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Mild steel chip reinforced highly stable epoxy asphalt composites for pavement application

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Asphalt composites a critical material widely used in road paving and various other applications due to its enhanced load-bearing capacity. To improve the sustainability of the asphalt composites, shape retention at high stress and water penetration characteristics have to be enhanced. The effect of mild steel reinforcement and epoxy content on the performances of asphalt composites has been investigated by varying proportion of reinforced content. All samples have been prepared according to established procedures, including the grading of raw materials and standardized mold dimensions. Subsequent tests have been conducted to evaluate marshal stability, specific gravity, contact angle, and water absorption. The results indicated that the conventionally prepared sample have shown a marshal stability value of 11.29 KN. Notably, the sample which incorporated mild steel reinforcement and epoxy content, has exhibited the highest stability value of 30.81 KN. The marshal stability values for the remaining samples ranged from 11 KN to 30 KN. Sample incorporated with mild steel reinforcement and epoxy content also displayed the lowest air void of 10.10%. Furthermore, superior hydrophobic properties, with a contact angle of 147° and 0% water absorption capacity has indicated its potential for enhanced performance in real-world applications.

Keywords: Epoxy asphalt composites, High stability, Hydrophobic, Low water absorption, Mild steel reinforced, Pavement

1 Introduction

Road paving is an integral part of transportation infrastructure. Pavements built with asphalt concrete makeup most of paved roads globally. The use of composite asphalt is not only limited to roads only but also in runways, track beds, playgrounds, tennis courts, barn floors, harbors are some of the areas of application[1]. Asphalt composites are a popular paving material because of their low initial cost compared to other alternatives, their availability, their ease of construction, and their ability to be used in low-traffic areas[1]. The words asphalt and bitumen are often used incorrectly to define the same thing. Asphalt is a compound of aggregate, sand and bitumen. Bitumen acts as a liquid binder that holds the asphalt together. Road surfaces that are only sealed with bitumen are also common, where a layer of bitumen is applied, covered with aggregate, and the process is repeated to obtain the two layers. Asphalt pavements tend to be more durable, with a layer thickness of about 22-40 mm and lasting more than 20 years[1]. On the other hand, bitumen-sealed surfaces and walkways are considered less durable. The layer thickness is about 10-20 mm and the lifetime is about 5-10 years[1]. In areas with little or no traffic, bitumen is an excellent and inexpensive alternative. The problem of stress and failure in asphalt composite pavements is considered complex as multiple factors contribute to pavement degradation and failure[2]. Improving the durability of asphalt composites requires a good understanding of failures and their causes. Aged deterioration and oxidation of the asphalt film led to deterioration[3]. This degradation effect increases rapidly as the porosity of the asphalt composite retains excess water. Binder volatilization makes the asphalt composite surface brittle, leading to water penetration and further deterioration[2]. Poor mix design, improper aggregate grading, and insufficient binder content lead to overlay failure[1]. A common asphalt surface failure is alligator tear or map tear which is caused by the relative movement of layers in the road when high wheel loads are repeatedly applied. Moisture also plays an important role in this type of disorder. Localized vulnerabilities in the underlying base layer can also lead to this type of failure[4]. Another failure is rutting which is a depression or groove worn into a road by the travel of wheels and caused due to repeated application of load along the same wheel path resulting longitudinal ruts[5].

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On the other side excessive wheel loading and low shearing resistance of pavement mixture are primary causes of another type of failure known as shear failure[6].

Bitumen plays a crucial role as it acts as a binding agent, effectively uniting mineral particles to create a robust coating of asphalt concrete. Due to its non-polar nature, bitumen boasts impressive water-resistant properties[2,3]. Moisture induced damage in asphalt concrete pavements stands as a primary cause of distresses in the various layers of the asphalt pavement[7,8]. While asphalt concrete is generally known for its substantial water resistance, moisture can infiltrate through its pores via various mechanisms. This can occur through impregnation, where surface water permeates the material[9]. Additionally, capillary forces can drive water from the base of the road upwards into the asphalt concrete[4,9]. Moreover, water vapor from the surrounding air can penetrate the pores and condense within. Furthermore, the pressure exerted by passing vehicles wheels can expedite the penetration of water into the pores of the asphalt concrete[10]. Hence, it becomes imperative to ensure both passive and active adhesion of the bituminous binder to the asphalt concrete to enhance its resistance to water penetration[6,10]. So it is important to use high-quality bituminous binders and aggregates in pavement construction to ensure the robustness of active adhesion, thereby fortifying the overall resilience of the asphalt concrete structure[11]. The adhesion mechanism in the bitumen aggregate system involves intricate interactions at the molecular level, ensuring the cohesion of these essential components in asphalt pavements. Understanding these interactions is essential for optimizing asphalt performance, especially in environments where moisture exposure can significantly impact adhesion and the overall durability of the pavement structure[12]. Epoxy asphalt (EA) has been originally applied in the pavement industry because of its superior rutting resistance when compared with traditional asphalt binder, as this structure was cross-linked during the curing process[13]. Epoxy Asphalt, typically a two-phase composite system, usually consists of epoxy resin as component A and asphalt, curing agent, diluent, fillers and toughening agents as component B[13]. The final composite, comprising components A and B with an added epoxy-based polymer structure, exhibits excellent resistance to fatigue loading, moisture damage, and oxidative aging[13]. The properties of cured epoxy can be effectively tailored by selecting the appropriate epoxy resin, curing agent, modifier, component composition, and curing conditions[13,14,15]. The choice of curing agent is determined by factors such as the application, processing techniques, curing environment, and the desired properties such as mechanical, chemical, thermal, and environmental limitations and costs. Curing agents are either catalytic or co-reactive[16]. Epoxy resin curing can be achieved either through epoxy-to-epoxy ring-opening homo-polymerization using catalytic curing agents or via co-polymerization with poly-functional co-reactive curing agents[17]. Key curing methods include chemical curing (at room or elevated temperatures), microwave curing, and radiation curing, such as electron-beam and ultraviolet curing[11].Various chemical reaction takes place during curing which can help to determine the kinetics or rate of cure required for a specific properties[13,18]. The heating rate normally depends on temperature, extent of reaction (αt) and pressure, the activation energy E and the universal gas constant R by following Eq (1)[(19)].

$$ln\frac{\beta_i}{T_{\alpha,i}^2} = A - \frac{E_\alpha}{RT_\alpha} \quad ...(1)$$

Where β is heating rate, T is temperature, R is gas constant, P is pressure, E is activation energy and A is constant. Epoxy and a curing agent are mixed with bitumen content at a specific percentage to provide optimum performance properties like excellent resistance to rutting, moisture damage[4,18]. An experiment was done by some researchers to find out the optimum bitumen content to improve the performance of epoxy asphalt composite. VG 40 grade bitumen, fine aggregates, coarse aggregate, fillers, epoxy resin was used for conducting the experiment[20]. Different percentages of epoxy resin in the bitumen mix were taken (1, 2, 3, 3.25, 3.5, 3.75 and 4) and stability, flow rate (deformation between no load and maximum load), air voids, softening point are observed[20]. The study found that an epoxy content of 3.25% in bitumen mixtures maximized stability, chemical resistance, and void fill, while achieving low shrinkage and moderate flow rate, penetration, and softening point, making it suitable for summer use. Additionally, lower air voids at this content reduce crack initiation, and the volume of mineral aggregates is minimized. Thus, 3.25% epoxy is considered optimal for enhancing epoxy asphalt composite properties[20].

Another important factor is binder leakage or premature deterioration leading to eventual failure of asphalt concrete, which can also be ameliorated by incorporating fibers[21]. Polymer styrene butadiene styrene (SBS), polyethylene, cellulose fibers, nylon, aramid, steel, coir, carbon fiber, glass fiber and rock-wool fiber are used to prevent bitumen leakage in asphalt concrete aggregates[22,23]. Among these steel fibers can be used to support the stresses generated in the surface layer of the pavement. Steel fiber reinforced asphalt concrete can also provide excellent resilience to minimize cracking and maximum resilience to withstand heavy loads[24]. The major advantages of steel fiber reinforced asphalt composite are self-healing properties, low temperature cracking resistance, increased durability and less cost[24]. Steel fiber or scrap chips should be mixed properly with the bitumen and aggregates mixture in proper dimension and amount otherwise agglomeration can occur which will affect the stability of composite[25]. In a study conducted by Al-Ridha *et. al.*[26] the impact of steel fiber content was examined across concentrations of 0.1%, 0.2%, 0.3%, and 0.4% relative to the total volume mix within a specific grade. The results show that no reinforcing effect was observed when the fiber length was 6 mm or less and the fiber diameter was 0.01mm or less[26]. Hooked end or twisted fibers had no significant effect in improving the toughness of the steel fiber/asphalt mixture. On the other hand, a twisted steel fiber with a length of 30mm and a diameter of 0.3 mm showed the best toughness improvement of 89.5%[24,26]. Short, large-diameter steel fibers have better strength-enhancing capabilities than long, small-diameter fibers. Fibers are subjected to shear, tensile and impact loads during the mixing process[27]. Clustering occurs when long fibers (≥ 7 mm, 0.41% clusters) are used instead of short fibers (≈ 2.5mm, 0.35% clusters)[24]. The cluster fraction also affects the porosity of steel fiber reinforced asphalt concrete. A high percentage of clustering leads to high porosity, which affects resistance to particle loss[24].

The benefits of this research could make a real difference in the way we build and maintain our roads and infrastructure. By creating asphalt composites that are stronger and more durable, we could see roads that last longer and need fewer repairs, saving time and money for everyone, from governments and local communities to everyday drivers who won't have to deal with as many road closures and detours. These improvements also mean safer roads, as the new materials can better withstand weather and wear, reducing the risk of accidents from potholes or degraded surfaces. And it's not just limited to roads; these advancements could improve other infrastructure projects, making them more reliable and sustainable.

2 Materials and Methods

Methodology for making asphalt composite is a standardized procedure including raw material grading, taking a specific percentage of each raw materials and making of standard sample for testing.

2.1 Raw material selection and grading

The required raw materials for producing final sample were coarse aggregates, fine aggregates, filler, bitumen, epoxy, and mild steel chips. Coarse, fine and filler material were graded with sieve analysis process. Sieves for coarse aggregates were (sieve size: 19, 9.4, 4.75, 2.36mm) and for fine aggregates were (sieve size: 0.60, 0.30, 0.15, 0.075mm). Bitumen was added 4% of total weight in asphalt composite to bind the coarse and fine aggregates together. The sample with 4 % bitumen showed best results for adhesion, water resistance[20]. The sample with 3.25% epoxy which shows the best load bearing capacity along with enhancement of adhesion[20], and 0.3% mild steel chips (shown in Fig. 1) from scrap was added in bitumen mix to reduce the crack propagation, wear and abrasion[20,25] Percentages of aggregates to prepare a 1200gm of sample are shown as shown in Table 1.

2.2 Sample preparation

Total nine samples were prepared in which one was a basic standard sample and others were standard samples with epoxy or etched aggregates or changed reinforcement percentage. Although the raw material of one sample varies from another, the dimension and basic sample making procedure were same for all. The sample was 101.4mm in diameter and thickness is 63.5mm. The amount of coarse and fine aggregates are also equal for all sample1200g[28]. Figure 2 shows the aggregate heating, mould in oven, transferring mixture in mould and hammering processes.

Standard S1 (Aggregates + 4% bitumen): For S1, according to marshal testing standard, total 1200gm. of coarse aggregates and fine aggregates were weighted according to Table 1 and aggregates were heated in a heater to temperature180℃.Compaction mould assembly for making standardized sample were first heated in an oven and the bitumen was carefully brought to a consistent temperature of 150℃. In the

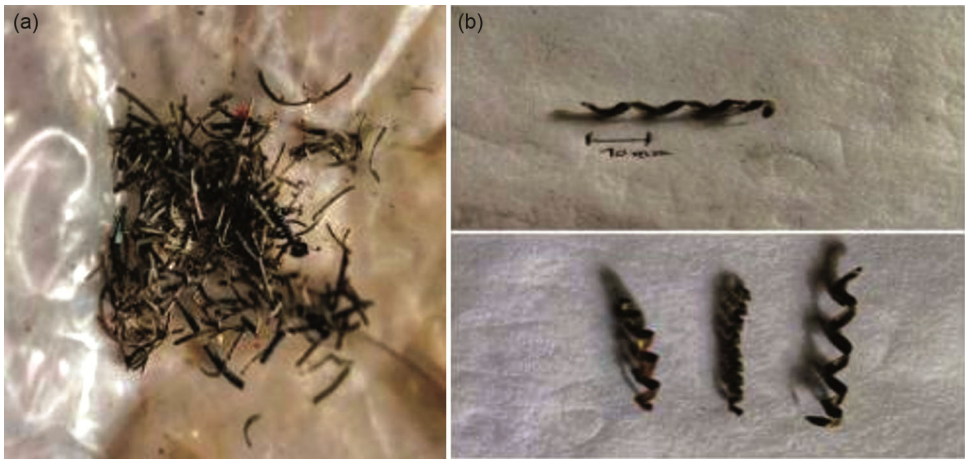

Fig. 1 — Mild Steel chips (a) straight and (b) spiral shape.

Fig. 2 — Sample preparation process (a) aggregate heating, (b) mould inside the oven, (c) transferring mixture into the mould and (d) hammering.

Table 1 — Percentages of aggregates to prepare a 1200gm of sample.

Grade (sieve size)	Percentage	Weight (gm)
25	0%	0
19	10%	120
9.5	20%	240
4.75	14%	168
2.36	14%	168
0.60	17%	204
0.30	7%	84
0.15	7%	84
0.075	7%	84
Filler	4%	48
Total		1200

next step 4% of molten bitumen was meticulously blended with the preheated aggregate particles. This strategic use of hot aggregates ensured that they did not draw heat away from the bitumen and consequently maintaining a consistent viscosity throughout the mixing process. The mold assembly, including a base mold and a collar, was removed from the oven, and a layer of lubricant was applied to minimize adhesion, allowing for easy sample extraction. The aggregate mixture was carefully transferred to the preheated base mould, and the extension collar was securely fixed at the top the base mould to allow a smooth and clean application of compressive load. To further enhance the process, a filter paper was thoughtfully positioned both at the top and bottom of the sample within the mould assembly. The mold assembly was positioned in the marshall compaction pedestal, where a 4.5 kg hammer applied compressive load by freely falling from a height of 45.7cm, delivering 50 blows to each face of the sample. Then the mould assembly was inverted and the process repeated for the opposite side. Each face of the sample experienced 50 blows individually. Then base mould was removed from the extension collar and rested it for minimum 30 minutes. After 30 minutes sample was removed from mould by using extraction plate and press. At last samples were left for curing for approximately 3-7 days at normal room temperature[31].

S2 (Aggregates Mixture + 4% Bitumen + 0.3% Straight Mild Steel Chips): S2 follows the same preparation method as S1. The main difference was that when the aggregate mixture is heated, 0.30% straight mild steel chips were also added with the mixture. The length of these chips ranges from 2 to 5mm. Larger or shorter length than this range of chips can affect porosity due to clustering[24].

Fig. 3 — Etched coarse aggregates

S3 (Aggregates Mixture + 4% Bitumen + 0.3% Spiral Mild Steel Chips): S3 and S2 were the basically same sample except in the fact that in S3 spiral or twisted mild steel chips were used instead of straight chips. And rest of the sample preparation method was as same as S1.

S4 (Aggregates Mixture + 4% Bitumen + 3.25% Epoxy + 0.3% Straight Mild Steel Chips): S4 can be termed as extended version of S2. The aggregate mixture with 0.30% straight mild steel chips heated altogether then bitumen was heated to a stable temperature and 4% of total weight was measured and mixed properly with 3.25% epoxy content. And rest of the procedure was same like S1.

S5 (Etched Coarse Aggregates + Fine Aggregates + 4% Bitumen + 3.25% Epoxy + 0.3% Spiral Mild Steel Chips): For S5 the 1st step was to etch the coarse aggregates with 15% HCl Solution. Treated coarse aggregates as shown in Fig. 3 are supposed to provide adhesion than untreated the coarse aggregates. The aggregate mixture and 0.30% straight mild steel chips were mixed and heated altogether then bitumen was heated to a stable temperature and 4% of total weight was measured and mixed properly with 3.25% epoxy content.

S6 (Aggregates Mixture + 4% Bitumen+ 3.25% Epoxy +0.3% straight Mild Steel Chips): S6 was as similar as S4. It was prepared just to recheck the stability and flow value of S4. The aggregate mixture mixed with 0.30% straight mild steel chips and heated altogether. Then 4% hot bitumen of total weight was measured and mixed properly with 3.25% epoxy content. Then epoxy bitumen mixture was mixed properly with aggregates and mild steel chips.

Fig. 4 — Total prepared 9 samples.

S7 (Aggregates Mixture + 4% Bitumen+ 3% Epoxy + 0.3% Straight mild steel chips): S7 was similar to S4 and 6 except the epoxy percentage. S4 and S6 were done with 3.25% epoxy content where in S7 epoxy percentage was 3 %.The aggregate mixture of total 1200gm. with 0.30% straight mild steel chips heated altogether then bitumen was heated to a stable temperature and 4% of total weight was measured and mixed properly with 3% epoxy content. Then epoxy and warm bitumen mixture was mixed properly with aggregates and mild steel reinforcement.

S8 (Aggregates Mixture + 4% Bitumen + 3.50% Epoxy + 0.3% straight Mild Steel Chips):S8 resembles S4, 6 and 7 but with different epoxy content. S8 contain 3.50% epoxy but rest of the composition and procedure were same as S6 and 7.

S9 (Aggregates Mixture + 4% Bitumen + 4% Epoxy + 0.3% straight Mild Steel Chips):S9 follows the same procedure as S7 and 8 but with 4% epoxy content. Figure 4 shows the 9 prepared sample for the investigation. A graphical representation of sample preparation process in details shown by Fig. 5.

2.3 Characterizations

Bulk specific gravity, Marshall stability and flow test, water absorption and contact angle were measured to investigate the improvement in performance.

2.3.1 Bulk specific gravity measurement

Specific Gravity or relative density is mainly the comparison of dry weight of a material with respect to weight in water. The common method for determining bulk specific gravity is finding ration of sample weight in air and in water. Water displacement method was used to determine bulk specific gravity by using Archimedes law through Eq. (2)[29]. For that at first, dry weight of samples were measured then sample weight in water bath was measured and recorded. At last, the sample was removed from water, surface dried and final weight (C) was

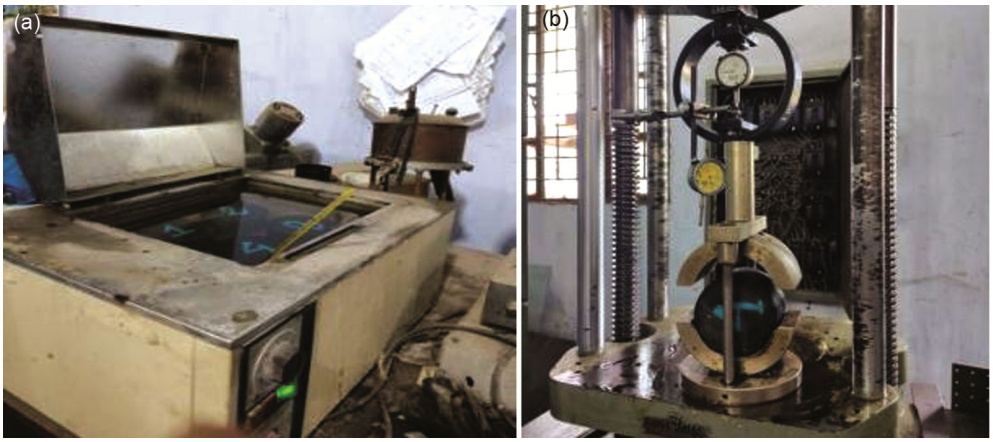

Fig. 5 — Instrument (a) water bath and (b) Marshall testing machine used in the present experiment.

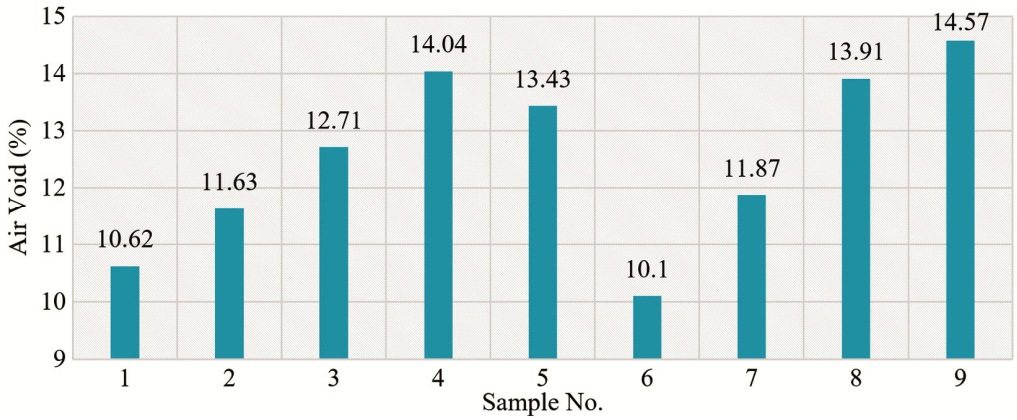

Fig. 6 — Variation of air %Va

measured which can be termed as Saturated Surface Dry weight when internal pore is filled with water and surface is dry.

$$G_B = \frac{W_D}{W_{SSD} - W_B} \quad ...(2)$$

Where G_B is the bulk specific gravity, W_D is dry weight of the sample, W_{SSD} is the saturated surface dry weight of the sample and W_B is the weight of sample in water bath.

2.3.2 Marshall stability and flow test

Marshall stability and flow testing require preparation of sample with standard dimension. Steps involving Marshall testing are, Initially, the water bath was filled with pristine water and elevated to a temperature of 60°C[28]. Subsequently, the specimens were submerged in the heated water bath for a duration of 30 minutes at the same temperature prior to undergoing the Marshall test. Upon extraction from the water bath, the specimen was carefully positioned on the lower section of the breaking head. The upper section of the breaking head was then aligned and the entire apparatus was affixed onto the testing machine. The loading head was meticulously brought into close contact with the upper breaking head. Following this, the flow meter was affixed and calibrated to zero. Subsequently, a compressive load was applied to the assembly, and readings from both the load meter and flow meter were recorded. The load value serves as an indicator of the specimen's capacity to withstand traffic induced loads without distortion, while the flow value provides insights into the extent of deformation during loading up to the point of maximum load. The instrument setup for the marshall test used in the work is shown in Fig. 5.

2.3.3 Water absorption test

Water absorption capacity determines how porous the material is. To determine the water absorption percentage at first dry mas of these samples in air were measured and recorded then a bucket was filled with water and the sample was submerged into the

water. The sample weight in water was measured and recorded. At last, the sample was removed from water after 24 hours and then the peripheral surface was dried and final weight was measured. Water absorption capacity was calculated by using Eq. (3).

$$A_W = \frac{W_{SSD} - W_D}{W_D} \times 100\% \quad ...(3)$$

Where A_W is the water absorption capacity, $W_D$is dry weight of the sample, and $W_{SSD}$is the saturated surface dry weight of the sample.

2.3.4 Contact angle measurement

For measuring the contact angle between the surface of the sample and water droplet at 1st the surface of the samples were cleaned. The sample was then placed on a flat surface and by using a dropper water droplet were placed carefully on the surface of the sample. Then a few images were captured by placing the camera lens parallel to the surface of sample. Finally, the contact angle was measured by analyzing the image. This method may not be able to give a specific value of angle but an approximate value can be obtained.

3 Results and Discussion

3.1 Bulk specific gravity of raw materials

Calculating the ratio of weight in air and in water yields Specific Gravity of each type of aggregates (coarse, fine, filler) and bitumen. The specific gravity values of materials used in bituminous mix are shown in Table 2. Bulk specific gravities of compacted samples (S1-S)) were shown in Table 3.

Figure 6 shows that S6 with 3.25% epoxy has the lowest air void of 10.1% and S9 with 4% epoxy has highest air void of 14.57%. this figure shows that %Va increases with increase and decrease in epoxy content from 3.25%. Figure 7 shows that the minimum value of %VMA is 15.72 and maximum is 24.52. %VMA increases due to addition of MS chips reinforcement and spiral MS chips introduce more void in mineral aggregate than that of straight one.

Table 2 — Bulk specific gravity of materials used in bituminous mix.

Material	Crushed Stone(CA)	Coarse Stone (FA)	Fine Stone(MF)	Binder Bitumen
Specific gravity G)	G_1 =2.790	G_2=2.461	G_3=2.630	G_b=1.02

Table 3 — Bulk specific gravity of compacted samples.

Sample Number	Description	Mass in Air (gm.) (W_D)	Submerged Mass (gm.) (W_B)	SSD weight (gm.) (W_{SSD})	Bulk Specific Gravity (G_B)
1	Aggregates mixture + 4% bitumen	1220	696	1222	2.3193
2	Aggregates mixture + 4% bitumen + 0.3% straight mild steel chip	1247	710	1248.5	2.3156
3	Aggregates mixture + 4% bitumen + 0.3% spiral mild steel chips	1250	705	1251.5	2.2872
4	Aggregates mixture + 4% bitumen + 3.25% epoxy + 0.3% straight mild steel chips	1254	679	1254.5	2.1789
5	Etched coarse Aggregates + fine Aggregates + 4% bitumen + 3.25% epoxy + 0.3% straight mild steel chips	1274	694	1274.3	2.1946
6	Aggregates mixture + 4% bitumen + 3.25% epoxy + 0.3% straight mild steel chips	1283	720	1283	2.2788
7	Aggregates mixture + 4% bitumen + 3% epoxy + 0.3% straight mild steel chips	1265	700	1265	2.2389
8	Aggregates mixture + 4% bitumen + 3.50% epoxy + 0.3% straight mild steel chips	1245	674.5	1245	2.1822
9	Aggregates mixture + 4% bitumen + 4% epoxy + 0.3% straight mild steel chips	1243	669	1243	2.1655

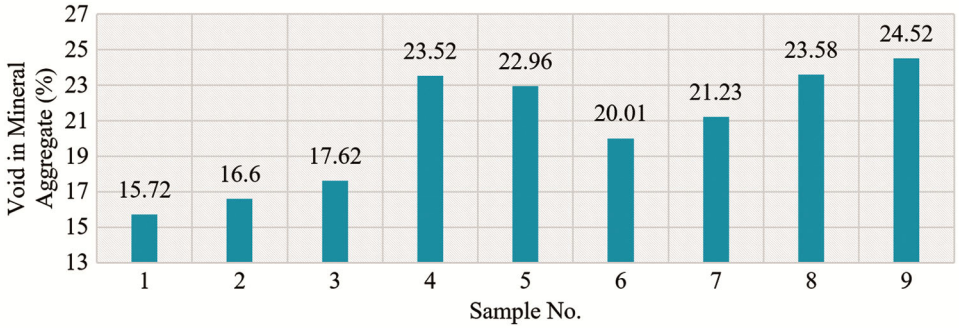

Fig. 7 — Variation of %VMA.

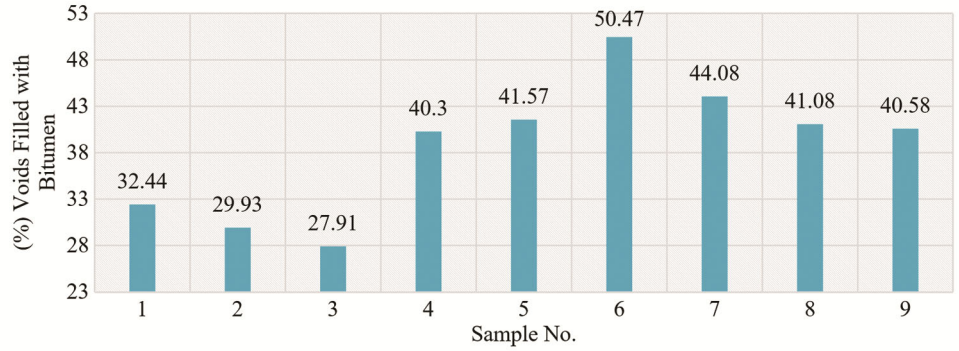

Fig. 8 — Variation of void filled with bitumen.

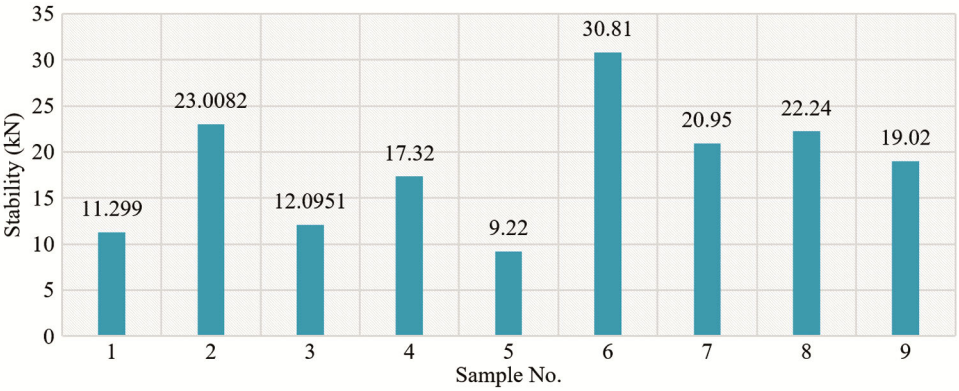

Fig. 9 — Variation in Marshall stability value in samples.

%VMA also increases with increasing epoxy content from 3.25% and below 3.25% of epoxy %VMA also increases. Figure 8 shows that S6 fills the maximum void of 50.47% with bitumen where S3 with spiral MS chips fills the minimum value of void 27.91% with bitumen. %VFB decreases with increasing epoxy content from 3.25% at epoxy content 3.25%VFB is maximum.

3.2 Stability and flow value from Marshall test

Stability refers to the maximum load that an asphalt specimen can withstand before it deforms or fails. Flow, on the other hand, is the total vertical deformation that occurs at the maximum load. Stability and flow Correlation Ratio is calculated as the ratio of stability to flow. This ratio provides valuable information about the performance characteristics of the asphalt mixture. A higher stability and flow correlation ratio indicates that the mixture can withstand a greater load before deformation, suggesting better resistance to structural failure under traffic loads. Figure 9 and 10 shows the result of Marshall test in term of Stability and flow value. Marshall stability of mix determine the ability

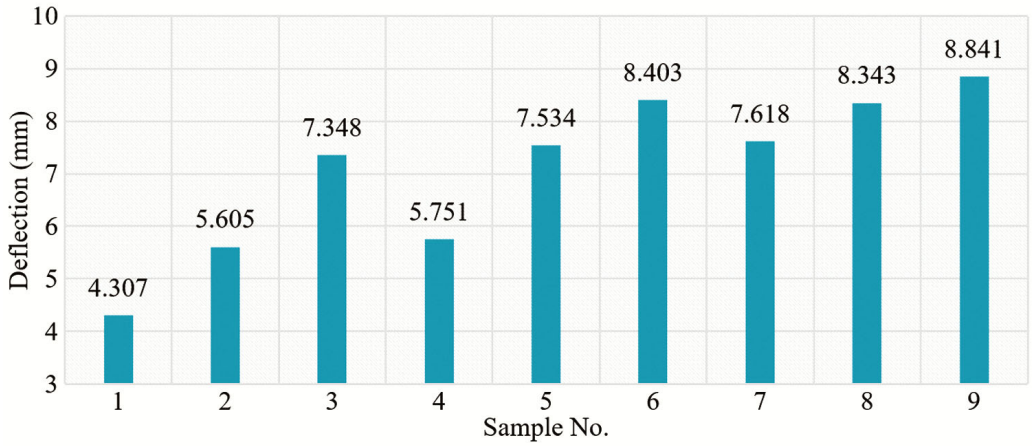

Fig. 10 — Variation in Marshall flow value.

of mix to withstand the traffic load without distortion and flow value indicate the deformation or distortion that the specimen undergoes during loading up to maximum load[30]. Figures 9 and 10 shows stability values ranges from 9 to 31 kN and deflection value varies from 4mm to 8.5mm. The objective of the work was to increase the stability value so that maximum traffic load can withstand by pavement without deforming. The composition of coarse aggregates, fine aggregates and bitumen that are used in real life road construction are our base road construction are our base composition for sample one or standard sample. Figure 9 indicate S1 has a stability value of 11.29 kN which means a standard sample can withstand load 11.29 kN without any deformation. Load larger than 11.29 kN will damage the sample. S6 gives the maximum value for load which is 30.81 kN and the S5 gives the minimum value for load which is 9.22 kN. S5 has a load value less than that of standard and this can lead to poor performance properties. S6 with highest load bearing capacity is the one that can justify the objectives.

S2 and S3 has the same ingredients except the shape and length of the reinforcement material. Spiral shape mild steel chips gives the lower value of load (12.09kN) compare to straight mils steel chips which shows the value of 23.008 kN. As straight mild steel chips significantly outperform spiral-shaped ones in load stability, further samples were prepared with straight MS steel reinforcement.

Then S4, S5 and S6 contain same mixture of aggregates or stone, sand, filler bitumen and extra epoxy was added to enhance water absorption properties and MS to enhance load bearing capacity. But the main difference between S4, S6 and S5 is S5 was made with etched coarse aggregates. Marshall stability value for S4, S5 and S6 is respectively 17.32, 9.22, 30.31 kN. Well, there difference between the value of S4 and S6 because of the malformation of marshall testing machine during the test of S4, so S6 was prepared to find out the appropriate stability value. We can see that etched sample didn't give favorable result it can be reason that etching exposed the micro irregularities with lower wettability that affect the bonding between aggregates and bitumen. In S7, S8 and S9 epoxy percentage were varied from 3% to 4% to find out the optimum epoxy content. Although the research paper[13] shows that the optimum epoxy content is 3.25% but these samples were prepared to find out if mild steel chips reinforcement has any effect on epoxy content. The tested Marshal stability value for S6 with 3.25% epoxy was 30.81 kN, S7 with 3% epoxy was 20.95 kN, and for S8 with 3.50% epoxy was 22.24 kN, and S9 with 4% epoxy was 19.02 kN. These data indicate that 3.25% is the optimum epoxy content. From Fig. 9 it was observed that S6 possesses the highest stability value where S5 has lowest. Flow values of samples varies from 4mm to 9mm. Minimization of flow value is important for improving performance as well as optimization of stability. A sample with minimum flow value and also with minimum stability value is not a favorable option for improving combination of performance. S1 with flow value 4.307 mm and stability value 11.29 kN falls into this group. But when resistance to deformation is more important than load bearing capacity the composition of S1 is considered as most relevant. S2, S4 and S6 show higher stability values and also comparatively higher deformation. But the extent to which load increase is more than

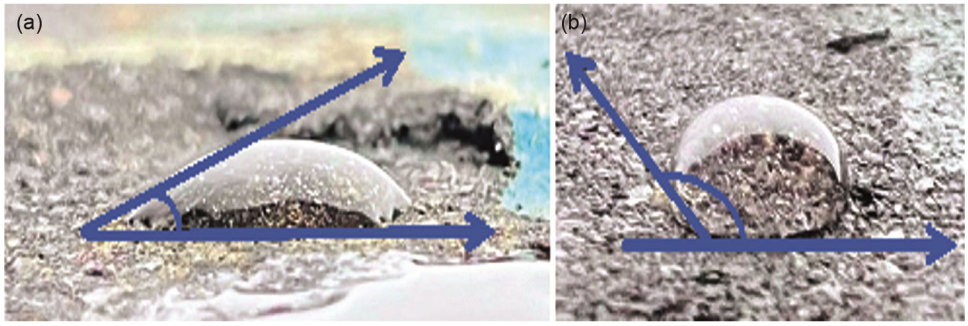

Fig. 11 — (a) Water droplet on S1 showing contact angle (<90°) and (b) Water droplet on S6 showing contact angle (>90°)

Table 4 — Calculation for moisture absorption.

Sample No.	Dry weight (W_1) gm.	Weight in water (W_2) gm.	Wet weight (W_3) gm.	Water retained ($W_3 - W_1$) gm.	Percentage water retained (W_3-W_1)/W_1) ×100%
1	1220	696	1222	2	0.1640%
2	1254	679	1254.5	0.5	0.0398%
3	1247	710	1248.5	1.5	0.1203%
4	1250	705	1251.5	1.5	0.12%
5	1274	694	1274.3	0.3	0.0235%
6	1283	720	1283	0	0%
7	1265	700	1265	0	0%
8	1245	674.5	1245	0	0%
9	1243	669	1243	0	0%

deformation value, so these can improve the overall performance of asphalt composite. When loading capacity is more important than resistance of deformation the compositions S2, S4 and S6 are considered as most appropriate value.

3.3 Water absorption

The incorporation of epoxy resin significantly increased the resistance to water absorption. Most of the samples which has epoxy bitumen mixture as matrix showed little to no water absorption. Table 4 shows that S1 without any epoxy content retained 0.164% of water where S4 and S5 retained water 0.12% and 0.235% respectively which is comparatively lower than the sample without epoxy content. On the other hand, S6, S7, S8, sample showed no water absorption.

3.4 Contact angle measurement

Epoxy due to hydrophobic nature of epoxy it also altered the contact angle of epoxy asphalt composite. Figure 11 shows the contact angle of a water droplet on S1 (without epoxy left side). Water droplet produced an angle of 26°. Contact angle on a surface lower than 90° is considered as hydrophilic surface providing good wettability. In Fig. 11 for S6 (right side) with epoxy, a contact angle of 147° was observed between the water droplet and surface of sample. A contact angle greater than 90° shows hydrophobic properties of surface and less wettability due to low surface energy. It should be also noted that increase in curing time increases water wetting angle[32]. Surface with high contact angle and low surface energy was produced due to use of epoxy resin in S4, S5, S6, sample7, S8 and S9. Materials with high surface energy have a greater tendency to interact with other substances. As the surface energy is lowered the composite become resistant to contaminants present in the surrounding environment.

4 Conclusion

The main purpose of this research was to enhance the performance and properties of epoxy asphalt composite. After investigating several samples with different compositions and parameters we were able to successfully establish a best composition for epoxy asphalt composite. In conclusion, this study highlights the promising potential of using mild steel reinforcement and epoxy content to significantly boost the strength and durability of asphalt composites. Among the tested samples, S6 stood out with its impressive Marshal stability of 30.81 kN, excellent hydrophobic properties with a contact angle of 147°, and zero water absorption. These results point to a breakthrough in creating more resilient, long-lasting materials that can withstand real-world

conditions more effectively than traditional asphalt. By reducing air voids and enhancing bitumen retention, this approach could pave the way for more durable roads, ultimately cutting down on maintenance costs and improving safety. Moving forward, continued exploration into the long-term behavior of these enhanced composites in diverse environmental conditions will be essential. This research marks an important step toward more sustainable and cost-effective road construction solutions, with the potential for far-reaching benefits in infrastructure and public safety. The further research regarding the effect on Marshal stability and water absorption by using modifier with epoxy bitumen mixture, study the effect of curing process of epoxy asphalt composite on Marshall stability at different temperature and weather would open a new era for asphalt composite. And also investigating the case whether the natural fiber like banana fiber/ jute/coir reinforced epoxy asphalt composite have the same or different effect on Marshall stability as MS chips reinforced epoxy asphalt composite, will further validate their applicability in large scale projects.

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