

Mechanical Properties And Durability of Asphalt–Concrete Mixture Modified With Recycled Concrete And Porcelain Aggregates

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Article History

Received: 06.01.2025

Revised: 04.02.2025

Accepted: 26.03.2025

Published: 27.03.2025

Communicated by: Asst. Prof. Dr.

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Abstract: Asphalt–concrete mixtures have various applications in engineering construction projects, with their performance influenced by external, internal, and environmental factors. Several studies have focused on modifying their required properties and performance. Researchers have utilized recycled concrete as an additive or replacement for natural aggregate in asphalt and cement concrete mixtures, yielding acceptable results. This research introduces another waste construction material, porcelain waste, as aggregates replacing recycled concrete aggregates in different proportions to modify the mechanical properties and durability of a binder–asphalt concrete mixture. This is an additional effort to save the environment from different waste construction materials. Following the Marshall requirements, the properties of the samples with optimized quantities were investigated using wheel trucks and Bohme abrasion tests. The modified mixture exhibited an increase in bulk specific gravity by 6% to 2.24, enhanced the Marshall flow from 3.5 to 4.6 mm, and increase in the stability by 5%, yielding the highest value of 33 kN. Subsequently, the mechanical properties and durability of the mixtures were affected with an increase in the rutting resistance. The highest abrasion resistance and service life were obtained when 25% porcelain replaced the recycled concrete aggregates, but the mixture became more temperature susceptible. Therefore, this study achieved economical, environmentally-friendly, and safe pavements.

Keywords: Mechanical Property; Abrasion Resistance; Rutting Resistance; Porcelain Waste; Asphalt–Concrete Mixture; Marshall Test

1. Introduction

Asphalt pavement technology has evolved with the changes in the road industry, owing to the increasing number of vehicles. Various materials, whether traditional or unconventional, are used to build roads with a long life span and increased compatibility with the environment and the country's economy through the use of available resources. Since the 1980s, traditional road materials have been merged with unconventional materials [1].

Waste production severely disrupts the environment [2]. The amount of environmental garbage produced by industrial and technological advancement is increasing, with tens of thousands of tons of industrial trash disposed annually. This global increase in waste production has prompted scientists to consider the combination of waste with conventional materials for road construction [3]. Reutilization of waste materials from landfills, including polymer, glass, steel slag, plastic, tires, aggregate dust, and recycled concrete aggregate, for pavement construction has significant advantages for environmental and resource conservation [4]. Consequently, the increasing use of recycled materials in asphalt pavements requires the environmental assessment of their effects on energy use and CO₂ emissions by reducing the energy consumption for preparing the mixtures [5]. Using construction and demolition (C&D) waste materials as aggregates in pavement layers at a proportion of 10% - 40% increases the

optimal binder content (OBC) and improves the rutting resistance while enhancing the moisture damage resistance [6]. With the serious hurdles posed by industrial enterprises on the civil engineering sector, the utilization of recycled materials to ration the use of natural resources in construction processes provides a potential solution [6].

In recent years, the storage and management of waste from destroyed concrete buildings has become a pressing global challenge that should be handled locally [7]. However, compared to a mixture made with natural aggregates, asphalt mixed with recycled concrete aggregates has limited technical features because of the low quality of the materials. In particular, concerns on the stripping potential of recycled cement–concrete aggregate mixtures have been raised and should be addressed [8].

As road surface durability is directly affected by the qualities of the porcelain, the tested aggregates should have sufficient properties in terms of grain form, frost resistance, and grinding resistance when applied to the wear layer of the asphalt concrete surface [9]. In addition to increasing the amount of binder, filler, and air voids, recycled ceramic aggregates resist plastic deformation and maintain their indirect tensile strength after immersion [10]. The use of 5% porcellanitic improved the compressive strength of roller-compacted concrete, which is a zero-slump concrete without forms, reinforcing steel, and finishing and has sufficient wetness to support compaction by vibratory rollers [11].

The use of nonporous ceramic granite refuse as a finely fragmented inorganic material in the bitumen–concrete mixture reduces the amount of bitumen and increases the water resistance, compressive strength, and shear resistance, thereby prolonging the service life of the road surface. Thus, ceramic granite production waste can be used as a mineral material for producing asphalt concrete to increase the construction and technical properties and durability of road surfaces [12].

Recycled ceramic aggregates and porcelain tile wastes as substitutes for natural aggregates were characterised by suitability tests for use in bituminous mixtures. The addition of recycled ceramic aggregates increased the binder, filler, and air void contents and resistance to plastic deformation while retaining the indirect tensile resistance after immersion. Recycled ceramic aggregates can replace up to 30% of natural aggregates under good mechanical conditions [10]. Moreover, hot bituminous mixtures with reasonable additions of recycled ceramic aggregates can satisfy the binder course performance requirements for medium- to low-traffic volume roads [10]. Several specialists have investigated the use of waste products to produce bitumen and asphalt concrete [13]. Using waste porcelain tile as a recycled aggregate in concrete can decrease environmental pollution and address the scarcity of natural aggregates while promoting the mechanical characteristics of concrete at room temperature. Therefore, leftover waste porcelain tile fine aggregates, as opposed to coarse aggregates, can be used in recycled concrete [14]. enhancing the characteristics, such as bulk specific gravity (G_m), flow, stability, abrasion resistance, and rutting. Further, recycled ceramic aggregates retain their indirect tensile strength and resist plastic deformation [15]. Researchers have emphasized the value of environmentally friendly building practices and the role of organic materials in creating a strong infrastructure [16]. However, asphalt mixed with recycled concrete particles exhibits inferior technical features than mixtures created with natural aggregates because of the low quality of the materials [17]. As waste generation severely affects the ecosystem [18], utilizing waste materials from C&D as aggregates in pavement layers enhances rutting resistance and raises OBC [19, 20]. In addition to reducing environmental pollution, using leftover porcelain tile as a recycled aggregate in concrete can address the scarcity of natural aggregates. However, recycled cement aggregates alone do not produce satisfactory results. Thus, this study demonstrated the optimized addition of two waste construction materials, namely recycled concrete and porcelain waste, to modify the mechanical properties and durability of a binder–asphalt cement mixture at low and high temperatures.

2. Significance of the research

To save waste construction materials that otherwise occupy valuable areas in natural areas and to repurpose these materials, this research aims to enhance the construction industry and to advice authorized directorates to focus on this approach. Especially if the modified materials improve the technical and durable properties of composite construction mixtures, which ultimately benefits the environment and finances. The implementation of treatment processes such as cleaning, crushing, and reshaping waste materials can yield significant benefits for humanity.

3. Experimental section

3.1 Materials

Asphalt grade 40–60, combined with concrete and porcelain waste from demolished residential buildings in Erbil City, were used in this study according to the aggregate gradation requirements for the asphalt binder course layer in ASTM D3531. Figure 1 illustrates the gradation and percent passing of the aggregates for road projects to comply with the binder parameters of a common specification band [14].

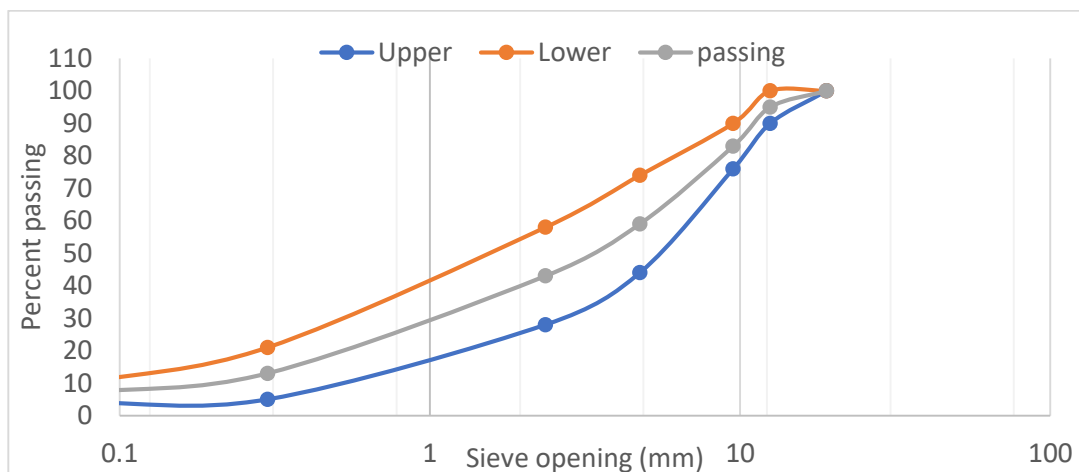


Figure 1: Gradation curve of the mixture aggregate per percent passing of the porcelain waste and recycled concrete at the upper, passing, and lower limits.

Asphalt bitumen from Lanaz Refinery in Erbil, with a grade of 40-60, was used for the testing program. The conventional properties are summarized in Table 1.

Table 1: Conventional results of the asphalt binder test.

bitumen 40/60	Test method	Unit	Specification	Conformity
Penetration @ 25°C	ASTM D5	mm/10	60-70	57
Softening point	ASTM D36	°C	49-56	52
Flash point	ASTM D92	°C	230 Min	280
Ductility	ASTM D113	cm	100 Min	130
Specific gravity @ 25°C	ASTM D70	Kg/cm ³	1.01-1.06	1.016

3.2 Waste Porcelain:

Waste porcelain has the properties shown in Table 2 and shapes as in Figure 2 from demolished buildings, made from Turkiye used in the testing program. The water absorption of waste porcelain at

0.57% indicates that the material has low porosity and is relatively impermeable. This characteristic suggests that waste porcelain can be effectively used as a component in an asphalt cement mixture.

Table 2: Waste porcelain properties.

Porcelain properties	Test method	Unit	Conformity
Density	ASTM C127	Kg/m ³	2380
Specific gravity	ASTM C127	-	2.27
Water absorption	ASTM C1585	%	0.57%

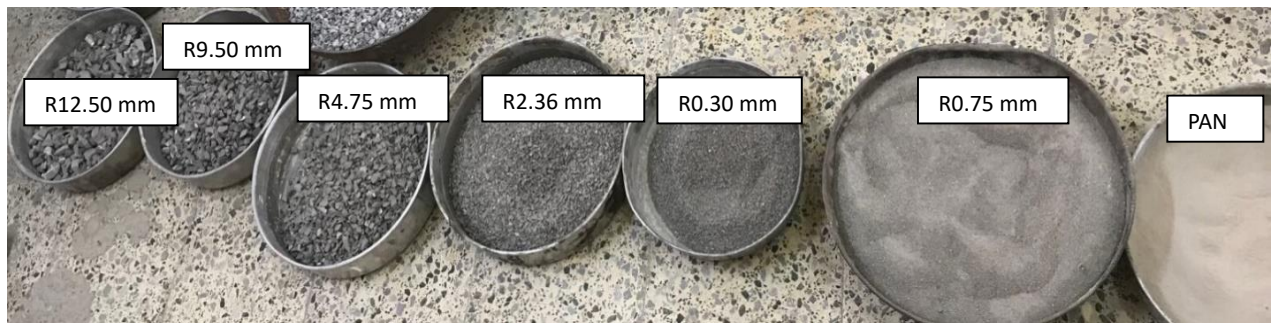


Figure 2: Gradation and particle shape of coarse, fine, and filler aggregates of porcelain waste. (R) refers to the particle size retained on the identified sieve number.

3.3 Recycled Concrete Aggregate:

The concrete obtained from demolished buildings in Erbil city used particle shapes shown in Figure 3, together with the characteristics enumerated in Table 3:

Table 3: Properties of the recycled concrete aggregate.

Aggregate Property	Test Code	Unit	conformity
Density	ASTM C127	Kg/m ³	2480
Specific gravity	ASTM C127	-	2.506
Water absorption	ASTM C1585	%	5.34

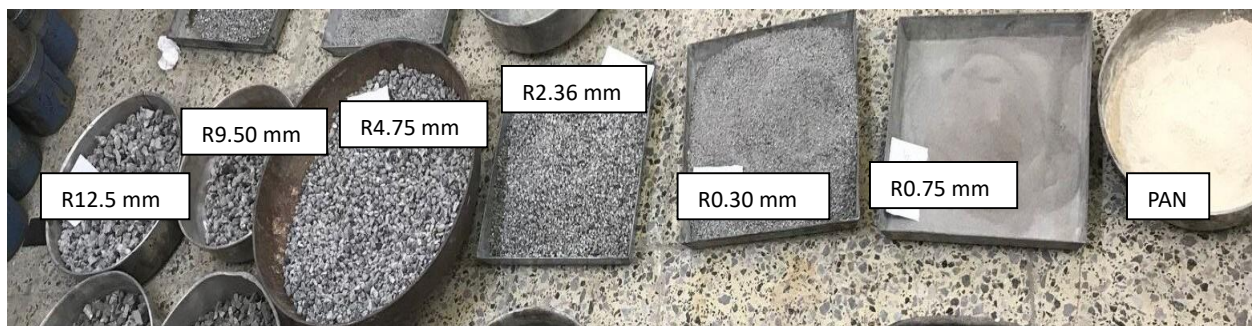


Figure 3: Gradation and particle shapes of the coarse, fine, and filler aggregates of recycled concrete waste. (R) refers to the particle size retained on the identified sieve number.

4. Testing Types

The rutting test was conducted following the Hamburg Wheel Tracking Test requirements as per AASHTO T 324-19, using two samples for each mixture, with half-circle beams 35 mm thick. Abrasion tests were performed using the Bohme abrasive wheel UTA-0615-T, with two samples of 70 × 70 × 100 mm for each mixture to evaluate the durability of the mixtures. The mechanical strength, flexibility, temperature susceptibility (TS), and index of retained strength (IRS) of the mixture were tested using the Marshall method as per ASTM D1559 and ASTM 6927-22, with three samples of 65 × 101 mm for each test. The shape and size of the devices used are shown in Figures 4a–c, respectively.

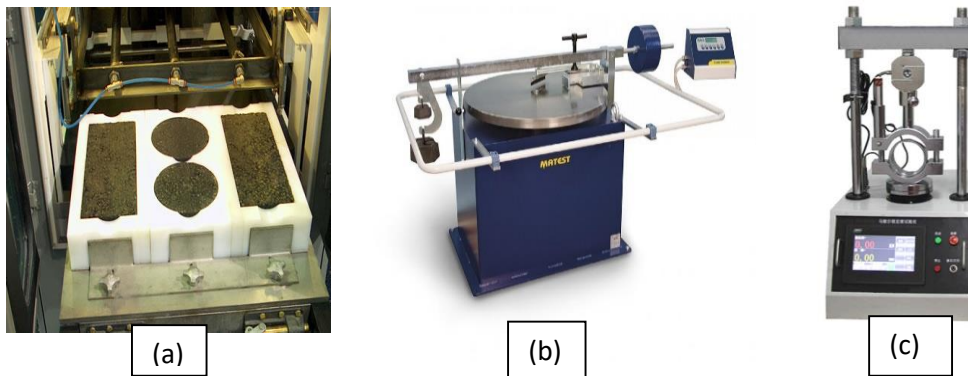


Figure 4: Test equipment: a) Hamburg wheel-truck device, b) Bohme abrasive test device, and c) Marshall test device.

Marshall tests were conducted at temperatures of 60°C and 25°C to determine the stability and flexibility, following the standard Marshall test procedures. Additionally, the temperature susceptibility (TS) and Index of Retained Strength (IRS) of the mixtures were evaluated according to ASTM D4123 and ASTM D1075/D1074, respectively. Below are four equations used to find out the (TS) and the (I.R.S.).

$$(1) \quad ST = \frac{2P_{ult}}{\pi t D} \quad (\text{kg/cm}^2)$$

where ST is tensile strength, P_{ult} is ultimate load applied (kg), t is sample thinness (cm), and D is sample diameter in (cm).

$$(2) \quad \text{T.S.} = \frac{S_{Ti} - S_{Tj}}{j - i} \quad (\text{kg/cm}^2/\text{c}^\circ)$$

where T.S. is the temperature susceptibility, and S_{Ti} and S_{Tj} are the tensile strengths of the mixtures at $i = 25^\circ\text{C}$ and $j = 60^\circ\text{C}$

$$(3) \quad S = \frac{P_{ult}}{2\pi r^2} \quad (\text{kg/cm}^2)$$

where S is the compressive strength, P_{ult} is the ultimate load applied (kg), and r is the radius (cm).

$$(4) \quad \text{I.R.S.} = \frac{S_2}{S_1} * 100 > 70\%$$

where S_1 is the compressive strength of the dry mixture tested at 25 °C and S_2 is the compressive strength of the conditioned mixture tested at 60 °C.

4.1 Asphalt mixture proportioning and sampling

This study used an asphalt combination with the specific quantities of recycled concrete and porcelain aggregates listed in Table 4. Four types of Marshall mixtures were prepared with three replacement rates of porcelain (25%, 40%, and 60%) for the recycled concrete aggregate for all mix gradations. Based on previous research [2, 9, and 10] these percentages were chosen to show the impact of the replaced materials on the test results. Higher percentages signify better environment cleaning and finance saving while maintaining specifications according to standards. The samples were prepared according to ASTM D6927-22 for heavy-load highway (75 blows) Marshall testing, with three samples for each test.

Table 4: Weights of the recycled concrete and waste porcelain aggregates according to proportions of selected gradation of road binder layer.

Sieve Size (mm)	M1	M2		M3		M4	
	100% Recycled concrete Agg. (g)	75% Recycled concrete Agg. (g)	25% Waste porcelain (g)	60% Recycled concrete Agg. (g)	40% Waste porcelain (g)	40% recycled concrete Agg. (g)	60% Waste porcelain (g)
19.000	0	0	0	0	0	0	0
12.500	222.3	166.73	55.58	133.38	88.92	88.92	133.38
9.500	108.3	81.23	27.08	64.98	43.32	43.32	64.98
4.750	199.5	149.63	49.88	119.70	79.80	79.80	119.70
2.360	176.7	132.53	44.18	106.02	70.68	70.68	106.02
0.300	262.2	196.65	65.55	157.32	104.88	104.88	157.32
0.075	91.2	68.40	22.80	54.72	36.48	36.48	54.72
PAN/filler	79.8	59.85	19.95	47.88	31.92	31.92	47.88

5. Results and Discussion

The average test results for the four types of mixtures are presented in Table 5. Porcelain is heavier than the replaced recycled concrete, as indicated by the increased density of the mixture with increasing rate of the porcelain replacement, except in M4. The decrease in the weight of M4 suggests that a further increase in the porcelain content forms gaps and voids in the material owing to its flat particle shape, as shown in Figure 5.

Table 5: Mixture properties, code, and test results.

Properties	Specifications according to	Mix Code			
		M1	M2	M3	M4
Density (g/cm ³)	AASHTO T 310	2.070	2.113	2.116	2.068
Bulk Sp. Gr. (G_{mb})	AASHTO T209-94	2.066	2.108	2.102	2.086
Apparent Sp. Gr. (G_{sb})	AASHTO T209-94	2.11	2.24	2.22	2.20
Stability at 60 °C (KN)	ASTM D6927-22	31.0	33.0	28.0	26.3
Marshall flow at 60 °C	ASTM D6927-22	3.6	4.6	4.2	4.4
Stability at 25 °C (kN)	ASTM D6927-22	52.0	50.3	49.0	47.3
Marshall flow at 25 °C	ASTM D6927-22	3.75	3.2	2.6	2.8

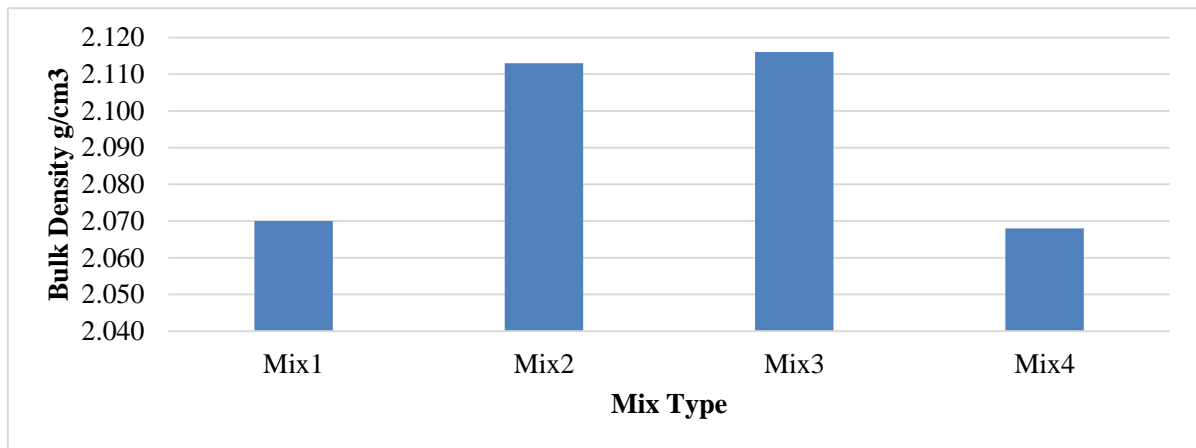
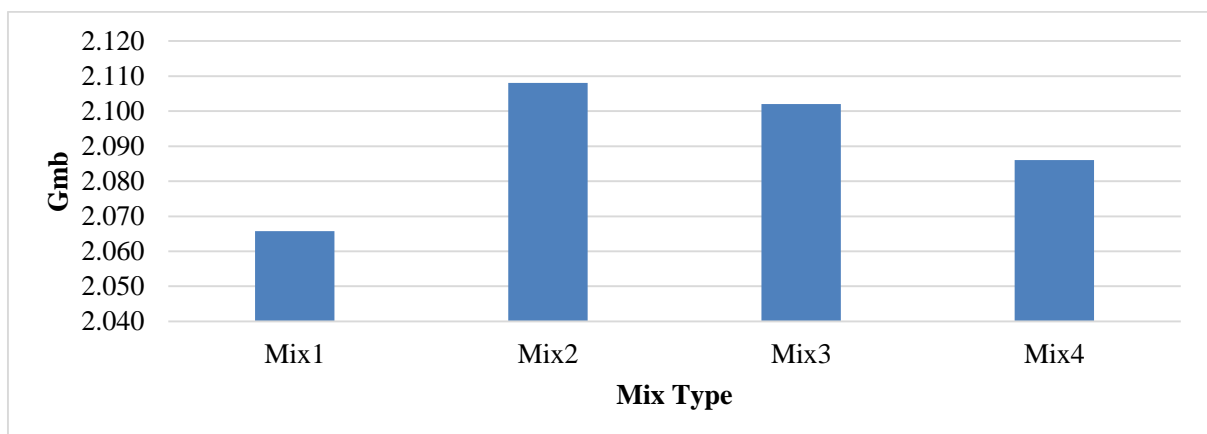
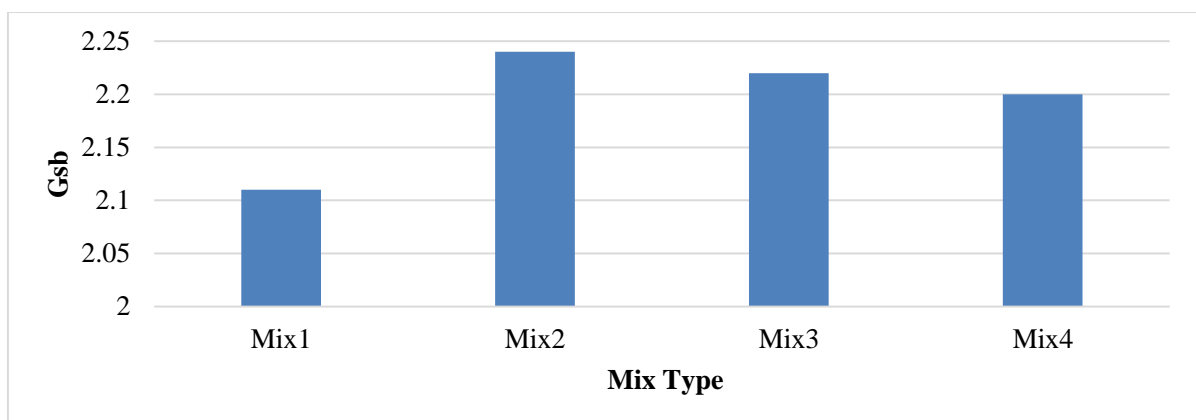


Figure 5: Density of different mixtures

Figures 6 and 7 show the G_{mb} and apparent specific gravity (G_{sb}), respectively, exhibiting the same trends. Replacing 25% recycled aggregate with porcelain yielded the highest G_{mb} and G_{sb} values of 2.108 and 2.24, respectively, implying an increase of 2.00% and 6.16%, respectively.

Figure 6: Bulk specific gravity (G_{mb}) of different mixtures.Figure 7: Apparent specific gravity (G_{sb}) of different mixtures.

Figures 8 and 9 show the Marshall stability of the mixtures at different temperatures. The Marshall hardness decreased to 47.3 kN with the increased substitution of ceramic, reflecting a reduction of roughly 9% at 25°C, attributed to the greater stiffness of the porcelain compared to the concrete block particles. Meanwhile, M2 tested at 60 °C yielded the highest Marshall stability of 33 kN, exhibiting an increase of 6.4% from that of M1. This indicates the increased hardness and stability of the porcelain particles.

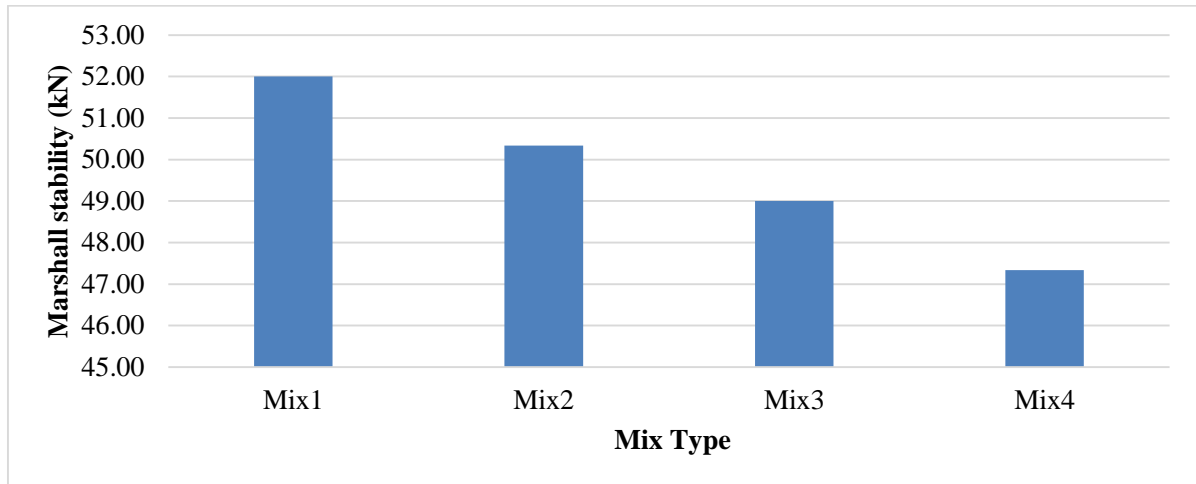


Figure 8: Marshall stability of different mixtures tested at 25 °C.

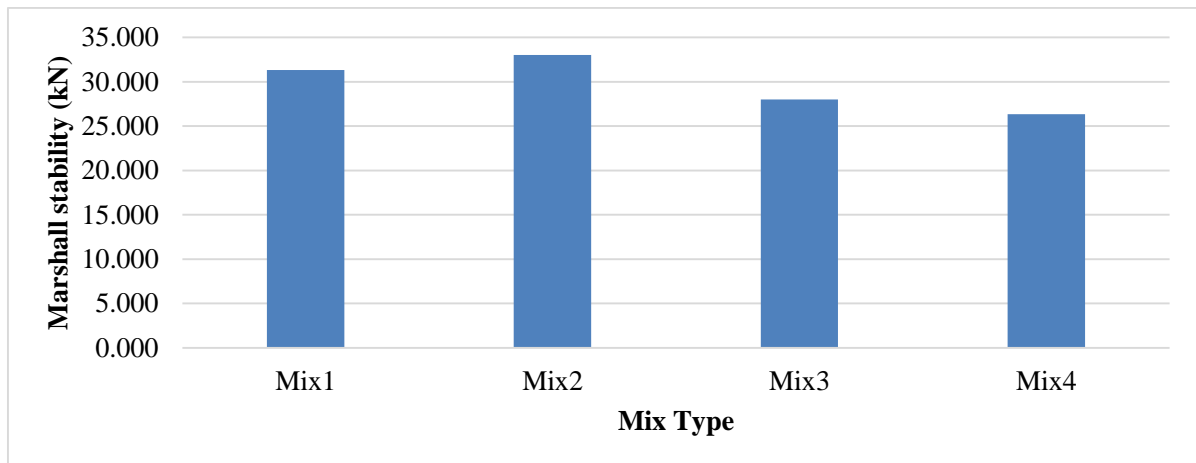


Figure 9: Marshall stability of different mixtures tested at 60 °C.

Figures 10 and 11 show the different flow trends owing to the homogeneity of the materials, including the sample, particle shapes, and air gaps. The replacement of the recycled concrete aggregate with porcelain decreased the Marshall flow of M3 from 3.75 to 2.6 mm at 25 °C and increased the Marshall flow of M2 from 3.6 to 4.6 mm at 60 °C. This indicates the stability of porcelain particles at low temperatures.

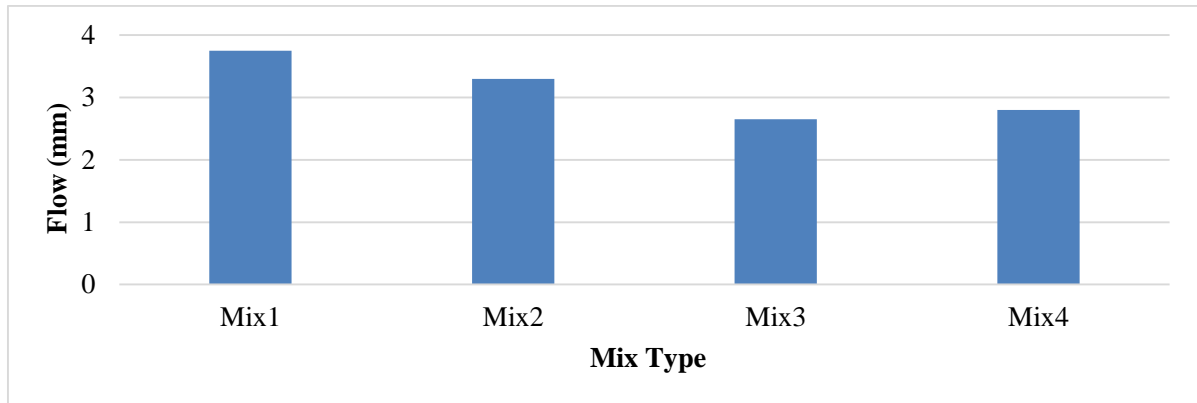


Figure 10: Marshall flow of different mixtures at 25 °C.

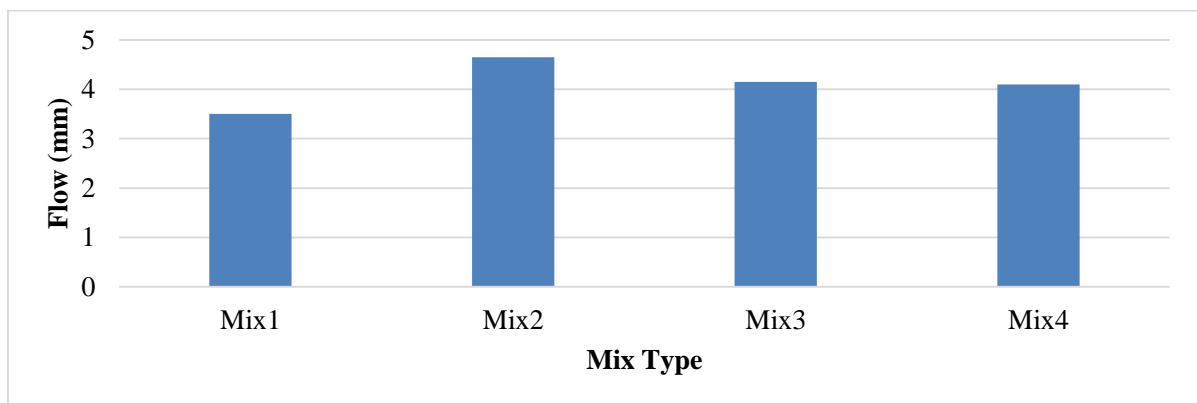


Figure 11: Marshall flow of different mixtures at 60 °C.

The rutting deformation resistance of M2 improved by 22%, as indicated by the bearing yield load, which is 732.1 kN. Meanwhile, the rutting depth of M2 only increased by 5% compared to Mix 4, which has a bearing load of 406 kN and a rutting depth of 2.623 cm (Figure 12). This suggests that porcelain addition should be limited based on the durability of the mixture. The recycled ceramic aggregates in hot mix asphalt, with a 20% proportion, significant improvements in Marshall stability and resilient modulus strength, with a 25% increment in Marshall stability and a 13.5% increase in resilient modulus strength [21].

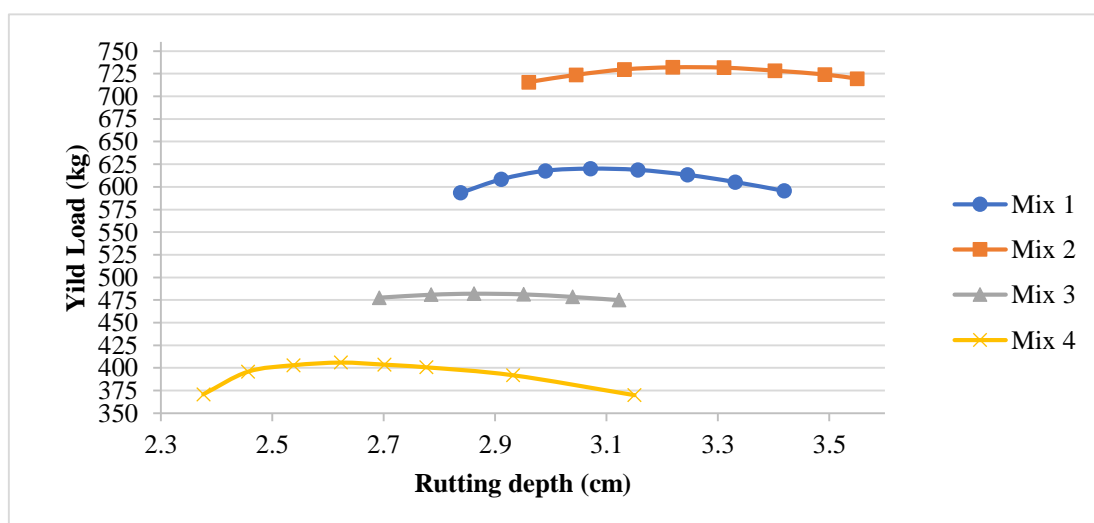


Figure 12: Rutting depth versus load applied for the mixtures.

Abrasion improved with the addition of porcelain, as shown in Figure 13. The highest abrasion resistance was obtained by adding 25% porcelain to M2, denoting the high durability of the mixture.

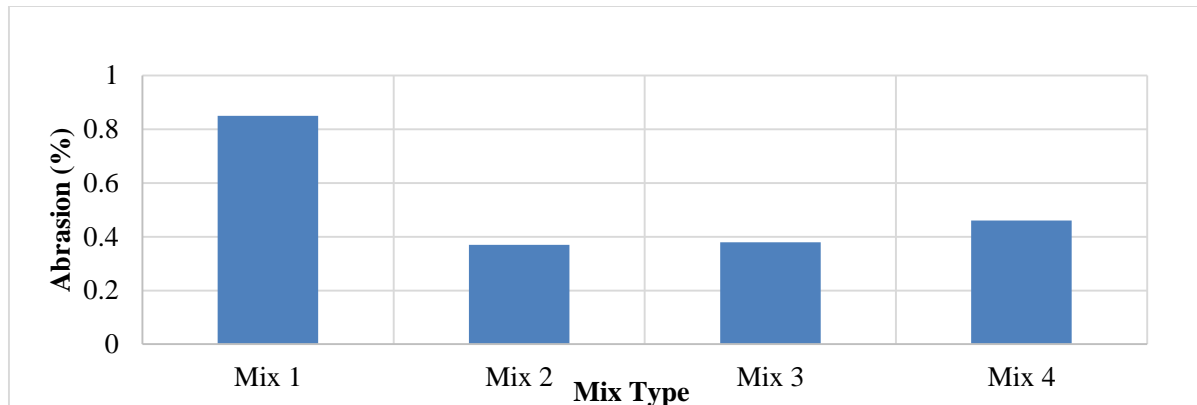


Figure 13: Abrasion resistance for all mixtures

The index of the retained strength was obtained according to ASTM D-1075 to determine the effect of the porcelain particles on the durability of the mixture. Mix 2 exhibited the highest external stress resistance and durability, as shown in Figure 14.

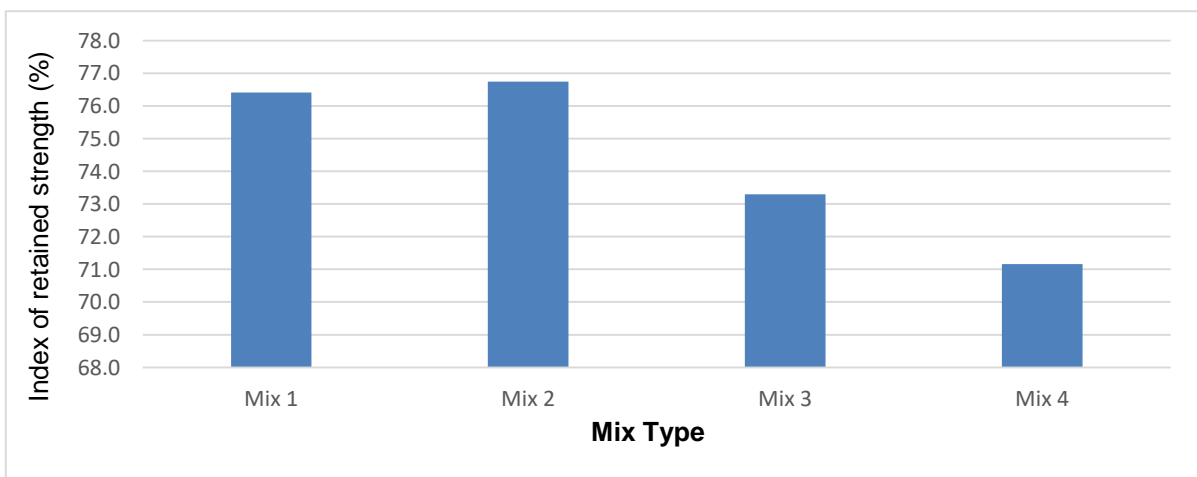


Figure 14: Index of retained strength for different mixtures.

The mixture's temperature susceptibility was affected significantly at mixture M2, replacing porcelain affected negatively and making the mixture more susceptible, as shown in Figure 15. Adding porcelain aggregates raises the bulk-specific gravity because the material is dense and doesn't have pores, which reduces air pockets and makes the mixture more compact. Also, porcelain doesn't absorb as much water as RCA does, which makes it stick better to the bitumen and improves Marshall stability. However, at high replacement levels, the asphalt becomes less flexible and more sensitive to changes in temperature. This is because porcelain has a rigid structure that makes it harder for the asphalt to handle thermal expansion and contraction.

Moreover, Studies from (Ref. 10) show that using recycled ceramic aggregates raises the amount of binder and air holes while also making the material more resistant to plastic deformation. In this study, however, adding porcelain waste reduced air gaps and increased density because it is finer and doesn't have pores. In the same way that ceramic granite waste (Ref. 12) improved water resistance, this study confirms that porcelain waste improves both abrasion resistance and rutting resistance, with a

replacement level of 25% being ideal. These differences highlight the unique mechanical behavior of porcelain aggregates compared to other recycled materials.

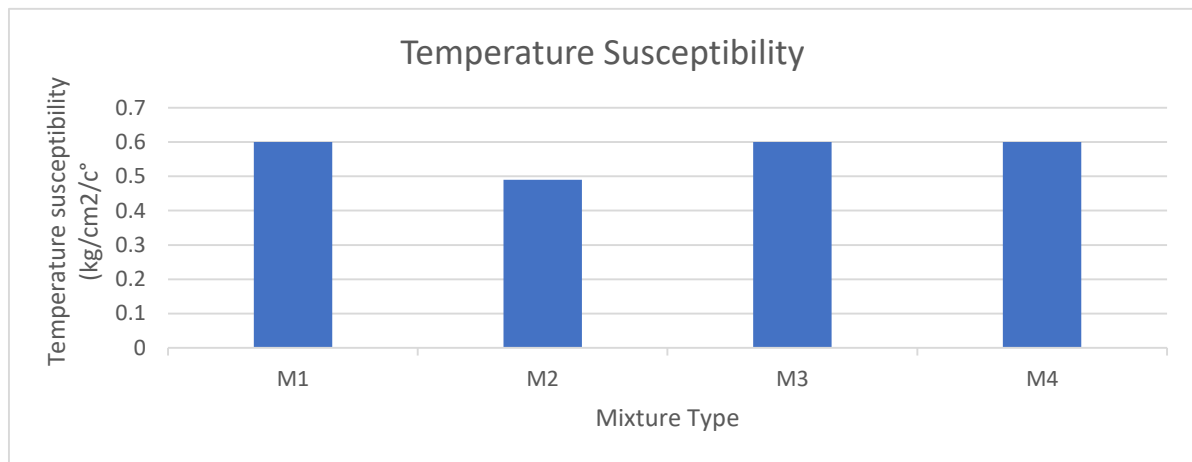


Figure 15: Temperature Susceptibility for different mixtures.

6. Conclusion

The development of sustainable construction materials is a global goal. In highway construction, natural materials play a major role in producing durable and strong mixtures to achieve structures with long service lives. The modification of these materials requires replacing, mixing, adding, and restrengthening their properties to produce stronger and more durable mixtures. This study focused on the use of eco-friendly materials by adding recycled concrete aggregate and replacing it with recycled porcelain to determine its effects on the mechanical properties and durability of asphalt–concrete binder mixtures. The main conclusions of this study are as follows:

1. The recycled concrete aggregate is a suitable and noticeably effective modifier for the asphalt binder mixture, yielding acceptable mechanical and durable results.
2. According to the test results, porcelain particles can replace recycled concrete aggregate at an optimal rate of 25%.
3. Adding porcelain increased the density of the mixtures. Compared to M1, the bulk density of M3 increased by 2.2%, whereas the G_{mb} of M2 increased by 2%.
4. Replacing porcelain decreased the mechanical properties of the asphalt mixtures at low temperatures. However, the mechanical properties improved with the porcelain replacement rate of only 25% in M2.
5. M2 improved the resistance of the asphalt mixture by 22% for the rutting deformation, 20% for the abrasion resistance, and 1% for the index of retained strength. However, it negatively affected the temperature susceptibility of mixture M2, making it more temperature susceptible by 18%.
6. Compared to earlier research on ceramic waste in asphalt (Refs. 10–12), this study confirms that porcelain waste effectively improves resistance to rutting and abrasion while maintaining structural integrity at the best level of 25% replacement. However, its increased temperature susceptibility should be considered in climate-sensitive applications. These findings contribute to developing sustainable and durable asphalt mixtures using alternative recycled materials.

By integrating the technical explanations of how porcelain aggregates influence mechanical properties and directly comparing these results with prior research, this study provides a clear foundation for future investigations on optimizing waste materials for asphalt applications.

7. Recommendations

Highway construction is an ongoing and essential requirement, making the replacement of primary components in highway mixtures with waste construction materials a sustainable and environmentally beneficial goal. This research demonstrates and recommends the utilization of waste concrete and porcelain aggregates in highway construction.

Further tests, particularly on the rheological properties of bitumen through bending beam rheometer and dynamic shear rheometer tests, are recommended to better understand the role of waste porcelain and recycled concrete aggregates as modifiers for pavement mixtures.

8. Conflict of Interest

The authors do not have any conflicts of interest to declare.

9. Acknowledgements

The authors would like to thank Erbil Polytechnic University and Tishk International University for the valuable support they gave to access the labs during the conducting of this research.

10. Author Contributions

Walid A. Hamad: Data curation, Laboratory work, Funding acquisition, Resources, Software, and original draft preparation.

Ganjeena J. Khoshnaw: Conceptualization, Supervision, Project administration, Investigation, Formal analysis, review, and editing.

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