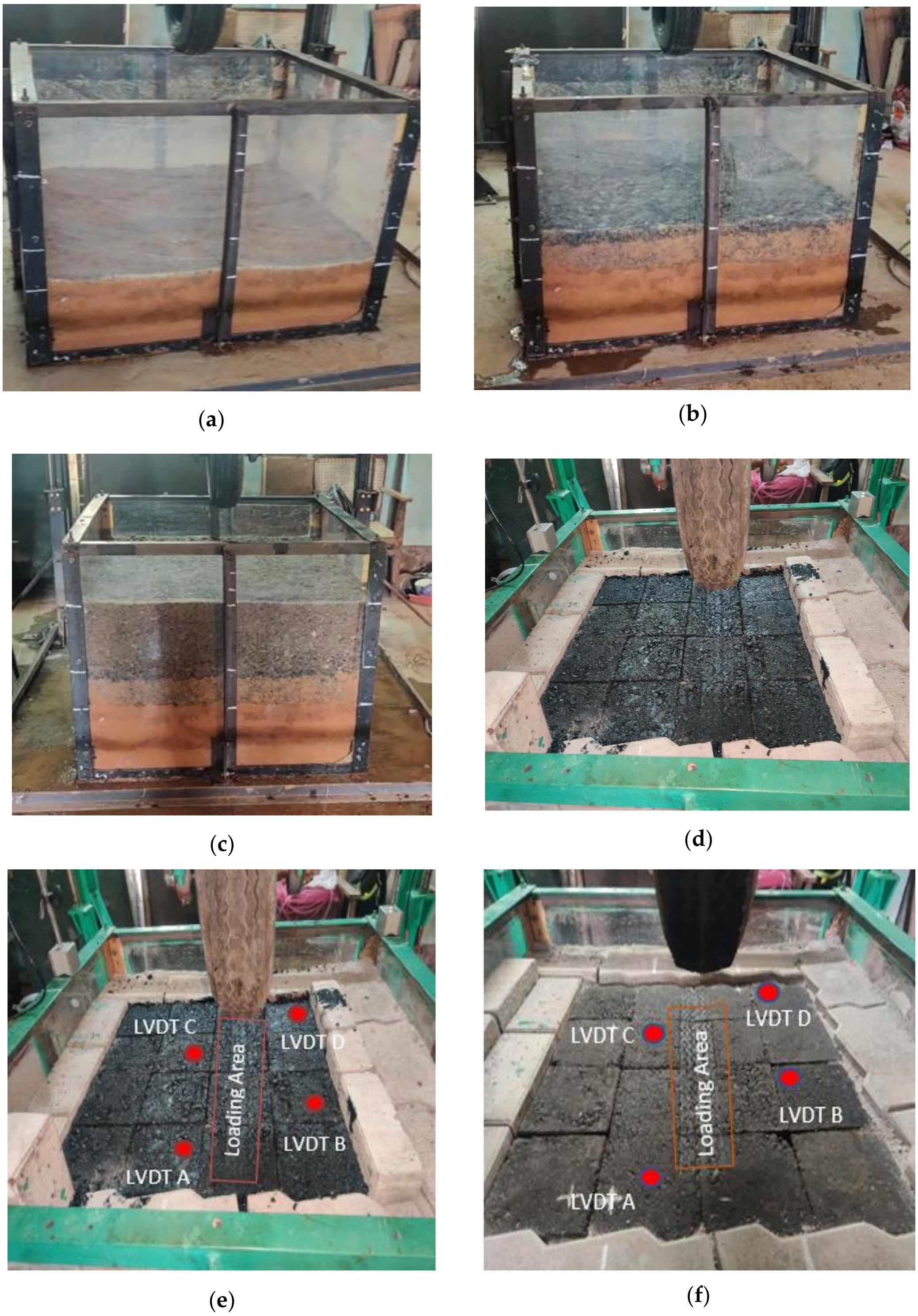

Figure 7. Bituminous block pavement setup (**a**) subgrade (300 mm thick); (**b**) sub-base (150 mm thick); (**c**) base course (250 mm thick); (**d**) bituminous block (55 mm thick); (**e**) loading over the center; (**f**) loading over the middle.

(**a**)

(**b**)

Figure 8. Deformation after loading (**a**) over the joint; (**b**) over the center. (Red Arrow – Depth of deformation).

Table 8. Field Simulation Test Results.

LVDT	Surface Deformation (mm)					
Position	**Control Mix Joint**	**Control Mix Center**	**Marble Mix Joint**	**Marble Mix Center**	**RAP Mix Joint**	**RAP Mix Center**
A	3.6	4.6	1.85	3.4	2.21	3.36
B	2.1	1	1.09	1.82	0.7	0.93
C	2.9	3.1	1.12	2.89	3.9	4.3
D	1.34	0.77	1.55	3.02	3.2	4.8

The deformation of bituminous blocks in the pavement far from the loaded area is significantly less than the deformation in the center for all the test trials. For the control mix loading on joint tests, the deformation value at location D is quite low compared to all other places since the load transferred to location D is insignificant. The load-deformation value at position C is nearly 19% lower than the deformation value at point A. The lowest deformation value was approximately 1.34 mm at point D for the control mix paver block, with loading on joint. Due to their close proximity to the loaded area, the deformation values at positions A and C are higher than those at positions B and D for the control mix blocks during the central loading trial.

Based on the measurement in the laboratory, the deformation at the center of the control mix specimens is approximately 6mm. The sustainable mix specimens using RAP and marble materials were then subjected to the field simulation test. The deformation along the wheel path after the dynamic loading is about 4mm and 2mm for the RAP and marble mix, respectively. The deformation value is significantly less at LVDT location B compared to all other positions for the sustainable mix. From Table 8, it is clearly observed that the deformation values are significantly higher when LVDTs are positioned very near to the loaded area (wheel track). In addition, the bituminous block does not require any jointing material due to the bonding and flexibility in the nature of the bituminous mix, along with its thermal response.

4.4. Cost Comparison

Apart from the scope of the study, a cost comparison of the bituminous block was carried out by comparing it to the conventional paver block. The cost comparison between the bituminous block and the conventional pavement block is shown in Table 9, based on the quantity of material required for the block paving and the standard rates specified. The chart shows the cost of materials required per square foot size. The ingredients required to make a single square foot of bituminous block cost roughly ₹25 ($0.30). The material cost of one square foot of conventional pavement block is roughly ₹39 ($0.47). The market value of one square foot of conventional pavement block, including transportation, is roughly ₹60 ($0.72). The modular bituminous block pavement is less expensive than the conventional pavement block in terms of cost. Material costs for conventional pavement blocks are 56% more than for bituminous blocks. Considering the study done by Rafiq et al. [61], the cost reduction was reported at about 14% using RAP compared with conventional material. Similarly, the use of sustainable materials in the manufacture of bituminous blocks decreases the cost much more comparatively.

Table 9. Cost Analysis (One Square Foot Size).

Materials	Quantity (kg)	Rate (₹/kg)	Cost (₹)
Bituminous Block			
12 mm	2.16	0.5	1.08
6 mm	3.24	0.5	1.62
Dust	5.4	0.4	2.16
Bitumen	0.594	34.6	20.55
	Total		₹25.41 ($0.30)
Conventional Pavement Block			
Coarse Aggregate	6	0.5	3
Fine Aggregate	9	1	9
Cement	3	9	27
	Total		₹39.00 ($0.47)

4.5. Trial Implementation in a Parking Lot

The study included a field trial in the parking lot with two small areas paved with modular bituminous block pavement and two with a conventional interlocking concrete pavement block. The construction site for bituminous blocks and conventional interlocking concrete pavement blocks is shown in Figure 9. From the field observation over one year, it was evident that the bituminous paver block would be suitable for use in parking lots, and for service maintenance works, rapid maintenance of bituminous pavement (pothole patching), etc. The joints were found to be bonded well without any jointing material, due to the viscoelastic nature of the mix.

Figure 9. Pavement block construction (parking lot).

4.6. Achievement of Sustainable Development Goals

Table 10 shows how the sustainable development goals (SDG) are achieved in the present study. Goals 9 and 12 are achieved to a great extent.

Table 10. Sustainable Development Goals Achieved by this Study.

Sl. No.	SDG Achieved	Contribution from the Present Work
1	SDG 9: Industry, Innovation and Infrastructure Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	• This research work is focused on the development of modular bituminous blocks using sustainable materials • After evaluation of the bituminous block in the field and laboratory, it shows a better performance • These bituminous blocks can be used as an innovative solution for the rapid maintenance of flexible pavement structures, utility service maintenance works, parking lot construction, etc.
2	SDG 12: Responsible Consumption and Production Ensure sustainable consumption and production patterns Target 12.5: Substantially reduce waste generation through prevention, reduction, recycling and reuse	• The consumption of natural resources can be reduced by 65% in bituminous pavement construction • By this method, the waste generated from the marble quarries/industry can be utilised as an ingredient for bituminous blocks • Recycling and reuse of materials from the existing pavement unit, i.e., bituminous block, is possible

5. Conclusions

A study was conducted on developing a novel bituminous block pavement using sustainable materials. The following are the most important conclusions drawn from this research study:

- Optimum bituminous mixes are obtained based on the Marshall test, and the optimum binder content is about 5.5% for the control mix.
- Utilization of sustainable materials in the bituminous mixes could reduce the use of conventional materials by 65%.
- Rut resistance offered by the sustainable bituminous paver blocks using RAP and marble is about 55% and 73%, respectively.
- As per the cost comparison, bituminous pavement blocks cost about 56% less than conventional paver blocks.
- As per the field trial test conducted, the bituminous pavement was found to be in a good and stable condition even after a year, promising durability too.
- From the field simulation test, it can be concluded that the bituminous block does not require any jointing material due to the flexibility in nature of the bituminous mix.
- However, a jointing material could improve the performance of bituminous blocks and load transfer; this needs further study.

Thus, from this study, it can be concluded that the proposed sustainable bituminous paver blocks can serve as a pavement-building unit for places such as parking lots, and in service maintenance works, rapid pavement maintenance, and pothole patching works. The road governing agencies and all stakeholders can implement this kind of innovation in regular practice, which makes it a way to achieve the SDGs fully in forthcoming years. A small step in the consideration of the SDGs in local-level constructions will make a huge impact, and this spreads to the country level as well as to the global level.

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References

1. MORTH. Basic _Road_Statics_of_India.pdf. 2019. Available online: https://morth.nic.in/basic-road-statistics-india (accessed on 10 November 2020).
2. Bressi, S.; Santos, J.; Orešković, M.; Losa, M. A comparative environmental impact analysis of asphalt mixtures containing crumb rubber and reclaimed asphalt pavement using life cycle assessment. *Inter. J. Pavem. Eng.* **2021**, *22*, 524–538. [CrossRef]
3. Forestier, O.; Kim, R.E. Cherry-picking the Sustainable Development Goals: Goal prioritization by national governments and implications for global governance. *Sustain. Dev.* **2020**, *28*, 1269–1278. [CrossRef]
4. United Nations General Assembly. Transforming our World: The 2030 Agenda for Sustainable Development. 2015. Available online: https://sdgs.un.org/publications/transforming-our-world-2030-agenda-sustainable-development-17981 (accessed on 17 May 2022).
5. Papagiannakis, A.T.; Masad, E.A. Pavement Rehabilitation. *Pavement Des. Mater.* 2012, in press. [CrossRef]
6. Akatsu, K.; Kanou, Y.; Akiba, S. Technical Approaches to the Recycling of Reclaimed Asphalt Pavement into Aggregate and Binder. *Constr. Mater.* **2022**, *2*, 85–100. [CrossRef]
7. Tarsi, G.; Tataranni, P.; Sangiorgi, C. The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review. *Materials* **2020**, *13*, 4052. [CrossRef]
8. Zhang, J.; Sesay, T.; You, Q.; Jing, H. Maximizing the Application of RAP in Asphalt Concrete Pavements and Its Long-Term Performance: A Review. *Polymers* **2022**, *14*, 4736. [CrossRef]
9. Hand, A.J.T.; Ragavan, P.; Elias, N.G.; Hajj, E.Y.; Sebaaly, P.E. Evaluation of Low Volume Roads Surfaced with 100% RAP Millings. *Materials* **2022**, *15*, 7462. [CrossRef]
10. Olita, S.; Ciampa, D. SuPerPave® Mix Design Method of Recycled Asphalt Concrete Applied in the European Standards Context. *Sustainability* **2021**, *13*, 9079. [CrossRef]

11. Sang, L.; Idowu, T.; Okumu, V. Evaluation of the performance of waste marble dust as a mineral filler in hot-mix asphalt concrete. *J. Civ. Eng. Sci. Technol.* **2021**, *12*, 1–14. [CrossRef]
12. Shekhawat, V.S.; Choudhary, P. Use of Marble Dust As Fillers in Asphalt Pavement. *Int. J. Mod. Trends Eng. Res.* **2017**, *4*, 196–204. [CrossRef]
13. Sufian, M.; Ullah, S.; Ostrowski, K.; Ahmad, A.; Zia, A.; Śliwa-Wieczorek, K.; Siddiq, M.; Awan, A. An Experimental and Empirical Study on the Use of Waste Marble Powder in Construction Material. *Materials* **2021**, *14*, 3829. [CrossRef]
14. Benjeddou, O.; Mashaan, N. Experimental Study of the Usability of Recycling Marble Waste as Aggregate for Road Construction. *Sustainability* **2022**, *14*, 3195. [CrossRef]
15. Wang, T.; Yang, W.; Zhang, J. Experimental Studies on Mechanical Properties and Microscopic Mechanism of Marble Waste Powder Cement Cementitious Materials. *Crystals* **2022**, *12*, 868. [CrossRef]
16. Gautam, P.K.; Kalla, P.; Nagar, R.; Agrawal, R.; Jethoo, A.S. Laboratory investigations on hot mix asphalt containing mining waste as aggregates. *Constr. Build. Mater.* **2018**, *168*, 143–152. [CrossRef]
17. Mistry, R.; Karmakar, S.; Kumar Roy, T. Experimental evaluation of rice husk ash and fly ash as alternative fillers in hot-mix asphalt. *Road Mater. Pavement Des.* **2019**, *20*, 979–990. [CrossRef]
18. Stępień, J.; Maciejewski, K. Using Reclaimed Cement Concrete in Pavement Base Mixes with Foamed Bitumen Produced in Cold Recycling Technology. *Materials* **2022**, *15*, 5175. [CrossRef]
19. Wang, Z.; Wu, S.; Yang, C.; Xie, J.; Xiao, Y.; Zhao, Z.; Wang, F.; Zhang, L. Quantitative Assessment of Road Performance of Recycled Asphalt Mixtures Incorporated with Steel Slag. *Materials* **2022**, *15*, 5005. [CrossRef]
20. Bilema, M.; Aman, M.; Hassan, N.; Al-Saffar, Z.; Mashaan, N.; Memon, Z.; Milad, A.; Yusoff, N. Effects of Waste Frying Oil and Crumb Rubber on the Characteristics of a Reclaimed Asphalt Pavement Binder. *Materials* **2021**, *14*, 3482. [CrossRef]
21. Khan, Z.H.; Koting, S.; Katman, H.; Ibrahim, M.; Babalghaith, A.; Asqool, O. Performance of High Content Reclaimed Asphalt Pavement (RAP) in Asphaltic Mix with Crumb Rubber Modifier and Waste Engine Oil as Rejuvenator. *Appl. Sci.* **2021**, *11*, 5226. [CrossRef]
22. Llopis-Castelló, D.; Alonso-Troyano, C.; Álvarez-Troncoso, P.; Marzá-Beltrán, A.; García, A. Design of Sustainable Asphalt Mixtures for Bike Lanes Using RAP and Ceramic Waste as Substitutes for Natural Aggregates. *Sustainability* **2022**, *14*, 15777. [CrossRef]
23. Awed, A.M.; Tarbay, E.W.; El-Badawy, S.M.; Azam, A.M. Performance characteristics of asphalt mixtures with industrial waste/by-product materials as mineral fillers under static and cyclic loading. *Road Mater. Pavement Des.* **2020**, *23*, 335–357. [CrossRef]
24. Edeh, J.E.; Ugama, T.; Okpe, S.A. The use of cement treated reclaimed asphalt pavement-quarry waste blends as highway material. *Int. J. Pavement Eng.* **2020**, *21*, 1191–1198. [CrossRef]
25. Tran, N.; West, R.; Taylor, A.; Willis, R. Evaluation of moderate and high RAP mixtures at laboratory and pavement scales. *Int. J. Pavement Eng.* **2017**, *18*, 851–858. [CrossRef]
26. Nandi, S.; Ransinchung, G.D.R.N. Laboratory investigation of Portland cement concrete paver blocks made with Reclaimed Asphalt Pavement aggregates. *Road Mater. Pavement Des.* **2022**, *23*, 546–564. [CrossRef]
27. Li, Y.; Zhang, Y.; Zhang, S. A High Proportion Reuse of RAP in Plant-Mixed Cold Recycling Technology and Its Benefits Analysis. *Coatings* **2022**, *12*, 1283. [CrossRef]
28. Saride, S.; Avirneni, D.; Javvadi, S.C.P. Utilization of Reclaimed Asphalt Pavements in Indian Low-Volume Roads. *J. Mater. Civ. Eng.* **2016**, *28*, 04015107. [CrossRef]
29. El-Maaty AE, A.; Elmohr, A.I. Characterization of recycled asphalt pavement (RAP) for use in flexible pavement. *Am. J. Eng. Appl. Sci.* **2015**, *8*, 233–248. [CrossRef]
30. Miró, R.; Valdés, G.; Martínez, A.; Segura, P.; Rodríguez, C. Evaluation of high modulus mixture behaviour with high reclaimed asphalt pavement (RAP) percentages for sustainable road construction. *Constr. Build. Mater.* **2011**, *25*, 3854–3862. [CrossRef]
31. Hajj, E.Y.; Sebaaly, P.E.; Shrestha, R. Laboratory evaluation of mixes containing recycled asphalt pavement (rap). *Road Mater. Pavement Des.* **2009**, *10*, 495–517. [CrossRef]
32. Vega, A.D.L.; Santos, J.; Martinez-Arguelles, G. Life cycle assessment of hot mix asphalt with recycled concrete aggregates for road pavements construction. *Int. J. Pavement Eng.* **2022**, *23*, 923–936. [CrossRef]
33. Wu, Z.; Yu, A.T.; Poon, C.S. Promoting effective construction and demolition waste management towards sustainable development: A case study of Hong Kong. *Sustain. Dev.* **2020**, *28*, 1713–1724. [CrossRef]
34. Pham, N.H.; Sauzéat, C.; Di Benedetto, H.; González-León, J.A.; Barreto, G.; Nicolaï, A. Fatigue and Thermal Cracking of Hot and Warm Bituminous Mixtures with Different RAP Contents. *Sustainability* **2020**, *12*, 9812. [CrossRef]
35. Hidalgo, A.; Moreno-Navarro, F.; Tauste, R.; Rubio-Gámez, M. The Influence of Reclaimed Asphalt Pavement on the Mechanical Performance of Bituminous Mixtures. An Analysis at the Mortar Scale. *Sustainability* **2020**, *12*, 8343. [CrossRef]
36. Antunes, V.; Neves, J.; Freire, A.C. Performance Assessment of Reclaimed Asphalt Pavement (RAP) in Road Surface Mixtures. *Recycling* **2021**, *6*, 32. [CrossRef]
37. Barraj, F.; Khatib, J.; Castro, A.; Elkordi, A. Effect of Chemical Warm Mix Additive on the Properties and Mechanical Performance of Recycled Asphalt Mixtures. *Buildings* **2022**, *12*, 874. [CrossRef]
38. Saboo, N.; Prasad, A.N.; Sukhija, M.; Chaudhary, M.; Chandrappa, A.K. Effect of the use of recycled asphalt pavement (RAP) aggregates on the performance of pervious paver blocks (PPB). *Constr. Build. Mater.* **2020**, *262*, 120581. [CrossRef]

39. Vandewalle, D.; Antunes, V.; Neves, J.; Freire, A.C. Assessment of Eco-Friendly Pavement Construction and Maintenance Using Multi-Recycled RAP Mixtures. *Recycling* **2020**, *5*, 17. [CrossRef]
40. Moon, K.H.; Falchetto, A.C. Double-Recycled Reclaimed Asphalt Pavement: A Laboratory Investigation at Low Temperatures Based on Different Mathematical Approaches. *Materials* **2020**, *13*, 3032. [CrossRef]
41. Gao, J.; Yao, Y.; Huang, J.; Yang, J.; Song, L.; Xu, J.; Lu, X. Effect of Hot Mixing Duration on Blending, Performance, and Environmental Impact of Central Plant Recycled Asphalt Mixture. *Buildings* **2022**, *12*, 1057. [CrossRef]
42. Pomoni, M.; Plati, C. Skid Resistance Performance of Asphalt Mixtures Containing Recycled Pavement Materials under Simulated Weather Conditions. *Recycling* **2022**, *7*, 47. [CrossRef]
43. Kore, S.D.; Vyas, A.K. Impact of marble waste as coarse aggregate on properties of lean cement concrete. *Case Stud. Constr. Mater.* **2016**, *4*, 85–92. [CrossRef]
44. Mohan, G.; Faizy, P.; Jacob, A.; Raju, G. Effect of Marble Waste and Coir Fibre Content on the Indirect Tensile Strength of Bituminous Concrete Mixtures. *Int. J. Curr. Eng. Technol.* **2016**, *6*, 1287–1294.
45. Sinha, R.; Kumar, S.; Garg, S.; Prasad, N.M. Use of electronic waste plastic in asphalt mix with marble dust as filler. *Indian J. Eng. Mater. Sci.* **2021**, *28*, 36–45.
46. Moghadas Nejad, F.; Azarhoosh, A.R.; Hamedi, G.H. Laboratory Evaluation of Using Recycled Marble Aggregates on the Mechanical Properties of Hot Mix Asphalt. *J. Mater. Civ. Eng.* **2013**, *25*, 741–746. [CrossRef]
47. Ullah, S.; Alam, M.; Khan, R. Re-use of Marble Waste as Filler Substitute in Bituminous Roads. *Int. J. Eng. Res. Appl.* **2017**, *7*, 58–62. [CrossRef]
48. Priya, P.; Archana, K.; Gohila, C.; Saraswathi, R. Utilization of Waste Plastic in Flexible Pavement with Marble Chips as Aggregate. *Int. J. Latest Technol. Eng.* **2017**, *6*, 159–162.
49. Akbulut, H.; Gürer, C. Use of aggregates produced from marble quarry waste in asphalt pavements. *Build. Environ.* **2007**, *42*, 1921–1930. [CrossRef]
50. Zhang, H.; Wu, J.; Fu, X.; Sui, B.; Lv, L. Comparative study on mechanical characteristics of precast HMA block versus concrete block. *Int. J. Pavement Eng.* **2018**, *21*, 549–558. [CrossRef]
51. Abdelgalil, A.; Nor, H. The influence of block thickness on the performance of asphalt paving blocks. *Res. J. Appl. Sci. Eng. Technol.* **2014**, *7*, 2129–2134. [CrossRef]
52. *IS 1201*; Methods for Testing Tar and Bituminous Materials: Determination of Specific Gravity. Bureau of Indian Standards: New Delhi, India, 1978; Volume 2.
53. *IS 1203*; Methods for Testing tar and Bituminous Materials: Determination of Penetration. Bureau of Indian Standards: New Delhi, India, 1978; Volume 2.
54. *IS 1205*; Methods for Testing Tar and Bituminous Materials: Determination of Softening Point. Bureau of Indian Standards: New Delhi, India, 1978.
55. *IS 1208*; Methods of Testing tar and Bituminous Materials: Determination of Ductility. Bureau of Indian Standards: New Delhi, India, 1978; Volume 1.
56. MoRTH. *Specifications for Road and Bridge*; Ministry of Road Transport and Highways: New Delhi, India, 2013; Third Revision.
57. SevilKofteci; Niyaziugurkockal. Using Marble Wastes as Fine Aggregate in Hot Mix Asphalt Production. In Proceedings of the International Conference on Advances in Civil, Structural And Construction Engineering-CSCE, Rome, Italy, 7–8 June 2014; Volume 1, Issue 3. pp. 117–121. Available online: http://seekdl.org/nm.php?id=3648 (accessed on 9 June 2020).
58. *IRC 37*; Guidelines for the Design of Flexible Pavements. (Issue Fourth Revision). Indian Road Congress: New Delhi, India, 2018.
59. *IS 516*; Method of Tests for Strength of Concrete. Bureau of Indian Standards: New Delhi, India, 1959; pp. 1–30.
60. Texas DoT, M. and T. D. Test Procedure for Cantabro loss. In TxDoT. Available online: https://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/200-F_series/pdfs/bit245.pdf (accessed on 1 August 2021).
61. Rafiq, W.; Musarat, M.A.; Altaf, M.; Napiah, M.; Sutanto, M.H.; Alaloul, W.S.; Javed, M.F.; Mosavi, A. Life cycle cost analysis comparison of hot mix asphalt and reclaimed asphalt pavement: A case study. *Sustainability* **2021**, *13*, 4411. [CrossRef]