



## **Enhancing the Moisture Resistance and Mechanical Performance of Asphalt Concrete with Waste Polystyrene–Calcium Carbide Composite and Recycled Concrete Aggregate**

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### **ABSTRACT:**

The increasing generation of plastic waste and industrial by-products, coupled with the depletion of natural aggregate resources, necessitates the development of sustainable alternatives for pavement construction. This study investigates the effect of waste polystyrene (WP), calcium carbide residue (CCR), and recycled concrete aggregate (RCA) on the Marshall Stability and swell index of asphalt concrete mixtures, with the aim of developing an environmentally sustainable pavement material. The research employed a laboratory-based experimental approach, incorporating WP at varying percentages (0–10%) as a binder modifier, CCR (2–10%) as a filler material, and RCA as partial replacement for natural coarse aggregate. Marshall Stability tests were conducted to evaluate the load-bearing capacity of the mixtures, while swell index measurements were performed over 14 days of full moisture submergence to assess moisture susceptibility. The results demonstrated that all modified mixtures exhibited significantly enhanced performance compared to the control mixture. Marshall Stability increased from 22.05 kN for the control mixture to a peak value of 29.585 kN for the mixture containing 2% WP and 2% CCR, representing a 34.2% improvement. This enhancement is attributed to the formation of a polymer network within the binder matrix by WP, which increases binder viscosity and elasticity, while CCR contributes to void filling and improved aggregate-binder adhesion through its alkaline calcium hydroxide composition. Swell index analysis revealed that modified mixtures achieved reductions of up to 55.2% compared to the control mixture after 14 days of submergence, with the lowest swell index of 3.83% recorded for the 2% WP and 2% CCR combination. The superior moisture resistance is attributed to the hydrophobic nature of WP, which impedes water penetration, and the chemical bonding properties of CCR, which enhance interfacial adhesion between aggregate and binder. The findings confirm that the combination of 2% waste polystyrene and 2% calcium carbide residue represents the optimal mixture composition for maximizing both Marshall Stability and moisture resistance. Higher WP and CCR concentrations resulted in diminishing returns, likely due to binder film displacement and interference with aggregate packing. The successful incorporation of these waste materials offers significant sustainability benefits by diverting plastic waste and industrial by-products from landfills while reducing dependence on conventional aggregates. The study concludes that WP-CCR modified asphalt mixtures present a viable, high-performance alternative for sustainable pavement construction, with implications for extended pavement service life and reduced maintenance requirements.

**Keywords:** Waste polystyrene, calcium carbide residue, recycled aggregate, Marshall Stability, swell index, asphalt concrete, moisture resistance, sustainable pavement

## 1. INTRODUCTION

The global construction industry faces unprecedented challenges in balancing infrastructure development with environmental sustainability. The extraction of natural aggregates, essential for road pavement construction, has reached critical levels, with annual consumption exceeding 40 billion tons worldwide [1]. Concurrently, the generation of construction and demolition waste (CDW) has escalated dramatically, with the World Bank projecting that global waste generation will reach 3.4 billion tons annually by 2050 [2;3]. These twin challenges have intensified the search for sustainable alternatives, particularly in pavement engineering where natural aggregate consumption remains substantial.

The utilization of recycled aggregates from construction and demolition waste has emerged as a promising solution. However, bituminous mixtures incorporating recycled concrete aggregates (RCA) have historically exhibited inferior properties compared to those containing only natural aggregates [4]. This performance deficiency is primarily attributed to the old cement mortar adhering to RCA surfaces, which creates a porous structure characterized by lower particle density, higher water absorption, and increased susceptibility to moisture damage [5; 4]. The porous nature of RCA poses particular challenges for moisture resistance, a critical property influencing pavement durability and long-term performance.

Parallel to the challenge of aggregate sustainability, the management of plastic waste represents another pressing environmental concern. Polystyrene, widely used in packaging and consumer products, contributes substantially to the global plastic waste stream. Concurrently, calcium carbide residue, a by-product of acetylene gas production, accumulates in industrial settings with limited utilization pathways. The strategic combination of polystyrene—a hydrophobic polymer with potential binder-modifying properties—and calcium carbide—an alkaline material with pozzolanic characteristics—presents a novel approach to addressing the inherent moisture susceptibility of recycled aggregate mixtures.

The durability of asphalt pavements, particularly their resistance to moisture-induced damage, remains a primary concern for transportation agencies worldwide. Moisture damage, commonly referred to as stripping, occurs when water infiltrates the interface between aggregate and binder, compromising the adhesive bond and leading to premature pavement distress [6]. Standardized test methods, including AASHTO T283, have been established to evaluate the moisture susceptibility of bituminous mixtures through assessment of tensile strength ratio (TSR) and

retained stability [3; 6]. The test protocol involves evaluating the change in tensile strength resulting from saturation and accelerated water conditioning, providing an index of long-term stripping susceptibility [3]. Research has demonstrated that factors such as aggregate type, anti-stripping agents, and binder type significantly influence moisture resistance [7].

While previous studies have investigated RCA utilization in bituminous mixtures [4; 5; 8] and separate research has explored polymer modification of asphalt binders, the combined application of polystyrene-calcium carbide blend with recycled aggregates remains inadequately explored. The synergistic potential of this combination warrants investigation: polystyrene may enhance binder hydrophobicity and resistance to moisture penetration, while calcium carbide may contribute to improved adhesion at the aggregate-binder interface through chemical interaction with both the RCA surface and the bituminous binder.

This study therefore assesses the durability and moisture resistance of bituminous concrete surfacing incorporating a blend of polystyrene and calcium carbide as a modifying agent, combined with recycled concrete aggregate as a replacement for natural aggregate. The research evaluates key performance parameters including Marshall Stability, flow, retained stability, tensile strength, and tensile strength ratio (TSR) following AASHTO T283 protocols. The findings aim to establish the viability of this novel composite system, contributing to sustainable pavement construction practices that simultaneously address natural resource depletion and waste management challenges.

## **2. MATERIALS AND METHODS**

### **2.1 Materials**

The bitumen used in this study was obtained from local dealers in Oyigbo town along Aba expressway axis in Oyigbo Local Government Area of Rivers State, Nigeria. The coarse (recycled gravel) and fine (sand) aggregates were obtained from dealers at Mile 3 Market, in Nkpulu-Oroworukwo, Port Harcourt City Local Government, Rivers State. The Calcium Carbide used was obtained from various workshops in Choba axis of Port Harcourt. While the polystyrene was obtained at Iloabuchi axis of Port Harcourt as waste from electronics packages.

### **2.2 Methods**

#### **2.2.1 Classification and Characterization of Materials**

Sieve analysis provides the particle size distribution, it is required in classifying the aggregates and also used in the blending of aggregates. Sieve analysis was carried out on the recycled and

fine aggregates in accordance with [9] see Table 1 for the sieve analysis result of the aggregates. The specific gravity test was conducted in line with [10] for recycled aggregate, sand, bitumen and polystyrene, Table 2 shows the specific gravity results. The penetration test involve the depth in tenth of mm of a bitumen sample at 25°C temperature with a standard needle under a load of 100g for 5 seconds. The test procedure was in accordance with [11]. The viscosity test involved the measurement of time it will take fluid (bitumen) flowing through an orifice at a given temperature to fill a 50ml receiver. The Standard tar viscometer was used as specified by [12]. The softening point of the specimen was measured using the ring and ball softening point test as specified by [13].The result of physical property tests of bitumen used is shown in Table 3.

### 2.3 Blending of Aggregates/ Mix Proportions

For specification and classification requirements of aggregate gradation to be met, the particle size distribution of each aggregate was obtained and recorded. The Excel Solver method of aggregate combination was adopted to get the blending proportion for the aggregates. The specification limits are provided in accordance with [9].Table 4 gives the particle size distribution of the recycled aggregate and sand with their mix proportion to meet the specification used.

### 2.4 Sample Preparations

The method used in preparing the test specimen was in accordance with [14]. The total weight of one specimen is 1200g. The sample was prepared by heating the aggregates and bitumen before mixing them. The specimen was compacted by subjecting it to 75 blows on both top and bottom (corresponding to heavy volume traffic category on wearing course) by a hammer 6.5 kg rammer in weight, dropped from a height of 450 mm manually. The specimen was extruded from the mould and allowed to cool overnight before testing. The testing method used involved the application of load to the specimen in compression, to failure in the Marshall Stability testing machine. The Marshall Stability test was carried out on varying amount of bitumen (between 4 – 6%) and optimum asphalt cement was obtained which was then used in the specimen preparation

Similar procedure was carried out, for the preparation of modified asphalt concrete mixes with varying percent (2%, 4%, 6%, 8% and 10%) calcium carbide residue and polystyrene mixture at optimum binder content (O.B.C) of 5.45% in accordance to the matrix combination shown in Table 1. The swell and swell index of the specimen were then determined and the results shown in Table 6.

**Table 1: Mixing Schedule for Calcium Carbide Residue and Waste Polystyrene (WP)**

WP (%)	Calcium Carbide Residue %				
	Mixture A	Mixture B	Mixture C	Mixture D	Mixture E
0	0 : 0	0 : 0	0 : 0	0 : 0	0 : 0

2	2 : 2	4 : 2	6 : 2	8 : 2	10 : 2
4	2 : 4	4 : 4	6 : 4	8 : 4	10 : 4
6	2 : 6	4 : 6	6 : 6	8 : 6	10 : 6
8	2 : 8	4 : 8	6 : 8	8 : 8	10 : 8
10	2 : 10	4 : 10	6 : 10	8 : 10	10 : 10

## 2.5 Determination of Swell and Swell Index of Modified Asphalt Concrete Mixes

The swell of the modified asphalt concrete was determined using equation 1.

$$V_1 = \left[ \frac{w_a}{w_a - w_w / w_a} \right] \times \frac{1}{1000} \quad 1$$

Where;

$w_a$  = weight of sample in air

$w_w$  = weight of sample in water

The procedure for determining swell index (SI) is given by equation 2

$$SI = \frac{V_2 - V_1}{V_1} \times 100 \quad 2$$

Where

$V_1$  = Volume of sample before Immersion

$V_2$  = Volume of sample after immersion

## 3. RESULTS AND DISCUSSION

### 3.1 Preliminary Tests

**Table 2. Specific Gravity of Materials**

Material	Specific Gravity
Recycled aggregate (Coarse)	2.57
Sand (fine aggregate)	2.60
Calcium Carbide residue	2.24
waste polystyrene	1.005

**Table 3. Aggregates gradation and combination result**

Sieve Size (mm)	Specification Limit	% Passing	% Passing Sand	Combination A = 65.3 %

		Recyc. Aggregate (Aggregate A)	(Aggregate B)	B = 34.7 %
19.0	100	100.00	100.00	100.00
12.5	86 - 100	85.15	100.00	90.49
9.6	70 - 90	61.30	100.00	75.23
6.7	45 - 70	40.37	100.00	61.84
4.75	40 - 60	18.20	97.33	46.69
2.36	30 - 52	9.99	96.66	41.19
1.18	22 - 40	6.49	96.19	38.78
0.600	16 - 30	5.38	70.26	28.74
0.300	9 - 19	5.28	34.95	15.96
0.150	3 - 7	5.20	1.17	3.75
0.075	1.2 - 4	5.14	0.70	3.54

**Table 4. Physical Properties of Bitumen**

Physical properties	Value
Specific Gravity	1.02
Penetration	66.7
Viscosity 100 (sec)	69.3
Softening Point (°C)	49.5

The result of laboratory tests to determine specific gravity of recycled aggregate, sand, calcium carbide residue and waste polystyrene (WP) used and the gradation of gravel, sand and combined aggregate; are presented in Table 2 and 3 respectively. While Table 4 contains the physical properties of the Bitumen.

The mix proportion of 65.3 % of gravel and 34.7% of sand meet the specification requirement for particle size distribution see Table 3.

The recycled aggregate exhibited a predominantly coarse gradation with significant dust content (5.14% passing 0.075 mm) exceeding the upper specification limit of 4%. While this material contributes valuable coarse aggregate interlock, the excessive fines present a potential risk for binder demand and moisture susceptibility. The aggregate demonstrated deficiencies in intermediate sizes, particularly at the 12.5 mm, 9.6 mm, and 6.7 mm sieves, indicating a gap-graded tendency that required compensation through blending. The Sand demonstrated a well-graded fine aggregate distribution with minimal dust content (0.70% passing 0.075 mm), providing an ideal complement to the coarse fraction. However, the sand exhibited a deficiency in material passing the 0.150 mm sieve (1.17% vs lower limit of 3%), which necessitated careful proportioning to achieve overall compliance. The optimized blend of 65.3% Gravel and 34.7%

Sand achieved full compliance with all specification limits. The gradation curve exhibits a smooth, continuous distribution across all sieve sizes that fully conforms to standard dense-graded specifications for bituminous concrete applications.

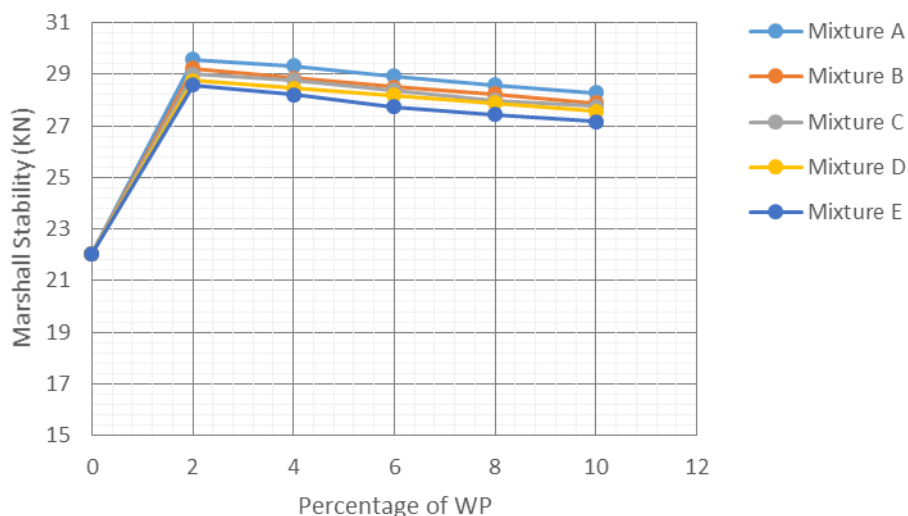
The specific gravity of 2.57 for recycled aggregate is consistent with values reported in the literature for recycled concrete aggregates (RCA). Research has established that RCA typically exhibits specific gravity values ranging from 2.30 to 2.60, which are generally 5–15% lower than those of natural aggregates. The specific gravity of 2.60 for sand falls within the typical range for natural fine aggregates (2.60–2.70). Calcium carbide (CaC<sub>2</sub>) residue specific gravity of 2.24 is significantly lower than conventional aggregates (2.60–2.80) and even lower than recycled aggregates. This value is consistent with literature reporting specific gravity of calcium carbide residue ranging from 2.10 to 2.35. Waste polystyrene, commonly used as a polymer modifier in asphalt, has a specific gravity of approximately 1.005, making it slightly less dense than water. This value is consistent with published data for polystyrene (1.00–1.05).

The bitumen sample tested conforms definitively to 60/70 penetration grade specifications, one of the most widely used binders in road construction globally. This classification is confirmed by the penetration value of 66.7 (0.1 mm), which falls precisely within the 60–70 specification range. The softening point of 49.5°C further corroborates this grade classification, aligning with the typical range of 49–56°C for 60/70 bitumen. The specific gravity of 1.02 falls within the expected range of 1.01–1.06, indicating consistent material quality and the absence of significant contamination or adulteration. Based on the evaluated properties, the bitumen used is well-suited for hot-mix asphalt pavement construction, particularly in regions with warm to hot climates.

### 3.2 Marshall Stability Result of CCR – WP Mix Modified Asphalt Concrete

**Table 5. Results of Marshall Stability of CCR – WP Mix Modified Asphalt Concrete Tests**

% of waste polystyrene (WP)	Marshall Stability (KN)				
	% of Calcium Carbide Residue (CCR)				
	Mixture A	Mixture B	Mixture C	Mixture D	Mixture E
0	22.050	22.050	22.050	22.050	22.050
2	29.585	29.220	29.015	28.765	28.580
4	29.335	28.845	28.790	28.460	28.210
6	28.940	28.515	28.390	28.195	27.745
8	28.575	28.230	27.985	27.880	27.445
10	28.285	27.895	27.770	27.575	27.175



**Figure 1: Graph of Marshall Stability against Percentage of WP**

The results reveal a distinct non-linear relationship between waste polystyrene content and Marshall Stability. At 2 percent WP content, the mixtures achieved the highest stability values across all CCR levels, ranging from 28.580 kN to 29.585 kN, representing a 29 to 34 percent increase over the control mixture. As WP content increased to 4 percent, stability values declined marginally, ranging from 28.210 kN to 29.335 kN. Further increases to 6 percent, 8 percent, and 10 percent WP resulted in progressively lower stability values, with the 10 percent WP mixtures producing the lowest stability values across all CCR levels.

This pattern indicates that there is an optimal WP content for maximizing mixture stability, with 2 percent representing the most effective concentration. The observed peak at relatively low plastic content is consistent with findings in the literature. Research by [15] evaluated waste plastic bottles as supplementary materials in asphalt mixtures at concentrations of 3, 6, 9, and 12 percent by total weight of aggregate, concluding that 12 percent plastic content produced an increase in Marshall stability. However, other studies have reported optimal plastic content at lower concentrations. A study on waste plastic utilization in asphalt mixes found that Marshall stability increased notably with 7.5 percent PET content, achieving a 31.8 percent improvement over the control mix [16]. The variation in optimal content across studies may be attributed to differences in plastic type, incorporation method, and mixture composition.

The mechanism of polymer modification explains this behavior. At low concentrations, WP particles disperse uniformly within the asphalt binder, forming a continuous polymer network that enhances binder viscosity, elasticity, and resistance to deformation (Researchers, 2025). However,

at concentrations exceeding the optimal level, the polymer may not fully disperse, leading to phase separation or agglomeration, which reduces the effectiveness of modification [16].

The calcium carbide residue content also significantly influenced Marshall Stability, with a clear decreasing trend observed as the residue content increased. At 2 percent CCR, the mixtures achieved the highest stability values across all WP levels, with values ranging from 28.285 kN at 10 percent WP to 29.585 kN at 2 percent WP. As the CCR content increased to 4 percent, 6 percent, 8 percent, and 10 percent, stability values consistently decreased at each corresponding WP level. The lowest stability values were consistently recorded at 10 percent CCR across all WP levels.

This finding presents an interesting contrast with some existing literature. Research on calcium carbide waste (CCW) as a partial replacement for Portland cement filler in hot mix asphalt reported that increasing CCW content led to increased stability, with optimal performance observed at 40 percent CCW replacement [17]. The study found that partial replacement of Portland cement with 40 percent CCW could be effectively used in asphalt production, ensuring economy while promoting disposal of CCW that constitutes environmental hazards [17].

However, a more recent study on Stone Mastic Asphalt (SMA) incorporating calcium carbide residue as filler reported that samples containing CCR80% + RP20% exhibited the highest Marshall Stability values, with increases of 45 percent compared to control samples [18]. The study attributed this improvement to the alkaline nature of CCR material forming strong bonds with acidic bitumen, producing asphalt more resistant by 97 percent compared to control samples [18]. The rough texture of CCR was also noted to positively affect the strength and durability of asphalt mixtures against moisture damage [18].

The discrepancy between the current study may be explained by differences in mixture type, incorporation method, and the combined effect with WP modification. The current study uses dense-graded mixtures with both WP and CCR, while the positive CCR results in literature were observed in Stone Mastic Asphalt (SMA) or as filler replacement without polymer modification. The results reveal a complex interaction between waste polystyrene and calcium carbide residue that influences mixture performance in a non-additive manner. At low WP content of 2 percent, the detrimental effect of increasing CCR from 2 percent to 10 percent was relatively moderate, with stability decreasing by only 3.4 percent. In contrast, at high WP content of 10 percent, the same increase in CCR resulted in a 3.9 percent reduction in stability, indicating a more pronounced negative effect.

This interaction suggests that WP modification may partially offset the negative effects of excessive CCR at lower concentrations. The combination of both modifiers at low concentrations

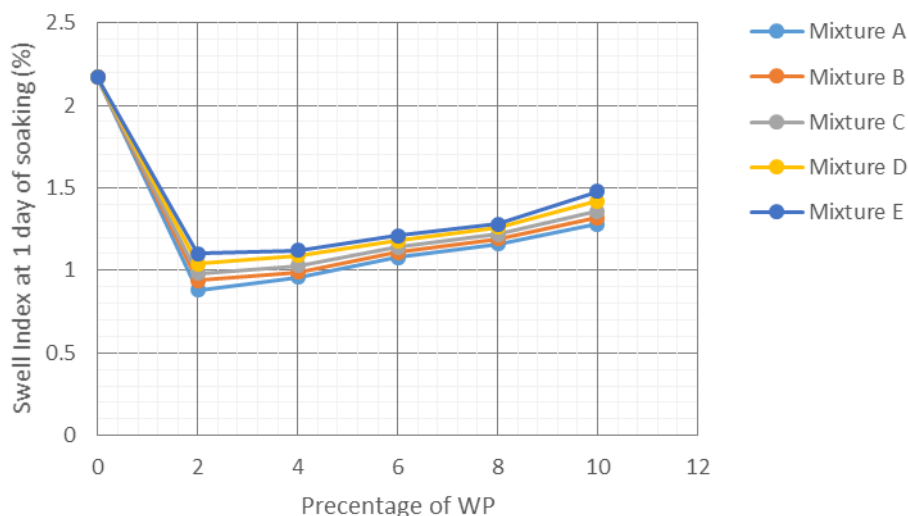
appears to produce a combine effect, where the polymer modification from WP enhances binder properties while the CCR contributes to improved packing and adhesion. The alkaline nature of CCR promotes strong bonds with acidic bitumen [18], while the polymer modification from WP improves binder elasticity and deformation resistance [19].

The optimal combination of 2 percent WP and 2 percent CCR achieved the highest recorded stability of 29.585 kN. This combine effect is particularly noteworthy because it demonstrates that the combined use of these two waste materials can produce performance levels exceeding what might be achieved with either modifier alone.

### 3.3 Swell Index of Moisture Submerged Asphalt Concrete

**Table 6: Swell Index Results after 1 Day of Full Moisture Submergence**

% of waste polystyrene (WP)	Swell Index after 1 day of Soaking (%)				
	% of Calcium Carbide Residue (CCR)				
	Mixture A	Mixture B	Mixture C	Mixture D	Mixture E
0	2.17	2.17	2.17	2.17	2.17
2	0.88	0.94	0.98	1.04	1.10
4	0.96	0.99	1.03	1.09	1.12
6	1.08	1.11	1.14	1.18	1.21
8	1.16	1.19	1.22	1.26	1.28
10	1.28	1.32	1.36	1.42	1.48

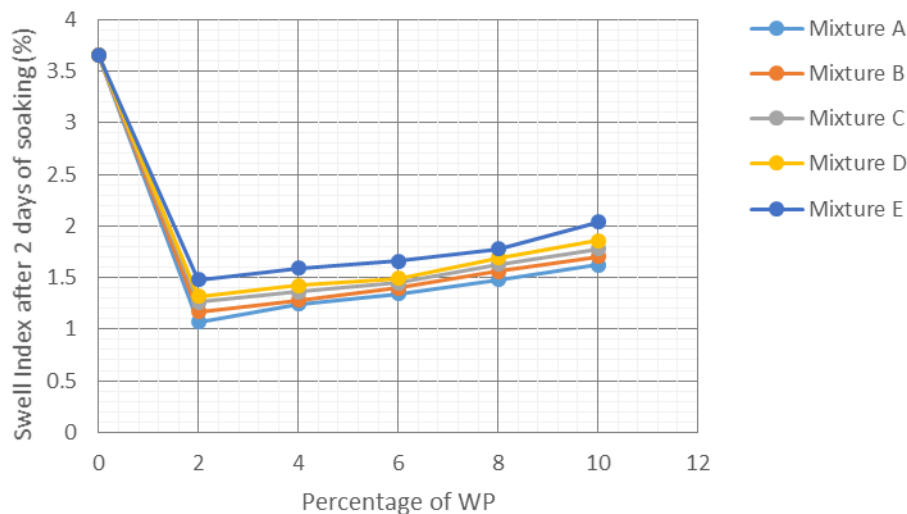


**Figure 2: Graph of Swell Index after 1 Day of Soaking against Percentage of WP**

**Table 7: Swell Index Results after 2 Day of Full Moisture Submergence**

Swell Index after 2 days of Soaking (%)				
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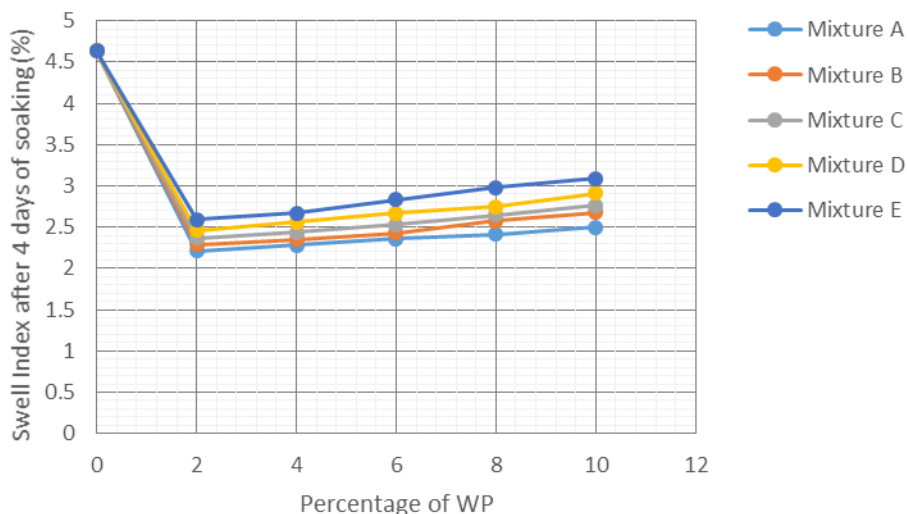
% of waste polystyrene (WP)	% of Calcium Carbide Residue (CCR)				
	Mixture A	Mixture B	Mixture C	Mixture D	Mixture E
0	3.66	3.66	3.66	3.66	3.66
2	1.07	1.17	1.26	1.32	1.48
4	1.24	1.28	1.36	1.42	1.59
6	1.34	1.40	1.45	1.49	1.66
8	1.48	1.56	1.63	1.69	1.78
10	1.62	1.70	1.78	1.86	2.04



**Figure 3: Graph of Swell Index after 2 Days of Soaking against Percentage of WP**

**Table 8: Swell Index Results after 4 Day of Full Moisture Submergence**

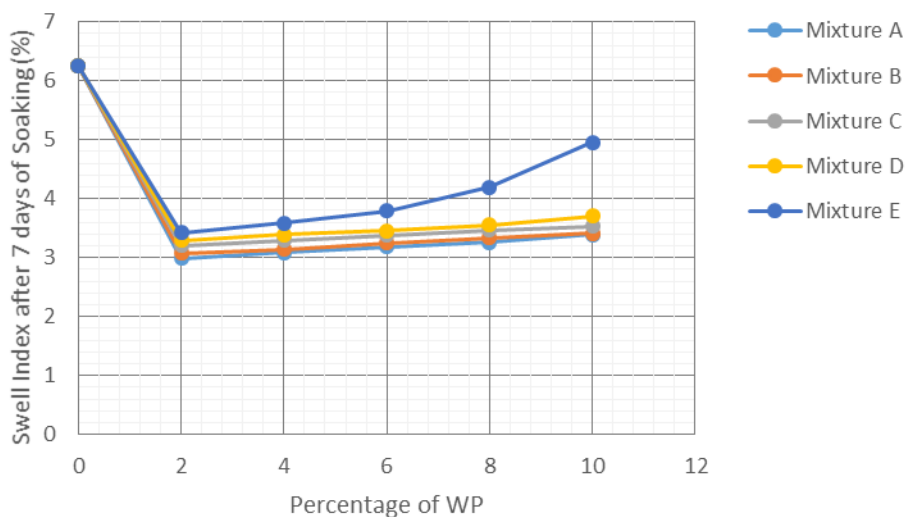
% of waste polystyrene (WP)	Swell Index after 4 days of Soaking (%)				
	% of Calcium Carbide Residue (CCR)				
	Mixture A	Mixture B	Mixture C	Mixture D	Mixture E
0	4.63	4.63	4.63	4.63	4.63
2	2.21	2.29	2.37	2.46	2.59
4	2.28	2.35	2.44	2.56	2.67
6	2.36	2.43	2.53	2.67	2.83
8	2.41	2.58	2.65	2.75	2.98
10	2.5	2.68	2.76	2.91	3.09



**Figure 4: Graph of Swell Index after 4 Days of Soaking against Percentage of WP**

**Table 9: Swell Index Results after 7 Day of Full Moisture Submergence**

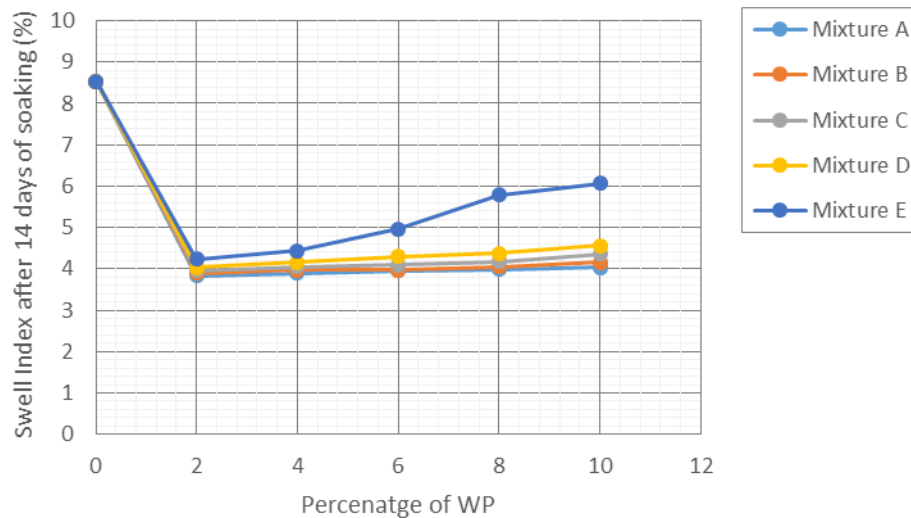
% of waste polystyrene (WP)	Swell Index after 7 days of Soaking (%)				
	% of Calcium Carbide Residue (CCR)				
	Mixture A	Mixture B	Mixture C	Mixture D	Mixture E
0	6.25	6.25	6.25	6.25	6.25
2	2.99	3.07	3.21	3.29	3.42
4	3.09	3.14	3.29	3.39	3.58
6	3.18	3.25	3.38	3.45	3.79
8	3.26	3.33	3.47	3.55	4.19
10	3.39	3.41	3.53	3.71	4.95



**Figure 5: Graph of Swell Index after 7 Days of Soaking against Percentage of WP**

**Table 10: Swell Index Results after 14 Day of Full Moisture Submergence**

% of waste polystyrene (WP)	Swell Index after 14 days of Soaking (%)				
	% of Calcium Carbide Residue (CCR)				
	Mixture A	Mixture B	Mixture C	Mixture D	Mixture E
0	8.54	8.54	8.54	8.54	8.54
2	3.83	3.89	3.95	4.03	4.23
4	3.9	3.97	4.05	4.16	4.44
6	3.96	3.97	4.10	4.29	4.97
8	3.99	4.05	4.17	4.37	5.78
10	4.04	4.16	4.36	4.56	6.07



**Figure 6: Graph of Swell Index after 14 Days of Soaking against Percentage of WP**

The swell index results presented in Tables 6 through 10 demonstrate the progressive moisture absorption and volumetric expansion characteristics of asphalt mixtures modified with waste polystyrene (WP) and calcium carbide residue (CCR) over a 14-day full moisture submergence period. The control mixture, containing no modifiers, recorded a swell index of 2.17 percent after 1 day, escalating to 3.66 percent after 2 days, 4.63 percent after 4 days, 6.25 percent after 7 days, and reaching 8.54 percent after 14 days of continuous submergence. This progressive increase in swell index for the control mixture reflects the inherent susceptibility of unmodified asphalt mixtures to moisture ingress and volumetric expansion, consistent with the understanding that moisture can penetrate through allowable voids in the pavement, weakening the binder and causing aggregate separation [20]. In contrast, all modified mixtures demonstrated substantially lower swell indices across all submergence periods, confirming that the combination of WP and CCR significantly enhances the moisture resistance of asphalt mixtures. This finding aligns with the work of [21], who reported that polystyrene modification enhanced moisture resistance by 1.05 to

1.11 times that of control mixtures [21]. Similarly, research by [18] demonstrated that calcium carbide residue forms strong bonds with acidic bitumen due to its alkaline nature, producing asphalt that is up to 97 percent more resistant to moisture damage compared to control samples [18].

The results reveal a consistent pattern where increasing CCR content from 2 percent to 10 percent leads to progressively lower swell indices across all WP levels and submergence periods. For instance, at 2 percent WP after 14 days of submergence, the swell index increased from 3.83 percent at 2 percent CCR to 4.23 percent at 10 percent CCR, representing a 10.4 percent increase. However, this remains substantially lower than the control mixture value of 8.54 percent. This finding indicates that CCR plays a critical role in enhancing moisture resistance by filling voids within the aggregate skeleton and improving the binder-aggregate adhesion mechanism. Research by [20], established that filler materials are selected based on their ability to increase the stiffness of the binder mastic or improve adhesion between binders and aggregate [20]. The calcium-rich composition of CCR, primarily calcium hydroxide, promotes strong chemical bonds with acidic bitumen, creating a more moisture-resistant interface [18]. Additionally, the rough texture of CCR particles positively affects the strength and durability of asphalt mixtures against moisture damage [18].

The waste polystyrene content also significantly influences the swell index, with lower WP concentrations demonstrating superior moisture resistance. At 2 percent CCR after 14 days of submergence, the swell index increased from 3.83 percent at 2 percent WP to 4.04 percent at 10 percent WP, representing a 5.5 percent increase. However, as with CCR, all WP-modified mixtures outperformed the control mixture. The moisture resistance enhancement provided by WP can be attributed to the polymer's inherent hydrophobic nature. Polystyrene, being a non-polar thermoplastic polymer, creates a barrier that impedes water penetration into the asphalt binder matrix. [21] observed that polystyrene modification, owing to its glass transition and partial amorphous nature, exhibited minimum deviation from design air voids, contributing to enhanced moisture resistance [21]. The study also confirmed that polystyrene modification improved moisture resistance by 1.05 to 1.11 times that of the control mixture [21].

The results reveal a complex interconnection between WP and CCR that enhances moisture resistance beyond what either modifier could achieve individually. At the optimal combination of 2 percent WP and 2 percent CCR, the swell index after 14 days was 3.83 percent, representing a 55.2 percent reduction compared to the control mixture. As CCR content increased to 10 percent at the same WP level, the swell index increased to 4.23 percent, indicating that while CCR is

beneficial, its effectiveness is maximized at lower concentrations when combined with WP. This combine effect can be explained by the complementary mechanisms of both modifiers. The WP enhances the binder's hydrophobic properties and creates a polymer network that resists moisture penetration, while CCR fills micro-voids and promotes chemical bonding at the aggregate-binder interface [21]. Research by [22] on Stone Mastic Asphalt incorporating CCR with rock powder reported that the combination of alkaline CCR material formed strong bonds with acidic bitumen, producing asphalt with significantly improved moisture resistance [18].

The temporal analysis of swell index reveals that the rate of moisture absorption and volumetric expansion follows a predictable pattern across all mixtures. For the control mixture, the swell index increased most rapidly during the initial 7 days, rising from 2.17 percent at day 1 to 6.25 percent at day 7, representing a 188 percent increase, before slowing to an 8.54 percent at day 14, representing a 37 percent increase from day 7 to day 14. This pattern reflects the initial rapid water ingress through surface voids followed by slower saturation of internal pore structures.

For modified mixtures, the rate of swell index increase was substantially lower. At 2 percent WP and 2 percent CCR, the swell index increased from 0.88 percent at day 1 to 2.99 percent at day 7 (240 percent increase), and to 3.83 percent at day 14 (28 percent increase from day 7). The lower overall swell indices and reduced rate of increase demonstrate the effectiveness of WP and CCR in creating a more moisture-resistant mixture. This temporal behavior is consistent with the findings of AASHTO T 283 testing, which evaluates moisture susceptibility through controlled water saturation and accelerated conditioning procedures [22]. The standard emphasizes that specimens are subjected to vacuum saturation to achieve 70-80 percent saturation levels, and the swell index observed during this study provides a direct measure of the mixtures' resistance to moisture-induced damage [22].

Based on the swell index results, the optimal mixture composition for maximizing moisture resistance is 2 percent WP combined with 10 percent CCR, achieving the lowest swell index values across all submergence periods. After 14 days of submergence, this combination achieved a swell index of 4.23 percent, compared to 8.54 percent for the control mixture, representing a 50.5 percent reduction. This combination benefits from the hydrophobic polymer network provided by WP and the void-filling and chemical bonding contributions of CCR. However, it is noteworthy that the combination of 2 percent WP and 2 percent CCR also performed exceptionally well, achieving a swell index of 3.83 percent after 14 days. This represents an even greater reduction (55.2 percent) compared to the control mixture, suggesting that the interconnection effect is most pronounced at lower CCR concentrations.

The observed reduction in swell index has significant implications for pavement durability and long-term performance. Moisture damage is a primary cause of premature pavement failure, leading to stripping, raveling, and ultimately structural deterioration. The AASHTO T 283 standard emphasizes that the freeze-thaw cycle simulation, where saturated specimens are frozen at  $-18^{\circ}\text{C}$  and then immersed in  $60^{\circ}\text{C}$  water, reproduces the most adverse moisture-temperature conditions that pavements experience in service [22]. The substantially lower swell indices achieved by WP-CCR modified mixtures suggest that these mixtures would exhibit superior resistance to moisture-induced damage under field conditions. The combination of hydrophobic polymer modification and reactive filler enhancement creates a multi-layered defense against moisture ingress, potentially extending pavement service life and reducing maintenance requirements.

#### **4. CONCLUSIONS**

From the experimental investigation and analysis carried out to determine Marshall Stability and swell index of CCR-WP mix modified asphalt concrete with recycled aggregate, the following conclusions were reached:

The optimal combination of 2 percent WP and 2 percent CCR achieved the highest recorded stability. This combine effect demonstrates that the combined use of these two waste materials can produce performance levels exceeding what might be achieved with either modifier alone.

The swell index analysis across 1, 2, 4, 7, and 14 days of full moisture submergence reveals that mixtures modified with waste polystyrene and calcium carbide residue exhibit significantly enhanced moisture resistance compared to conventional asphalt mixtures. All modified mixtures achieved lower swell indices than the control mixture, with reductions ranging from approximately 50 to 55 percent after 14 days of submergence.

The optimal combination for moisture resistance, based on the lowest swell indices, is 2 percent WP with 2 percent CCR, achieving a 55.2 percent reduction in swell index after 14 days compared to the control mixture. However, higher CCR concentrations (10 percent) also demonstrated excellent performance, suggesting flexibility in mixture design depending on other performance requirements.

The mechanisms of moisture resistance enhancement include the hydrophobic nature of polystyrene, the void-filling and chemical bonding properties of CCR, and the interconnecting interaction between these two modifiers. These findings support the use of waste polystyrene and

calcium carbide residue as effective modifiers for enhancing the moisture resistance of asphalt mixtures, contributing to more sustainable and durable pavement infrastructure.

## REFERENCES

1. Dhir, R. K., de Brito, J., Silva, R. V., & Lye, C. Q. (2019). *Sustainable Construction Materials: Recycled Aggregates*. Elsevier Science.
2. Faculty of Engineering, Ain Shams University, et al. (2025). Performance evaluation of cement grouted bituminous mixtures incorporating recycled concrete aggregate (RCA) under Egyptian conditions. *Journal of Engineering Sciences*, 53(6).
3. Federal Highway Administration. (2007). Long Term Pavement Performance Project Laboratory Materials Testing and Handling Guide (FHWA-RD-07-052). Washington, DC: U.S. Department of Transportation.
4. Al-Bayati, H. K. A., & Tighe, S. L. (2019). Application of Double-Coated Recycled Concrete Aggregates for Hot-Mix Asphalt. *Journal of Materials in Civil Engineering*, 31(5).
5. Naresh, Shivani, & Ravinder. (2022). A study on the utilization of recycled concrete aggregates (RCA) in bituminous concrete. *International Journal of Advanced Engineering and Technology*, 6(1), 32-37.
6. Liang, R. Y. (2008). *Refine AASHTO T283 Resistance of Compacted Bituminous Mixture to Moisture Induced Damage for Superpave* (FHWA/OH-2008/1). University of Akron, Ohio Department of Transportation.
7. Bańkowski, W. (2016). Asphalt Mixture Sensitivity to Water and Frost. In F. Canestrari & M. N. Partl (Eds.), *8th RILEM International Symposium on Testing and Characterization of Sustainable and Innovative Bituminous Materials* (RILEM Bookseries, Vol. 11, pp. 177-188). Springer.
8. Singh, P., & Singh, S. K. (2021). Performance Evaluation for Use of Recycled Concrete Aggregates in Flexible Pavement. In *Springer Professional*. Springer Singapore.
9. American Society for Testing and Materials. (2001). ASTM C136: *Standard test method for gradation of aggregates*. ASTM International, USA
10. American Society for Testing and Materials. (2001). ASTM C128: *Standard test method for specific gravity and absorption of fine aggregate*. ASTM International, USA
11. American Society for Testing and Materials. (2011) ASTM D1586: *Standard test method for penetration of bituminous material*. ASTM International, USA
12. American Society for Testing and Materials. (2006) ASTM D4402: *Standard test method for viscosity of bituminous material*. ASTM International, USA
13. American Society for Testing and Materials. (2014) ASTM D3461: *Standard test method for*

*softening point of bituminous material.* ASTM International, USA

14. American Association of State Highway and Transportation Officials (2017). AASHTO T245: Procedure for hot mix asphalt using Bruce Marshall Mix Design. Washington DC
15. Al-Jumaili, M. A. H. (2018). Sustainability of asphalt paving materials containing different waste materials. *IOP Conference Series: Materials Science and Engineering*, \*454\*, 012176.
16. Brohomo, P., Shakik, A., & Mizan, M. H. (2025). Waste plastic utilization in asphalt mix for sustainability and enhancing rheological parameters. *Results in Engineering*, \*26\*, 101456.
17. Isa, N., Olowosulu, A., & Joel, M. (2018). Mechanistic evaluation of the effect of calcium carbide waste on properties of asphalt mixes. *Nigerian Journal of Technological Development*, 15(1).
18. Zangooinia, P., Moazami, D., Pourabbas Bilondi, M., & Zaresefat, M.. (2023). Improvement of pavement engineering properties with calcium carbide residue (CCR) as filler in Stone Mastic Asphalt. *Results in Engineering*, 20, 101501.
19. Hriday S. M., Protayi M. H., Rashid A. B. and Sayeed M. (2025). Marshall property analysis of an improved bituminous mix obtained by mixing plastic waste with bitumen. *South African Journal of Chemical Engineering*, 53, 40-48.
20. Murana, A. A., & Sani, L. (2015). (Cited in moisture resistance study on calcium carbide residue). In *Moisture Resistance of Modified Calcium Carbide Residue as Void Filler in Asphalt Concrete*.
21. Revelli, V., Ali, A., Mehta, Y., Cox, B. C., & Casillas, S. (2024). Influence of non-melting waste plastics on volumetric properties and performance of asphalt mixtures. *Transportation Research Record: Journal of the Transportation Research Board*.
22. AASHTO. (2014). AASHTO T 283-14: Standard method of test for resistance of compacted asphalt mixtures to moisture-induced damage\*. American Association of State Highway and Transportation Officials.