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Performance evaluation of HMA using recycled brick powder as filler with Superpave aggregate gradation

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Abstract:
The performance of hot-mix asphalt (HMA) typically hinges on the quality of the ingredients utilized in blending the asphalt concrete. In this study the Superpave mix design method is used to investigate the performance of HMA with recycled brick powder (RBP) added as a filler. A non-probability sampling technique was used to gather samples. The engineering characteristics of materials used in HMA components, such as bitumen (80/100 penetration grade), aggregates, RBP, and crushed stone dust (CSD), were verified against standard specifications. The impact of RBP as a filler substance on the Marshall properties, stripping tests, moisture susceptibility, and permanent deformation in asphalt mixtures were assessed. Chemical analysis of the RBP indicated that silicon dioxide, aluminium oxide, and iron oxide collectively constituted 62,68; 14,74 and 9,16 %, respectively, of its composition satisfying the minimum requirements for natural pozzolan materials. The RBP specific gravity and plastic index, were 2,66 and non-plastic, respectively. HMA specimens were prepared with conventional filler CSD in three proportions (4, 5, and 6 %) and eight bitumen contents from (3,0-6,5 %) with 5,0 % of CSD selected as the control mix. The CSD filler in proportions of 4, 3, 2, 1, and 0 % was combined with RBP in proportions of 1, 2, 3, 4, and 5 %, respectively, to replace the 5 % CSD control mix. The optimum bitumen content was maintained at 5,45 %. The replacement rates of 3 % RBP + 2 % CSD meet ERA standard specifications for Marshall properties, offering a cost-effective solution with low permanent deformation (2,88 mm) and high tensile strength ratio (94,39 %). Incorporating RBP in HMA aligns with the criteria suggested in the Superpave aggregate gradation for up to 3 % RBP + 2 % CSD replacement of conventional filler in HMA production.

Keywords:
recycled brick powder; crushed stone dust; Superpave aggregate gradation; rut depth; tensile strength ratio

1 Introduction

The use of recycled construction materials is becoming increasingly common worldwide, representing a popular and interesting area of research owing to their various advantages [1]. Conventional and non-conventional filler materials play an important role in hot-mix asphalt (HMA) mixture production, including crushed stone dust (CSD), cement, marble, volcanic cinder, and limestone, which pass through a 0,075 mm sieve. These materials, particularly HMA, are increasingly accepted as filler materials when building roads [2-4]. Previous studies [5-7] have confirmed that the applicability of these materials is mainly based on their availability and particle size distribution. Fine materials can act as fillers or extenders in asphalt–cement binders. Early investigations into the engineering properties of filler materials for HMA production recommended checking the stiffening properties and sizes of the filler materials. Additionally, some fine particles in the mixture may increase the risk of moisture-related damage to the HMA [5]. Brick filler significantly influenced the asphalt mix characteristics, acting as an active constituent in the mastic behaviours. This helps fill the spaces between the coarse and fine aggregates and modifies the mechanical properties of the asphalt binders. The mastic quality influences the mechanical properties and workability of asphalt mixtures [8].

The presence of filler in HMA influences the overall performance in affecting the amount of asphalt content, workability during preparation and compaction, and mechanical properties of the resulting asphalt filler mastic. The fundamental bituminous mix variables (filler content, binder content, and asphalt binder type) influence compaction resistance. Higher compaction resistance leads to higher measured stiffness values and better resistance to permanent deformation in the asphalt. Pavement performance is expected to improve, and adding additional fines increases the measured stiffness at the expense of compaction resistance [8]. Numerous studies have investigated the effects of fines, fillers, and mortar on the HMA performance in laboratories and outdoors. Modelling the entire interaction between the filler and binder, characterising the particle size or packing, and mortar-based binder testing are the three basic methodologies used to characterise fillers [9]. The amount and quality of the constituent parts of the mixture directly affect the performance of bituminous surface roads [10], [11]. Asphalt mixed designs have been a major concern in several research studies, which have shown that changing the type, size, and gradation of aggregates, as well as the filler-to-asphalt ratio and type and volume of the filler, alters the physical properties of HMA concrete. Depending on the type, studies have demonstrated that fillers contribute to the effectiveness of asphalt mixtures beyond filling holes [12]. The finest constituent in HMA concrete mixtures is that used to fill the granulometry and aids in minimising voids. This filler material can reduce the heat susceptibility of an asphalt pavement during its design life and control the overall thickness and mechanical properties of the film of mastic covering stone-based aggregates [13].

Brick debris accounts for a significant amount of the solid waste generated by the construction industry and demolition operations worldwide, leading to increased environmental pollution and land consumption. Cement manufacturing processes are not environmentally friendly because of the use of natural resources and greenhouse gas emissions. Crushing leftover bricks into recycled brick powder (RBP) and using it instead of cement as a sustainable building material is considered a viable option [14]. Asphalt concrete mixtures with RBP exhibit lower permanent creep deformation than that for mixtures with limestone as a filler material, indicating better high-temperature performance with respect to the control asphalt mixtures [15], [16]. The main objective of this study was to determine how RBP fillers with different contents can be used when passing through a 0,075 mm filter in different mixtures. To achieve this, several laboratory tests were conducted on different mixture proportions using multiple mix designs, including Marshall tests and performance tests, based on specified standard requirements.

2 Methodology

2.1 Research methods

In addition to determining the volumetric characteristics of the Marshall mix design, the stability and flow values were examined using the Marshall design approach to investigate the properties of the asphalt mixture and determine the suitability of using RBP as a filler with CSD in different proportions in asphalt mixtures, as shown in Figure 1. The norms of each standard are indicated for each test, along with the methods, results, and discussions.

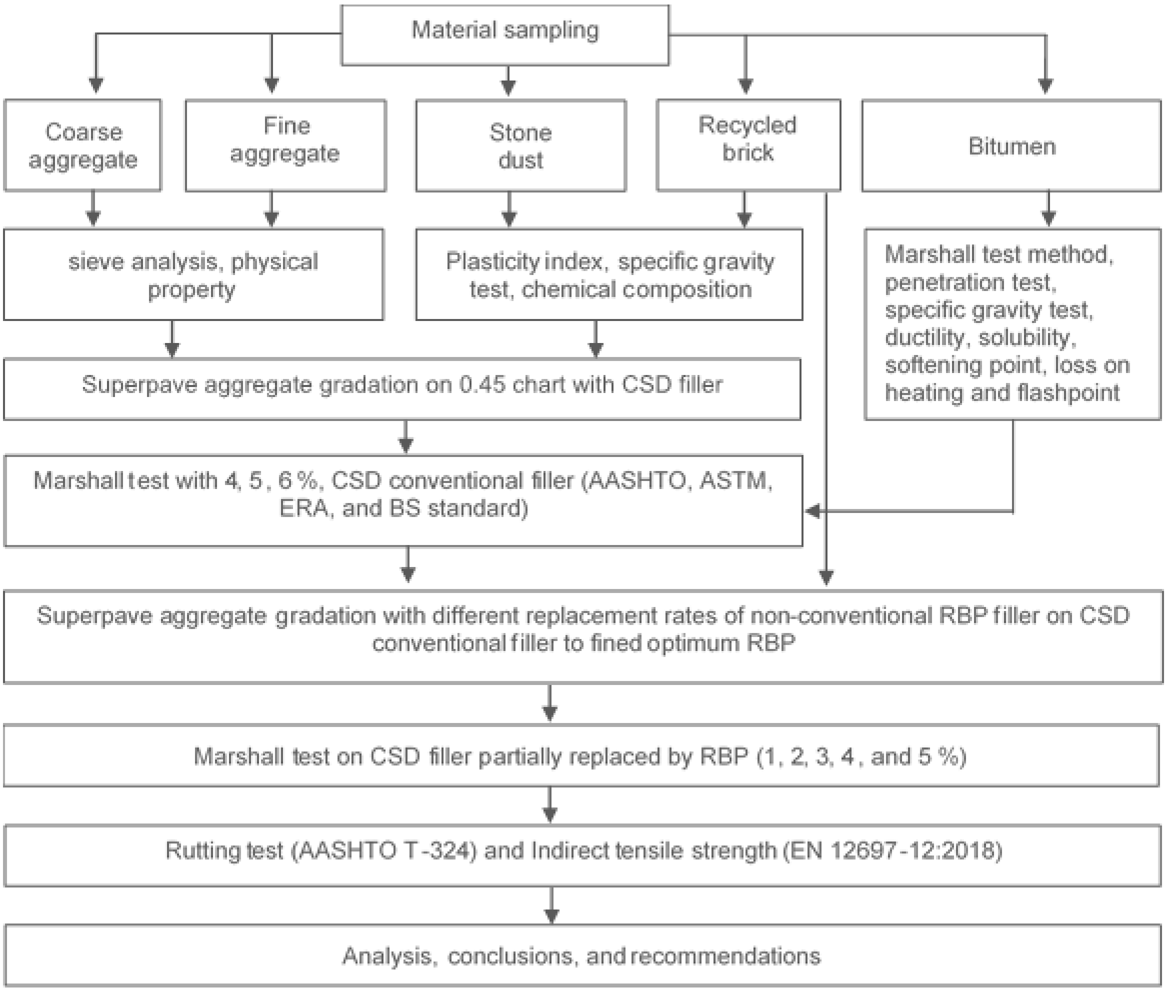

Figure 1. Overall research approach with 1-5 % recycled brick powder (RBP) replacement

2.2 Materials

To verify this study, non-probability sampling selection criteria were implemented to collect materials used for the investigation. The materials used and their specific sources were as follows:

- Crushed stone aggregates (coarse, and fine) were collected from the Ethiopian Road Administration (ERA) quarry site in Kality Sub-city, Addis Ababa, Ethiopia.
- Bitumen (80/100 penetration grade) was collected from Addis Ababa City Road Authority (AACRA) bitumen stock, Addis Ababa.
- CSD from the ERA batching plant, Addis Ababa and RBP from Ethio Brick Factory, Burau, Addis Ababa, Ethiopia, were used as mineral fillers.

Specific gravity and plasticity index tests were conducted before the demolished bricks were collected. The conditions and quality of the materials were then determined to check whether they could be reused. This material was collected from different waste brick demolition sites of the Ethio Brick Factory around Burau in Addis Ababa, Ethiopia, and the CSD from the ERA batching plant.

2.2.1 Physical properties of aggregate

Numerous laboratory tests have been conducted to investigate the physical properties of the aggregates used in this study and their suitability for HMA road construction. Before proceeding with the additional testing of the aggregates, the initial step involved preparing samples through quartering to obtain an unbiased representation of the samples. Following the AASHTO T 248-96 [17] guidelines, the crushed stone aggregate samples were quartered and prepared for the different tests.

The aggregates used in this study were sieved to the required sizes and recombined to meet the design gradation specified in the standard requirements for the intended purpose, as listed in Tables 1-6. In this study, the Superpave gradation was used to formulate a trial Marshall mix design. The plot of the crushed stone aggregate particle distribution differs from that of a conventional graph and is depicted on a 0,45 power chart. The accepted aggregate blending gradations are shown in Figure 2.

Table 1. 25 mm maximum nominal size aggregate gradations

Sieve analysis (sieve size in mm)		25	19	12,5	9,5	4,75	2,36	1,18	0,6	0,3	0,15
nominal maximum aggregate sizes	19	100	73,1	3,9	2,0	1,4	1,0	0,7	0,5	0,3	0,1
	9,5	100	100	100	4,8	2,4	1,5	0,9	0,6	0,4	0,2
	4,75	100	100	100	100	6,4	4,1	2,6	1,4	0,8	0,5
	2,36	100	100	100	100	100	57,9	29,9	12,5	1,1	0,6
	filler	100	100	100	100	100	100	100	100	100	95,6

In HMA mixture preparation, design gradation is one of the most important parameters for determining the properties and quality of the mixture. The blended aggregate gradations were designated according to the Superpave chart below the restricted zone (SCBRZ4, SCBRZ5, and SCBRZ6), describing the Superpave gradation below the restricted zone with 4.0, 5.0, and 6,0 % CSD filler proportions, respectively. As mentioned earlier, aggregates from the crushing site were delivered in five different sizes: nominal maximum sizes of 19; 9,5; 4,75; 2,36; and fillers.

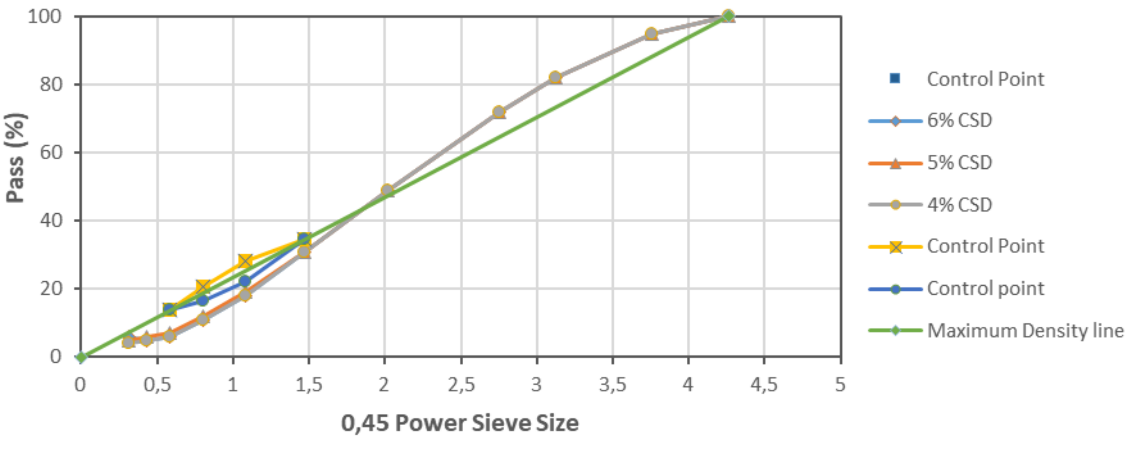

Figure 2. Superpave gradation 0,45 power chart used for 4, 5, and 6 % CSD filler

Laboratory tests were conducted to evaluate the physical and chemical properties of the CSD and RBP fillers, as listed in Tables 2, 3, and 4. As can be seen from the results, both the RBP and CSD pass the ERA 2013 [18] specifications.

Table 2. RBP filler physical test result

No.	Test Description	Test methods		Result	ERA Specification
		AASHTO	ASTM		
1	Plastic Index, (PI)	T89 or T90	D 423 or 424	NP	≤ 4,0
2	Specific gravity (kg/m^3)	T 100 or 104	D 854 or C 88	2,660	N/A

Table 3. CSD filler physical test result

No.	Test Description	Test methods		Result	ERA Specification
		AASHTO	ASTM		
1	Plastic Index, (PI)	T89 or T90	D 423 or 424	NP	≤ 4,0
2	Specific gravity (kg/m^3)	T 100 or 104	D 854 or C 88	2,768	N/A

Table 4. Chemical composition of fillers

Chemical Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LoI
Content (%) RBP	62,68	14,74	9,16	3,24	0,84	2,28	2,36	0,28	0,19	0,53	0,40	1,83
Content (%) CSD	54,08	9,2	10,32	11,44	1,36	0,84	0,82	0,40	0,60	4,54	1,77	5,44

Regarding the surface roughness or smoothness of the fillers, high-resolution scanning electron microscopy (SEM) images revealed that the core morphology of the recycled fillers exhibited irregular or rough surfaces [19]. Conventionally used CSD was included to prepare control mixes for comparing results. Figures 3 and 4 show the physical and SEM images (ASTM E986, 2010) [20] of the morphological appearance of the CSD and RBP fillers. The SEM results show that the surface of the RBP is much rougher and its particle distribution is more homogeneous than that of the CSD, indicating that RBP has higher absorption capacity than the CSD filler.

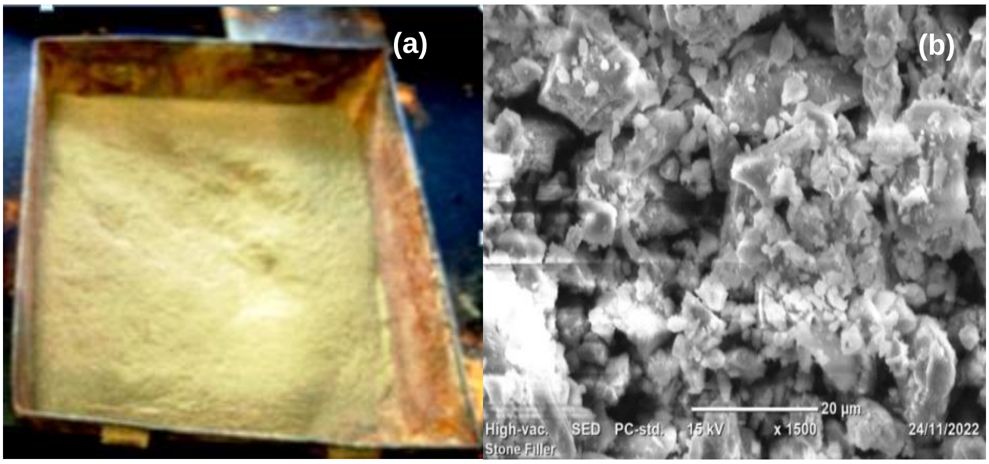

Figure 3. (a) CSD filler; (b) SEM image of CSD

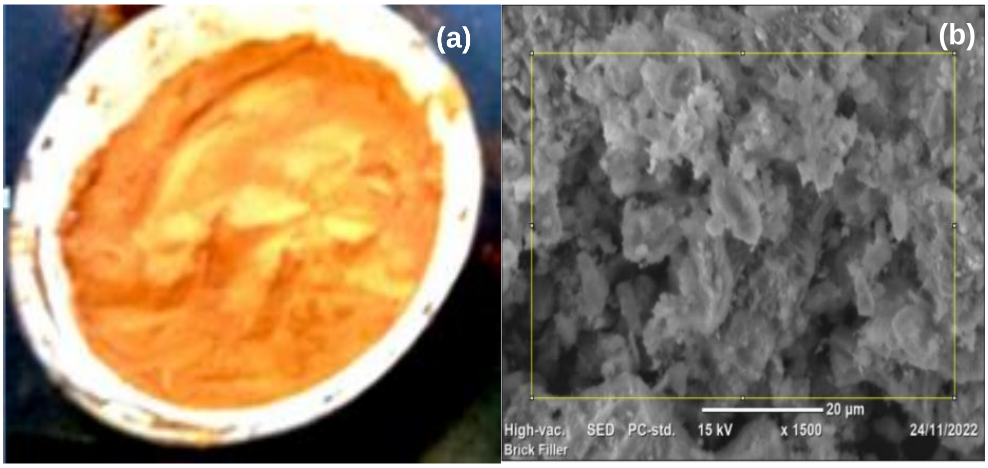

Figure 4. (a) RBP; (b) SEM image of RBP

Laboratory tests were conducted to evaluate the physical properties of crushed rock aggregates as shown in Table 5. The laboratory results for the crushed rock aggregate satisfied the ERA 2013 [18] specifications for HMA mixtures.

Table 5. Aggregate quality test results

No.	Test Description		Standard	Result	Requirements (ERA 2013)
1	Los Angeles Abrasion - LAA (%)		AASHTO T 96	16,000	< 30,00
2	Aggregate Crushing Value - ACV (%)		BS 812 part 104	15,000	<25,00
3	Durability and Soundness (%)		ASTM C 128	2,000	<12,00
4	Aggregate Specific Gravity (kg/m^3)	Fine	AASHTO T 85	2,719	N/A
		Course		2,851	
5	Water Absorption (%)		ASTM C 127	1,50	<2,00
6	Particle shape, Flakiness (%)		BS 812, Part 110	23,000	<45,00
7	Aggregate Impact Value - AIV (%)		BS 812 Part 112	10,000	<25,00
8	Affinity for Asphalt (Coating and Stripping) (%)		AASHTO-182	98,000	> 95,00

The bitumen quality tests were conducted as listed in Table 6. A grade 80/100 petroleum asphalt from the AACRA was used in this study. This grade is commonly used in road construction in Ethiopia. Before the experiment, the bitumen was checked in the laboratory for material acceptance based on the ERA 2013 [18] specifications. The results were accepted based on the specifications.

Table 6. Bitumen (80/100) quality tests method and description

No.	Test Description	Test Method ASTM / AASHTO	Result	ERA specification
1	Penetration 25 ^{o}c	ASTM D5/ T49	82,00	80-100
2	Specific gravity (kg/m^3)	ASTM D70/ T228	1012,00	1020 ±
3	Ductility, 25 ^{o}c (cm) min	ASTM D113/ T51	100$^+$	> 75,00
4	Solubility, % min	ASTM D2042/ T44	99,49	99,00
5	Softening Point, ^{o}C	ASTM D36/ T53	49,00	42-51
6	Loss on heating, % max	ASTM 36/ T47	0,09	0,80
7	Flash Point, ^{o}C min	ASTM D 92/ T48	278,00	min 232

2.2.2 Marshall test procedure on replacing the filler using optimum bitumen content and designed CSD

After the determination of optimum bitumen content (OBC) and the designed CSD, the CSD content in proportions of 4, 3, 2, 1, and 0 % was combined with RBP in the proportions of 1, 2, 3, 4, and 5 %, respectively, of the mass of the total optimum filler content. The filler was replaced while keeping the Superpave gradation design and OBC unchanged. Three samples, each weighing 1200 g, were fabricated for each filler proportion, and the average values of the bulk specific gravity of the mix, Marshall stability, flow, air voids (AV), voids in the mineral aggregate (VMA), voids filled with asphalt (VFA), and performance tests such as indirect tensile strength (ITS) and rutting were determined and compared with the control mix, as well as with the specifications.

2.2.3 Permanent deformation (rutting) test

As per AASHTO T 324 [19], the following parameters were tested, and several passes were conducted to reach the predefined maximum allowable rut depth, Hamburg wheel-tracking device test, and proportional rut depth.

2.2.4 ITS

The HMA specimens were extracted from the moulds, the test specimens were stored for 72-96 h at 20 °C, and tightly covered with a plastic film. They were wrapped and sealed in a plastic bag containing 10 ml of water then placed in a freezer at -18 ± 3 °C for a minimum of 16 h. After freezing, the specimens were placed in a 60 ± 1 °C water bath for 24 ± 1 h. These procedures were repeated for several cycles until surface cracks appeared. At the end of each complete cycle, the specimens were carefully examined to check the appearance of cracks. A crack was observed at the end of three cycles. An ITS test was then performed.

3 Results and discussions

3.1 Analysis of asphalt properties

Tables 7, 8, and 9 present the different percentages of CSD filler with Superpave gradation below the restricted zone Marshall test results. The main purpose of these tests was to compare the mechanical properties of the asphalt mixtures with CSD and RBP fillers in HMA production. The Superpave gradation suggested that the filler content be in the range from 4-6 %. Based on the results listed in Tables 9-11, all pass the required Superpave gradation inside the restricted zone. Previous studies on the effects of fillers on bituminous mixtures have revealed that the type and amount of filler significantly affect the performance of HMA mixtures [6], [8], [10], [11], [13-16], [21]. The results obtained in this study are discussed in the following sections.

Table 7. 4% CSD filler Marshall properties of bituminous mixture with different asphalt content

Asphalt by total mix (%)	**Bulk specific gravity** (gm/cm^3)	**Unit weight** (kg/m^3)	**G** (mm)	**Air void** (%)	**VMA** (%)	**VFA** (%)	**Corrected stability** (kN)	**Flow** (mm)
3,0	2,39	2382,71	2,61	7,52	15,62	51,88	8,58	3,04
3,5	2,40	2394,67	2,59	6,85	15,20	54,92	9,18	2,99
4,0	2,42	2411,36	2,57	6,00	14,61	58,93	9,40	2,84
4,5	2,43	2420,73	2,55	4,86	14,72	67,02	9,60	2,83
5,0	2,43	2425,89	2,54	4,02	14,99	73,21	9,71	2,82
5,5	2,43	2425,89	2,54	4,02	14,99	73,21	9,71	2,82
6,0	2,46	2450,21	2,50	1,70	15,04	88,72	9,22	2,85
6,5	2,44	2436,83	2,49	1,64	15,95	89,74	8,00	2,85

Table 8. 5% CSD filler Marshall properties of bituminous mixture with different asphalt content

Asphalt by total mix (%)	**Bulk specific gravity** (gm/cm³)	**Unit weight** (kg/m³)	**G** (mm)	**Air void** (%)	**VMA** (%)	**VFA** (%)	**Corrected stability** (kN)	**Flow** (mm)
3,0	2,35	2340,72	2,62	9,36	17,11	45,31	6,94	3,34
3,5	2,36	2357,68	2,60	8,52	16,51	48,41	7,30	3,12
4,0	2,37	2365,25	2,58	7,98	16,24	50,88	7,63	2,93
4,5	2,38	2373,71	2,56	6,89	16,38	57,94	8,13	2,89
5,0	2,40	2392,22	2,54	5,57	16,17	65,55	8,79	2,84
5,5	2,38	2377,06	2,53	6,81	16,26	58,13	8,18	2,88
6,0	2,41	2406,45	2,51	3,80	16,55	77,06	9,02	3,05
6,5	2,41	2399,22	2,49	3,26	17,25	81,10	8,65	3,08

Table 9. 6% CSD filler Marshall properties of bituminous mixture with different asphalt content

Asphalt by total mix (%)	**Bulk specific gravity** (gm/cm³)	**Unit weight** (kg/m³)	**G** (mm)	**Air void** (%)	**VMA** (%)	**VFA** (%)	**Corrected stability** (kN)	**Flow** (mm)
3,0	2,37	2365,69	2,62	8,52	16,22	47,43	6,77	3,26
3,5	2,39	2380,35	2,60	7,72	15,70	50,87	7,31	3,08
4,0	2,39	2383,22	2,58	7,38	15,6	52,67	8,01	2,90
4,5	2,41	2398,98	2,56	6,01	15,49	61,21	9,65	2,88
5,0	2,42	2412,58	2,54	4,66	15,45	69,87	9,91	2,86
5,5	2,43	2425,14	2,52	3,55	15,46	77,04	11,78	2,84
6,0	2,43	2425,93	2,50	2,79	15,88	82,45	9,25	2,88
6,5	2,42	2411,50	2,48	2,45	16,82	85,43	8,65	2,95

3.2 Determinations of OBC and CSD filler

The Marshall test was used to determine the OBC. Five percentages of bitumen were examined to determine the best percentage of bitumen for the aggregates used, including 3,0; 3,5; 4,0; 4,5; 5,0; 5,5; 6,0; and 6,5 % by weight of the total mix, with three specimens for each percentage. The procedure for determining the OBC of a particular mixture under evaluation was adopted from the Asphalt Institute of MS-2 Manual (Asphalt Institute, MS-2, 2014) [22] and ASTM D1559 [23]. Accordingly, the OBC was taken as the average of the bitumen content values that correspond to 4 % AV from the bitumen variation with voids in the total mix (VTM) graph. Once the bitumen content at 4 % AV was determined, it was used as the initial point for all parameters from the graph. The OBCs of the three mixtures produced from the CSD of Superpave gradation, namely CSD4 (CSD at 4 %), CSD5 (CSD at 5 %), and CSD6 (CSD at 6 %) were 5,95, 5,45, and 5,10 %, respectively. The stability values were 9,1; 10,1; and 9,7 kN, respectively; flow values were 2,64, 2,80, and 2,81 mm; VMA values were 16,6; 15,6; and 14,1 %, respectively; VFA values were 75,6; 74,0 and 72,5 %, respectively; and bulk density values were 2,402, 2,418, and 2,428 gm/cm^3, respectively. From these data, the VFA value of 75,6 % for 4 % CSD was outside the standard requirement of the pavement design manual. Therefore, they were excluded from comparison. However, both 5 % and 6 % CSD fillers satisfied this requirement. Although both met the requirements, 5 % CSD filler and 5,45 % OBC were selected for the design because of their higher Marshall stability and lower Marshall flow. The selected Marshall and volumetric parameters are listed in Table 10.

Table 10. Summary of selected results

Marshall Parameters	Result at CSD = 5 % and OBC = 5,45	ERA, 2013 specification		Remark
		Min.	Max.	
Flow, (mm)	2,8	2	3,5	ok
Air voids (%)	4	3	5	ok
VMA	15,6	12	-	ok
Stability (kN)	10,10	8	-	ok
VFA	74	65	75	ok
Bulk Density, (g/cm^3)	2,418	-	-	ok

3.3 Effects of RBP and CSD fillers

Keeping the designed filler content of 5 % constant and applying the acquired OBC, CSD contents at 4, 3, 2, 1, and 0 % were combined with RBP at 1, 2, 3, 4, and 5 %, respectively, by mass, as shown in Table 11. The Marshall test results satisfied the ERA specifications listed in Table 10. The selection of the optimum replacement was based on the effects of the RBP on each of the parameters of the Marshall test results.

Table 11. Marshall mix design and Superpave gradation results for different RBP %

5% of Fillers (RBP &CSD) respectively	Asphalt by total mix (%)	Bulk Density (gm/cm^3)	G (mm)	Air Void (%)	VMA (%)	VFA (%)	Corrected Stability (kN)	Flow (mm)
1 % & 4 %	5,45	2,409	2,515	4,2	16,2	73,9	10,58	2,83
2 % & 3 %	5,45	2,403	2,51	4,2	16,3	74	10,53	2,83
3 % & 2 %	5,45	2,397	2,504	4,3	16,5	74,2	10,48	2,83
4 % & 1 %	5,45	2,394	2,497	4,1	16,6	75,1	10,41	2,83
5 % & 0 %	5,45	2,387	2,493	4,2	16,8	74,9	10,22	2,82

3.4 Effects of RBP on VTM

The VTM refers to the total volume of small pockets of air between the coated aggregate particles throughout the compacted paving mixture and is expressed as a percentage of the bulk volume of the compacted paving mixture. The AV decreased as the bitumen content increased. When the filler percentage decreased, the AV increased. This trend of increasing AV is attributed to the absorptive properties of the porous portion, which creates a thick film, hindering the interlocking of the aggregates. In addition, during compaction, the attached mortar may detach from the natural aggregate, adding to the filler VTM. At the midpoint of the ERA 2013 [18] specifications, the VTM specification is from 3-5 %, and the ERA recommends 4 %. At this point, different OBC levels were found depending on the different proportions of CSD filler content (Figure 5). Table 12 shows the AV and percentage of the RBP fillers. A polynomial equation was generated using regression analysis to determine the relationship between the percentage of RBP filler and the AV.

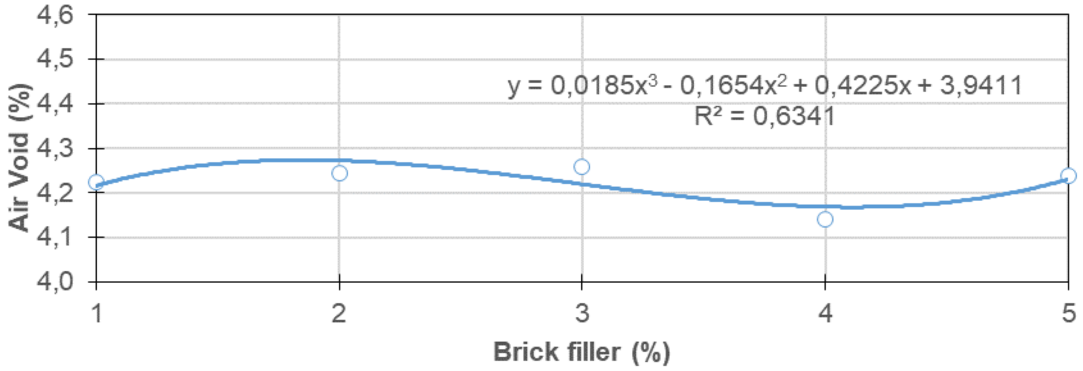

Figure 5. AV variation with RBP

3.5 Effects of RBP on VFA

The ERA Marshall criterion for VFA is from 65–75% as shown in Table 11. VFA > 73,9 % for all categories of filler types, where the criterion is important for the durability of the mixes because it is related to the effective asphalt content in the mix. This can be explained by the fact that the asphalt film around the aggregate particles is thick, leaving few voids. This increased amount of effective asphalt resulted in bleeding and lower stiffness of the mix. Therefore, based on the test results presented in Table 12, the VFA at 1, 2, 3, 4, and 5% RBP were 73,9; 74,0; 74,2; 75,1; and 74,9 %, respectively. At 3,0 % RBP and 74,2 % VFA, the bitumen content in the mix met the requirement because RBP is rougher than CSD, and rougher materials require more bitumen, making the mix more durable. However, at 4 % RBP and 75,1 % VFA, which is above the requirement, the bitumen content was excessive. Figure 6 shows the linear regression analysis between the RBP and VFA, indicating the relationship between the two variables. If the VFA is lower than the indicated limit, there will be less asphalt film around the aggregate particles. In this case, the limit was exceeded, and the VFA was high; therefore, the high asphalt film around the aggregate particles required indicates a potential durability problem.

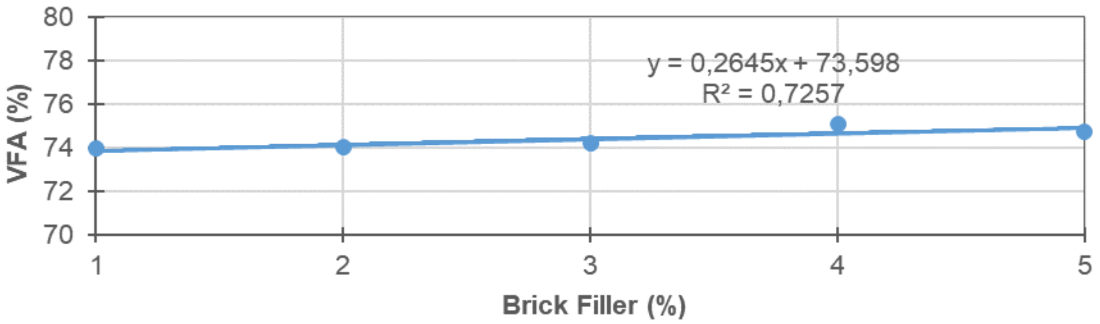

Figure 6. VFA variation with RBP

3.6 Effects of RBP on stability

Stability refers to the ability of a bituminous mixture to resist excessive permanent deformations during axial load applications. In the normal case of the Marshall mix, the stability increases with an increase in the asphalt content in the mixture until it reaches its peak and then decreases. In this case, as the RBP filler percentage increased, the stability of the mixture decreased to 5,0 % RBP and 0 % CSD, as shown in Figure 7. Peak stability for the asphalt mixture is 10,58 kN at 1 % RBP, and the other values are 10,53; 10,48; 10,41; and 10,22 kN, for 2, 3, 4, and 5 % RBP, respectively. These data were obtained from Table 12, and the graph was plotted using regression analysis.

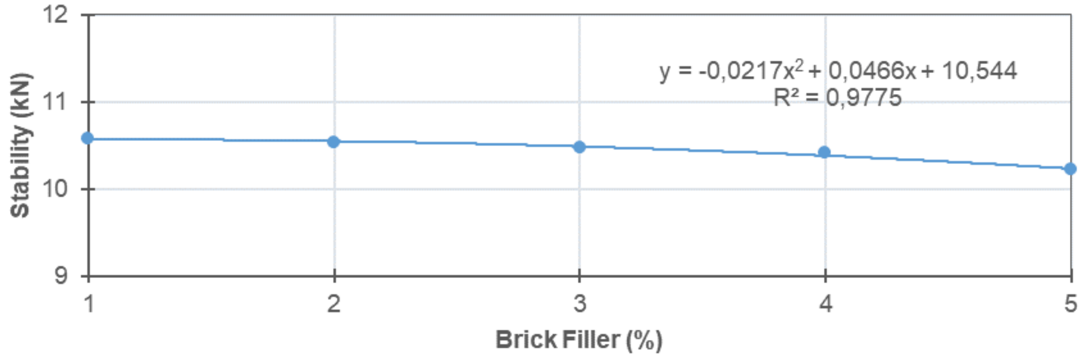

Figure 7. Stability variation with RBP

3.7 Effects of RBP on flow

As shown in Figure 8, the Marshall flow values obtained from the laboratory results by the prepared mixes using RBP meet the Marshall criteria (2,0-3,5 mm) indicated in the ERA 2013 [18] specifications. For the mixes prepared using RBP at 1, 2, 3, 4, and 5%, the flow values obtained were relatively constant (Table 12). The relationship between the percentage of RBP and flow was plotted using the regression analysis shown in Figure 8. At a higher RBP filler content, lower flow values were obtained because the characteristics of the CSD filler were finer and stiffer in the mixture than that for other types of filler materials. A high flow indicates that the plastic mix is prone to permanent deformation, whereas a low flow indicates a brittle mix.

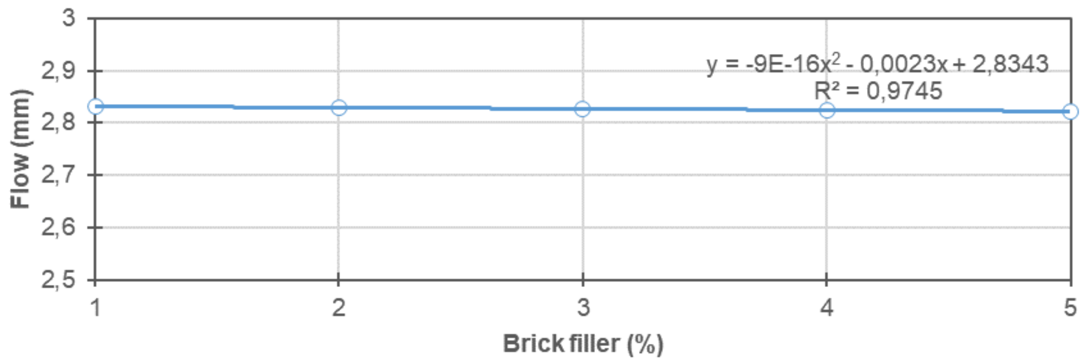

Figure 8. Flow variation with RBP

3.8 Effects of RBP on unit weight

The unit weight of the mix was not significantly affected by the percentage of RBP. The effects of both the filler type and filler content on the unit weight of the compacted mixes are shown in Figure 9, and the data are presented in Table 12. The relationship between unit weight and percentage RBP was formulated using regression analysis. The prepared mixes made with different percentages of RBP showed the unit weight decreasing slightly with increasing RBP because the specific gravity of the RBP was less than that of the CSD. In this case, the RBP filler unit weight was approximately 2,4 g/m^3 and the unit weight for mixes made with 0 % RBP and 5 % CSD fillers was 2,42 g/m^3. Therefore, the effects of different relative percentages of

RBP and CSD were insignificant. Using the unit weight as a reference, the ERA 2013 [18] specification indicates that both fillers can be used in HMA.

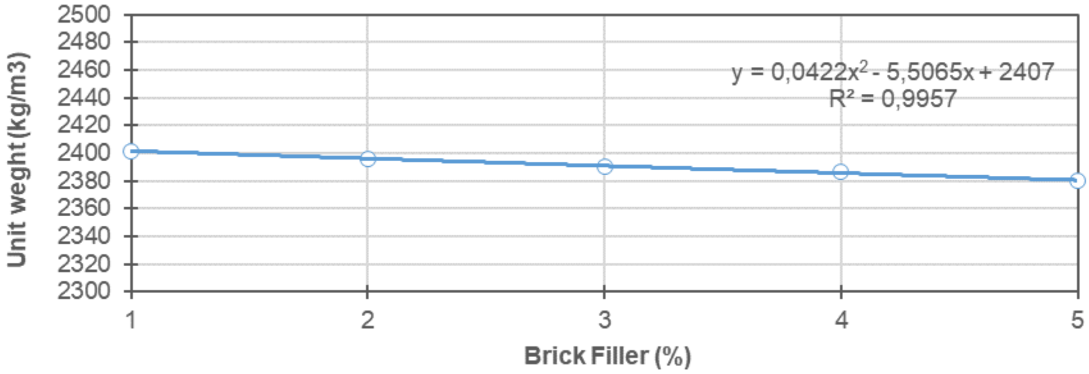

Figure 9. Unit weight variation with RBP

3.9 Effects of RBP on VMA

The effect of the filler combination on the VMA is depicted in Figure 10. The data were obtained from Table 12, and the relationship was formulated using regression analysis. Mixtures using RBP and CSD fillers demonstrated relatively similar engineering properties within the specifications of both international and local standards. However, for mixtures containing the RBP filler, the VMA consistently increased within the range of 16,2-16,8 % as the percentage of RBP in the mix increased from 1-5 %. The largest AV (16.80 mm in the mineral aggregate) were obtained from the mixes prepared with 5 % RBP filler content. This is attributed to the coarser nature of RBP compared to CSD. The lowest VMAs were observed in the mixes prepared using 1 % RBP. These mixtures maintained a constant optimum binder content relative to the mixes prepared with both CSD and RBP fillers, resulting in the lowest VMAs. Furthermore, the impact of the filler content was found to be more significant than that of the filler type. Examining the effect of the filler content on the VMA values suggests that there may be an optimal filler content that enhances the performance of bituminous mixtures.

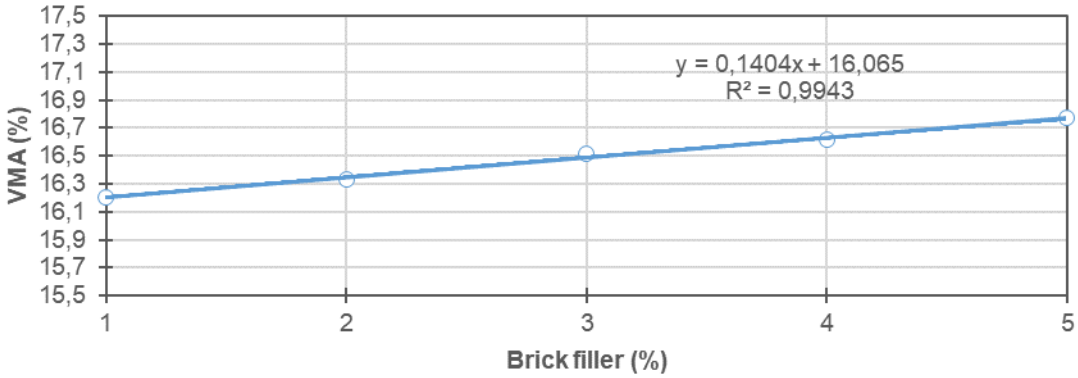

Figure 10. VMA variation with RBP

3.10 Summary of effects of RBP on Marshall test values

The design bitumen content in the mixture was determined using two methods: The Asphalt Institute method (MS-2)[22] and the NAPA [24] method. In the NAPA method, the asphalt content is determined at the mid-specification of AV (in most specifications, 4 %); here, the ERA specifies heavy traffic of 1-5 million people using 4% AV. Hence, at 4 % AV, bitumen contents are taken, and the other criteria are checked from the bitumen–stability graphs, Bitumen vs. bulk density, bitumen vs. flow, Bitumen vs. void space filled with bitumen, and Bitumen vs. VMA. However, in these cases, the design is already at 4 % AV and there is no need to use either the MS-2 or NAPA method; rather, the AV at maximum stability, least flow, highest bulk density, VMA, VFA, and unit weight within the specification of ERA 2013 [18] specifications was selected (Table 12). The stability decreased as the percentage of RBP in the mix increased and remained constant at the OBC, as listed in Table 13. The VMA, VFA, stability, and flow criteria in accordance with the ERA 2013 [18] specifications were met for each paving mixture in the analysis. However, the VFA was outside the specification limit for 4 % RBP. The Marshall stability, flow, VMA, VFA, AV and bulk specific gravity were determined from the plotted curves of RBP versus the design parameters. Finally, tests were conducted for stripping and rutting. The values of all design parameters were compared with the ERA 2013 [18] specifications, and analyses were performed.

Table 12. Summary of CSD and RBP fillers of final selected result

Marshall parameters	Result OBC = 5,45 % 5 % filler = 3 % RBP + 2 % CSD	Result CSD = 5 % OBC = 5,45 %	ERA, 2013 specification		Remark
			Min.	Max.	
Flow, (mm)	2,83	2,80	2,0	3,5	ok
Air voids (Va %)	4,30	4,00	3,0	5,0	ok
VMA	16,50	15,60	12,0	-	ok
Stability (kN)	10,48	10,10	8,0	-	ok
VFA	74,20	74,00	65,0	75,0	ok
Bulk Density	2,41	2,42	-	-	

3.11 Effect of RBP on stripping

In this investigation, the test was applied to the aggregate fraction passing through a 9,5 mm sieve and retained on a 2,36 mm sieve. Based on this analysis, as shown in Table 13, the difference in the stripping percentage after 24 h was only 3,0 % which means that 97,0 % was achieved at 3 % RBP and 2 % CSD, which is less than the maximum requirement (5 %) of ERA 2013 [18] specifications, causing a moisture susceptibility problem.

Table 13. Stripping and coating of aggregate and bitumen affinity test result

RBP to CSD Filler by total weight	Weight of aggregate (gm)	Weight of bitumen (gm)	Weight of brick (gm)	Weight of stone dust (gm)	Uncoated number of aggregate	Total number of aggregate	Striping value of aggregate	Remark
3 % & 2 %	200	10	5,50	3,67	5	133	> 97	OK
5 % & 0 %	200	10	9,17	0	7	130	> 96	OK
0 % & 5 %	200	10	0	9,17	4	130	> 98	OK
Aggregate + Bitumen	200	10	-	-	4	132	100	OK

3.12 Effect of RBP on rutting

The higher percentage of silica/quartz (SiO2) observed in recycled bituminous pavement than that in hydroxymethyl carbon black powder may lead to a reduction in the rutting resistance and higher moisture sensitivity of the asphalt mixture [16]. As shown in Figure 11, the sample with 5 % CSD had a mean rut depth of 3,4115 mm, whereas the sample with 3 % RBP had a mean rut depth of 2.882 mm. In addition, a wheel-tracking test for each test specimen per 1000 cycles was investigated. The wheel truck tests for the control mix and 3 % RBP were 0,0917 and 0,0873, respectively. The proportional rut depths for each specimen tested in different cycles were also examined. The mean proportional rut depths of the control mix and 3 % RBP were 4,538 % and 5,860 %, respectively which are less than 6 %; therefore, the result fulfilled the EN31108 permanent deformation performance requirement for use as a filler material of HMA with Superpave gradation. The general trend of the results for all specimens shows that the rutting depth decreased as the percentage of RBP increased (and CSD decreased).

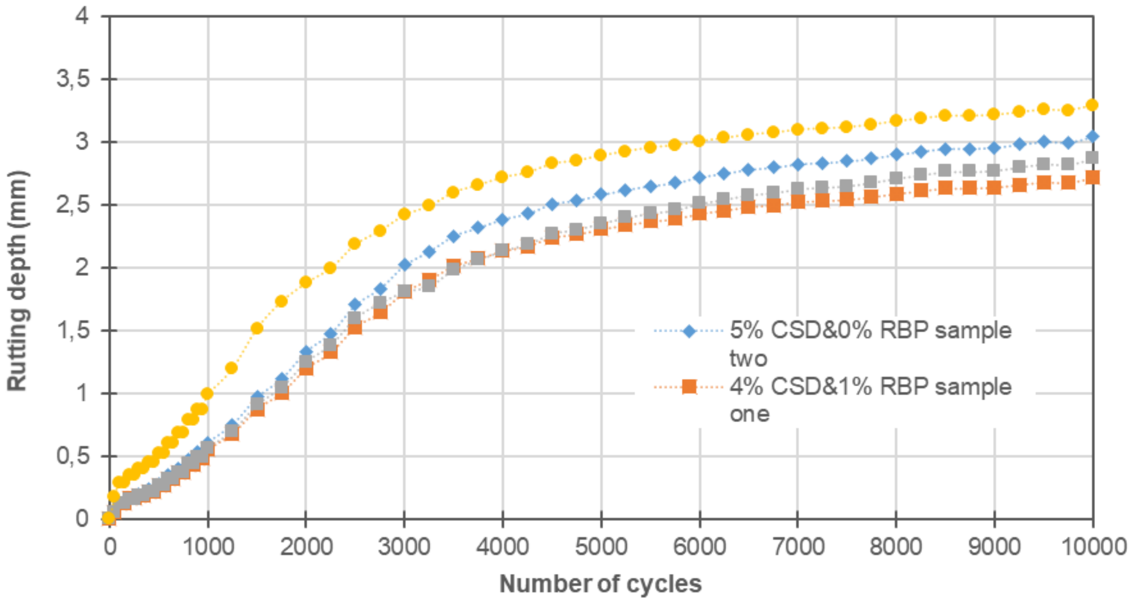

Figure 11. Rutting depth variation with cycles

It can be concluded that replacing the CSD by 3 % RBP and using the full 5 % of the CSD satisfied the requirements for the rut depth, Hamburg wheel-tracking device test, and proportional rut depth following the standards of AASTHO T-324 [19]. The results of this test are summarised in Table 14.

Table 14. Summary of wheel truck test result and specifications

Sample types	Rut Depth (RD)		HWTDT (mm/1000 cycle)		PRD		Specifications as per EN 31108 & AASHTO T-324			Remark
	RD	Avg.	HWTDT	Avg.	PRD	Avg.	WTS (mm/ 1000 cycle)	PRD (%)	RD (mm)	
3 %RBP & 2 % CSD	3,045	2,8820	0,0924	0,0873	4,795	4,538	< 0,15	< 8	< 6	Ok
	2,719		0,0822		4,282					
0 %RBP & 5 % CSD	2,873	3,4115	0,1032	0,0917	4,524	5,372	< 0,15	< 8	< 6	Ok
	3,950		0,0802		6,220					

3.13 The effect of RBP filler on ITS

A higher SiO_2 (quartz) content is associated with the toughness of materials and good mechanical strength, which shows the capacity to interlock well within the mineral skeleton of recycled mineral fillers [25]. The ITS ratio of the mixture containing 3 % RBP was higher than that of the control mix design and 5 % RBP, as shown in Table 15. The experimental moisture susceptibility tests of the control set of aggregates showed noticeable variations before and after moisture conditioning. A higher ITS results in a longer fatigue design life [26]. The HMA mixtures exhibited tensile strength ratios ranging from 83,65-93,63 %; therefore, all of them were above the reference value and met the EN standards. The European standard (EN 12697-12:2018) [27] allows for different energy levels for the impact compaction of these specimens.

Table 15. The average ITS results for different RBP and CSD

Percentage of RBP to CSD replacement	Maximum Load		Tensile strength of conditioned (kPa)	Tensile strength of unconditioned (kPa)	Tensile strength ratio
	Conditioned (N)	Unconditioned (N)			
0 % - 5 %	7830,7	8363,0	773,09	825,65	93,63
3 % - 2 %	7992,5	8467,1	789,07	835,93	94,39
5 % - 0 %	7165,0	8565,7	707,37	845,66	83,65

3.14 Summary of best replacement rate as final selected result

In this study, the reference mixture for laboratory tests was 5,45 % OBC with an optimum filler content of 5 %. A comparison of the Marshall and volumetric properties of the asphalt mixture indicated that the 3 % RBP content by weight was optimal. The asphalt mixture with 3 % RBP and 2 % CSD by mass of the total constituent of aggregates satisfied the requirements of the ERA 2013 [18] specifications) and the Asphalt Institute (MS-2) [22] specifications for all tested parameters and performance test methods. Therefore, the use of RBP filler at 3 % RBP with 2 % CSD by mass of CSD filler when combined with a below-restricted zone of Superpave gradation is acceptable for HMA.

4 Conclusions

The objective of this study is to examine the effects of RBP as a partial mineral filler for CSD in the production of HMA. Through a series of laboratory experiments, we analysed the significant effects of RBP filler on HMA when used in conjunction with Superpave aggregate gradation. The physical quality test results (specific gravity and plastic index) for the brick and stone satisfied the standard specifications for use as fillers in the HMA.

- The examined mineral fillers (RBP and CSD) and aggregates met the requirements of the ERA specifications for Superpave gradation and could be used in asphalt mixtures. Their properties are comparable to those of other conventional fillers. All Marshall mix properties for all mixtures with varying filler proportions of 4 %, 5 %, and 6 % with three different below-restricted zones of Superpave aggregate gradation satisfied both local and international specifications. Evaluation of the volumetric properties, stability, and flow of the asphalt concrete mixtures revealed that the fillers (RBP and CSD) improved the HMA mixtures.
- The VFA values increased proportionally with increasing filler content. Based on the ERA requirements, the study findings were above the lower limit.
- The bulk density decreased with increasing replacement rate of the RBP filler content in the CSD mixture, however, the mix of 3 % RBP and 2 % CSD had a higher bulk density than that with 5 % CSD filler content.
- The partial replacement of the CSD filler with RBP when combined with Superpave gradation significantly affected the stability of the HMA mixture at a replacement rate of 3 % RBP. At 3 % RBP, the HMA mixture provided a stability of 10,48 kN, relatively similar flow value, and all other mix design parameters were within allowable limits.
- The rutting, stripping, and ITS characteristics of the asphalt mix prepared with 3 % RBP and 2 % CSD were nearly identical to those of the control mix. Both mixes satisfy the required specifications. This study proved that using RBP as a replacement filler in asphalt mixtures can enhance the performance, similar to the use of 5 % CSD filler.

The test results indicated that the mixes containing RBP exhibited mechanical properties comparable to those obtained using CSD fillers. This suggests that RBP fillers can effectively address issues such as the permanent deformation (rutting) and moisture susceptibility in asphalt mixtures.

- Generally, the mechanical properties of HMA made with the RBP filler surpass those of HMA made with the CSD filler. Furthermore, using recycled materials, such as RBP, promotes environmental protection by diverting waste from landfills and reducing the consumption of conventional materials.

References

[1] Bolden, J.; Abu-Lebdeh, T.; Fini, E. Utilization of Recycled and Waste Materials in Various Construction Applications. *American Journal of Environmental Science*, 2013, 9 (1), pp. 14-24. https://doi.org/10.3844/ajessp.2013.14.24

[2] Harun-Or-Rashid, G. M.; Mohayminul Islam, M. A Review Paper on: Effect of Different Types of Filler Materials on Marshall Characteristics of Bitumen Hot Mix. *International Journal of Materials Science and Applications*, 2020, 9 (3), pp. 40-46. https://doi.org/10.11648/j.ijmsa.20200903.11

[3] Belay, S.; Quezon, E. T.; Geremew, A. Effect of Selected Conventional and Non-conventional Mineral Fillers with 'Enset' Fibers on Compaction Characteristics of Stone Mastic Asphalt Pavement (SMAP). *Jordan Journal of Civil Engineering*, 2021, 15 (1), pp. 30-40.

[4] Kibru, Y.; Geremew, A.; Yigezu, B. Potential use of 'enset' fiber ash as partial replacement of conventional filler material in hot mix asphalt. *Journal of Civil Engineering, Science and Technology*, 2021, 12 (2), pp. 91-111. https://doi.org/10.33736/jcest.3973.2021

[5] Khattab, M.; Hachemi, S.; al Ajlouni, M. F. Recycled Refractory Brick as Aggregate for Eco-friendly Concrete Production. *Journal of Advances Sciences and Engineering Technologies*, 2021, 4 (1), pp. 32-49. https://doi.org/10.32441/jaset.04.01.04

[6] Zulkati, A.; Diew, W. Y.; Delai, D. S. Effects of Fillers on Properties of Asphalt-Concrete Mixture. *Journal of Transportation Engineering*, 2011, 138 (7), pp. 902-910. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000395

[7] Mulatu, T.; Yigezu, B.; Geremew, A. Study on the Suitability of Reclaimed Asphalt Pavement Aggregate (RAPA) in Hot Mix Asphalt Production. *Journal of Engineering Research*, 2023, 11 (2A), pp. 167-186. https://doi.org/10.36909/jer.14605

[8] Chen, Y.; Xu, S.; Tebaldi, G.; Romeo, E. Role of mineral filler in asphalt mixture. *Road Materials and Pavement Design*, 2020, 23 (2), pp. 247-286. https://doi.org/10.1080/14680629.2020.1826351

[9] Rashwan, N. K. Evaluation of aggregate and mineral filler types on characteristics of hot mix asphalt. *International Journal of Civil Engineering and Technology (IJCIET)*, 2015, 6 (6), pp. 213-222.

[10] Tamiru, A.; Geremew, A.; Jemal, A. Laboratory Performance Evaluation of Hot Mix Asphalt Mixture Using Belessa Kaolin as a Filler with Superpave Aggregate Gradation. *Advances in Civil Engineering*, 2022, 2022 (1), 7491279. https://doi.org/10.1155/2022/7491279

[11] Ahmed, K. U.; Geremew, A.; Jemal, A. The comparative study on the performance of bamboo fiber and sugarcane bagasse fiber as modifiers in asphalt concrete production. *Heliyon*, 2022, 8 (7), e09842. https://doi.org/10.1016/j.heliyon.2022.e09842

[12] Mehari, Z. B. *Effect of Different Types of Filler Materials on Characteristics of Hot-Mix-Asphalt Concrete*. [master thesis], Addis Ababa University School of Graduate Studies, Ethiopia, 2007. Accessed: December 15, 2024. Available at: https://www.academia.edu/download/40796129/Thsesis_on_Effect_of_Different_Types_of_Filler_Materials_on_Characteristics_of_Hot-Mix-By_ZEMICHAEL_BERHE.pdf

[13] Sangiorgi, C. et al. Alternative Fillers for the Production of Bituminous Mixtures: A Screening Investigation on Waste Powders. *Coatings*, 2017, 7 (6), 76. https://doi.org/10.3390/coatings7060076
[14] Wu, S.; Zhu, J.; Zhong, J.; Wang, D. Experimental investigation on related properties of asphalt mastic containing recycled red brick powder. *Construction and Building Materials*, 2011, 25 (6), pp. 2883-2887. https://doi.org/10.1016/j.conbuildmat.2010.12.040
[15] Chen, M.-z.; Lin, J.-t.; Wu, S.-p.; Liu, C.-h. Utilization of recycled brick powder as alternative filler in asphalt mixture. *Construction and Building Materials*, 2011, 25 (4), pp. 1532-1536. https://doi.org/10.1016/j.conbuildmat.2010.08.005
[16] Kuity, A.; Jayaprakasan, S.; Das, A. Laboratory investigation on volume proportioning scheme of mineral fillers in asphalt mixture. *Construction and Building Materials*, 2014, 68, pp. 637-643. https://doi.org/10.1016/j.conbuildmat.2014.07.012
[17] American Association of State Highway and Transportation Officials (AASHTO). AASHTO T 248-96: Standard Specifications for Transportation Materials and Methods of Sampling and Testing.
[18] Ethiopian Road Administration FDRE. Pavement Design Manual Volume 1: Flexible pavement, 2013.
[19] American Association of State Highway and Transportation Officials (AASHTO). AASHTO Designation: T 324-14. Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA).
[20] American Society for Testing and Materials. ASTM E986: Standard Practice for Scanning Electron Microscope Beam Size Characterization.
[21] Rondón-Quintana, H. A.; Ruge-Cárdenas, J. C.; de Farias, M. M. Behavior of Hot-Mix Asphalt Containing Blast Furnace Slag as Aggregate: Evaluation by Mass and Volume Substitution. *Journal of Materials in Civil Engineering*, 2018, 31 (2), 04018364. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002574
[22] Asphalt Institute. *MS-2 Asphalt Mix Design Methods*. 7th Edition. Lexington, KY: Asphalt Institute, 2014.
[23] American Society for Testing and Materials. ASTM D1559-89: Standard Test Method for Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus.
[24] Ray Brown, E. et al. *Hot Mix Asphalt Materials, Mixture Design and Construction*. 3rd Edition, USA: National Asphalt pavement Association, 2023.
[25] Sherre T. K.; Liao, M.-C. Characteristics of Recycled Mineral Fillers and Their Effects on the Mechanical Properties of Hot-Mix Asphalt When Used as Limestone Filler Replacements. *Journal of Materials in Civil Engineering*, 2022, 34 (1), 04021395. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004033
[26] Khosla N. P.; Harikrishnan, K. I. *Tensile strength – a design and evaluation tool for superpave mixtures*. North Carolina State University, HWY-2005-14, 2007.
[27] British Standards Institutions. BS EN 12697-12:2018-TC: Bituminous mixtures, Test methods- Determination of the water sensitivity of bituminous specimens.