Interfacial bond strength and moisture induced damage characteristics of asphalt mastic-aggregate system composed of Nano hydrated lime filler

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Abstract

The present study was undertaken to investigate the impact of a unique combination of fillers on interfacial bond strength and moisture-induced damage potential of asphalt mastic. One asphalt binder (AC-30), three fillers including Basalt (B), Hydrated Lime (HL), and Nano-Hydrated lime (NHL) were selected to prepare asphalt mastics for a wide range of filler-binder (f/b) ratio (0.6 to 1.2). The dosages of HL and NHL were considered 0%, 5%, 10%, 15%, and 20% by weight of asphalt binder, and the dosage of B filler was adjusted to meet the respective f/b ratio. The interfacial bond strength and moisture-induced damage potential of asphalt mastic specimens were determined using the Bitumen Bond Strength (BBS) test. The BBS test parameters inferred that both B-HL and B-NHL filler combinations can enhance the bond strength and moisture damage resistance of asphalt mastic. Besides, asphalt mastic composed of B-NHL filler can be less susceptible to bond failure and moisture damage with improved adhesion and cohesion properties than B-HL filler. Additionally, asphalt mastic composed of a lower percentage (10%-15%) of NHL filler showed better bond strength and moisture damage resistance over mastic composed of a higher percentage (15%-20%) of HL filler. Asphalt mastic prepared with an f/b ratio less than 1.0 was found to be suitable to achieve better performance considering the moisture-induced damage properties. Grey relational analysis (GRA) method was used to analyze the correlation degree between filler properties and moisture damage properties of asphalt mastics. Based on the GRA results, Rigden voids and specific surface area are suggested to be the two most influential properties on the moisture-induced damage potential of asphalt mastic.

Keywords: Basalt; Hydrated lime; Nano hydrated lime; Asphalt mastic; Filler- binder ratio; Bond strength; Moisture-induced damage

1. Introduction

Moisture-induced damage of asphalt mix is one of the critical issues affecting the long-term performance of the pavement. A common manifestation of moisture-induced damage is a loss of adhesion at asphalt mastic-aggregate interface and/or loss of cohesion within the bulk asphalt mastic [1-3]. It has been reported that the cohesive strength of asphalt mastic is not only governed by the asphalt binder but also by the interaction between asphalt and mineral filler [4]. Also, type, nature, and quantity of mineral fillers play a critical role in the asphalt-filler interaction, affecting the interfacial bond strength and moisture damage potential of asphalt mastic. HL filler is well-known among different fillers as an anti-stripping and anti-aging agent, which can enhance the rheological and moisture damage resistance properties of asphalt mix [5-8]. Besides, the previous studies have stated the beneficial impact of a unique combination of inert-active filler in improving

the performance of the asphalt mastic [9-11] (inert: stone dust of parent aggregate, eg. Basalt (B)) and active: reactive with asphalt (eg. Hydrated Lime (HL)). The promising outcome of the studies on filler combination is limited to rutting, fatigue, and fracture performance of mastic. Besides, there is a lack of research on the moisture damage potential of asphalt mastic-aggregate systems that could explain the role of a combination of fillers. Therefore, the present work was motivated to investigate the effects of the filler combination (eg. the combination of (B) and HL filler) on interfacial bond strength and moisture-induced damage potential of asphalt mastic.

In addition to the filler combination, reducing the size of HL to Nano level (Nano Hydrated Lime, NHL) can have potential benefits in improving the performance of asphaltic materials due to its high surface area and higher interaction points [9,12,13]. At the same time, the NHL filler application is limited to the rheological performance of asphalt binder, mastic, and mixes. Moreover, NHL filler's impact on moisture-induced damage behavior of asphalt mastic-aggregate is not well-understood, which was motivated to establish an understanding of the influence of NHL filler in combination with an inert filler (eg. B with NHL) on the moisture damage potential of asphalt mastic. Additionally, Filler to Binder ratio (filler proportion, f/b) significantly affects

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the mastic and aggregate interfacial bond. Inappropriate selection of f/b ratio can lead to a tender mix and may result in moisture damage chances in the mix. For example, higher f/b can promote less free asphalt content, which may cause bonding failure in the mastic-aggregate interface. Thus, it is essential to pay attention to the filler quantity for asphalt mastics. However, previous studies are based on preliminary investigations that merely explain the impact of the f/b ratio on mastic-aggregate moisture damage potential. Hence, the present study takes a comprehensive approach to understand the effect of the f/b ratio on the moisture damage potential of asphalt mastic.

Therefore, the present study was motivated to address the impact of a unique combination of fillers on bond strength and moisture-induced damage potential of asphalt mastics. A control grade AC-30 binder with different combinations of fillers (B, B-HL, and B-NHL) was used to prepare thirty-six types of mastics for 0.6 to 1.2 f/b ratios. The moisture damage potential of asphalt mastic was studied using Bitumen Bond Strength (BBS) test. The BBS test is a reliable test to investigate moisture's effect at the asphalt mastic-aggregate interface [14]. Also, the present study evaluated the influence of the filler properties (Rigden voids, surface area, density) and quantity of HL and NHL on the bond strength and moisture damage parameters of asphalt mastic using Grey Relational Analysis (GRA). It is expected that the present study would help to assess the suitable application of a unique combination of filler based on the moisture damage potential of asphalt mastic-aggregate system.

2. Bitumen bond strength (BBS) test

BBS is a reliable test method that evaluates the moisture damage resistance of asphalt mastic at the aggregate-mastic interface. BBS test is conducted using a Pneumatic Adhesion Tensile Testing Instrument (PATTI) that determines the tensile force required to remove a specially designed stub attached to a solid substrate with asphalt binder (Fig. 1(a)). The change in tensile strength of asphalt mastic-aggregate system before and after moisture conditioning provides the moisture susceptibility properties of asphalt mastic. Besides, this test helps to identify the type of failure (adhesion/cohesion), which can be useful in selecting an appropriate filler type and filler proportion for better performance. The BBS device comprises a portable pneumatic adhesion tester, pressure hose, piston, reaction plate and a metal pull-out stub (Fig. 1(a)).

The BBS test's resulting parameters are Pull-off Tensile Strength (POTS) in dry and wet conditions and Bond Strength Ratio (BSR). The POTS can be calculated using Eq. (1).

$$POTS = \frac{(BP \times A_g) - C}{A_{ps}} \quad (1)$$

where, BP is Burst pressure in kPa, A_g is the contact area of Gasket with reaction plate in mm^2 (2.009 mm^2), C is Piston constant (0.25) and A_{ps} is the area of the pull-off stub in mm^2 (0.4869 mm^2). To

Table 1

Basic characterization of AC-30 binder.

Properties	Absolute Viscosity @ 60°C, Poise	Kinematic Viscosity @ 135°C, cSt	Penetration @ 25°C, 0.1 mm	Softening Point, °C	Ductility @ 25°C, mm	Superpave performance grade
Results	2618	467	46	48	>100	PG70-XX
Standard values (IS 73 2013)	2400 - 3600	≥250	≥45	≥47	-	-

Fig. 1. (a) BBS test set up, (b) sample preparation, (c) cohesive failure, and (d) adhesive failure.

access the moisture susceptibility of asphalt mastic, BSR was calculated using Eq. (2).

$$BSR (\%) = \frac{POTS_{wet}}{POTS_{dry}} \times 100 \quad (2)$$

where, $POTS_{dry}$ is POTS measured in a dry condition at ambient temperature and $POTS_{wet}$ is measured after conditioning in a water bath at 40°C for 24 hrs. Intuitively, the higher POTS and BSR value indicate better resistance to bond failure and moisture damage. A typical BBS test set up is shown in Fig. 1.

3. Materials

The present study used a viscosity grade (AC-30) asphalt binder and three types of mineral fillers: Basalt stone dust (B), Hydrated lime (HL), and Nano hydrated lime (NHL). The B and HL fillers were collected from local resources in Mumbai. NHL filler was produced from HL filler through the milling process using a planetary ball mill [9,13]. The milling of HL was done in two-step process: 6 hours milling at 250 rpm speed followed by 4 hours milling at 200 rpm speed. The 10 hours of milling process resulted in a size reduction in HL particle from 17 μm to 220 nm. The properties of AC-30 binder were found to be within the limiting values as per IS73 2013, indicating its suitability for paving (Table 1).

The B, HL, and NHL fillers were sieved, and only fractions passed through 75 μ were used for mastic preparation. The physical properties of the fillers were presented in Table 2. Fig. 2(a)-2(c) shows the particle size distribution curves of fillers. B and HL filler's particle size distribution was done in a light scattering method, and a dynamic light scattering method was used for NHL filler. The D_{90} of B, HL, and NHL filler was determined as 45 μm , 17 μm , and 220.6 nm, respectively. The reduction in HL particle size (17 μm to 220.6 nm) may help in better filler-filler and filler-binder interaction. FEG-SEM (Field emission gun scanning electron microscope) images indicate the filler's rugous surface texture, which may have a better bond between filler and binder (Fig. 2(d)-(f)).

Specific Surface Area (SSA) of fillers was determined using the Brunauer–Emmett–Teller method (BET, 1938). The SSA of B, HL, and NHL fillers are found to be 9.5 m²/g, 2.15 m²/g, and 43.17 m²/g, respectively. The reduction in particle size of HL resulted in a significant increase in SSA of NHL filler (43.17 m²/g), which may help in developing a strong filler-filler and filler-binder interaction. The SG results indicate that B fillers are denser than HL and NHL fillers. The Rigden Voids (RV) of fillers were calculated as per EN 1097-4. The RV of B, HL, and NHL fillers were 39.5%, 52%, and 43.7%, respectively. The reduction in particle size of HL resulted in a decrease in RV, which may help in reducing less binder absorption in mastic. The plasticity index of the fillers is within the standard values as specified in MoRTH 5th revision, 2013 (i.e., PI < 4).

3.1. Preparations of asphalt mastic specimens

The dosages of HL or NHL fillers were selected as 0%, 5%, 10%, 15%, and 20% by mass of AC-30 binder. The optimum dosages of 20% were preferred based on the equivalent percentage of HL added in asphalt mix preparation (1% to 2% by weight of dry aggregates). The mastic sample preparation involved two stage

Table 2

Basic characterization of fillers.

Fillers	D ₉₀	SSA (m ² /g)	SG	RV	PI
B	45 µm	9.2	2.78	39.5%	Non-Plastic
HL	17 µm	2.15	2.19	52%	<4
NHL	220.6 nm	43.17	2.15	43.7%	<4

(D₉₀ = 90% of particle passed through respective size, SSA = specific surface area, SG = specific gravity, RV = Rigden voids, PI = Plasticity Index).

Fig. 2. (a–c) Particle distribution curve of fillers and (d–f) FEG-SEM images of fillers.

Table 3

Details of combinations of asphalt mastics (0.6 f/b).

Mastic type (*)	Composition of Mastic			f/b ratio = $\frac{\% (B+HL \text{ or } NHL)}{\% (AC-30)}$
	AC-30 (%)	B-filler (%)	HL or NHL-filler (%)	
M-60B-0	100	60	0	0.6
M-55B-5HL	100	55	5 (HL)	
M-50B-10HL	100	50	10 (HL)	
M-45B-15HL	100	45	15 (HL)	
M-40B-20HL	100	40	20 (HL)	
M-55B-5NHL	100	55	5 (NHL)	
M-50B-10NHL	100	50	10 (NHL)	
M-45B-15NHL	100	45	15 (NHL)	
M-40B-20NHL	100	40	20 (NHL)	

Note: M-XX-YY implies mastic type, M- stands for mastic, XX- stands for the B filler, and YY- stands for HL or NHL filler.

process. The first stage involved B-HL and B-NHL fillers' blending, while the second stage included mixing of B-HL blend and AC-30. In the first stage, the fillers were oven-dried at 110±5°C for 24 hours to remove the moisture. After that, the B and HL filler was blended using manual stirring method. In the second stage, the preheated B-HL filler and AC-30 binder were mixed by maintaining with a 2500 rpm speed at 150±5°C for 1 hour using a mechanical mixer. A similar process was followed for B-NHL combinations. A total of 36 types of asphalt mastic samples were produced, covering a wide range of f/b ratios (0.6–1.2) [15]. For each f/b ratio, nine combinations of asphalt mastic were produced (one base asphalt mastic (only B filler), four B-HL and four B-NHL combinations). Prior to testing, short-term aging of mastic samples was done using a Thin-film oven at 163°C for 5 hours (ASTM D1754 [16]) to simulate the field condition of asphalt mastic after mixing and compaction in the field. The detailed combinations of mastics for 0.6 f/b are presented in Table 3. A similar procedure was followed for asphalt mastic combinations in the cases of 0.8, 1.0, and 1.2 f/b ratios.

4. BBS test of asphalt mastic-aggregate system

In the present study, the BBS test was conducted on short-term aged asphalt mastic samples containing B, B-HL, and B-NHL for dry and wet conditions at ambient temperature (Fig. 1(a) and (b)) as per AASHTO T 361 [17]. Basalt stone was used as an aggregate base plate. The aggregate base plate preparation was done in three steps: cutting, polishing, and ultrasonic cleaning. The smooth polished surface of the aggregate plate was done for testing so that friction would not contribute to the bond strength of asphalt mastic. Five replicates of each combination of asphalt mastic were tested, and average values of resulted POTS and BSR were reported in this study.

5. Grey relational analysis

Grey Relational Analysis (GRA) is used to determine the optimum selection of the influential degree of factors in an uncertain system [18,19]. It has been reported that the application of GRA is very helpful to optimise the mix design parameters and to analyse the influential factors affecting the performance of asphalt mastic [18–22]. Thus, considering the beneficial outcome of the GRA method, the present study utilized GRA method to study the most influential filler properties on the bond strength and moisture damage potential of asphalt mastic. The GRA method is performed in three steps: pre-processing of data, calculation of grey relational coefficient, and determination of grey relational grade [20].

5.1. Step-I: Pre-processing of data

In this step, the original sequence is transferred to a comparable sequence. The data can be normalized in three different methods [23]. In this study, data sequences are normalized considering an approach: “the larger, the better”. The normalization is mentioned in Eq. (3). The original reference sequence and comparative sequence are denoted as $x_0(k)$ and $x_i(k)$, respectively ($i = 1, 2, \dots, m$; $k = 1, 2, \dots, n$).

$$x_i^*(k) = \frac{[x_i^0(k) - \min x_i^0(k)]}{[\max x_i^0(k) - \min x_i^0(k)]} \quad (3)$$

where, $x_i^0(k)$ is the original sequence, $x_i^*(k)$ is the sequence after data pre-processing, $\max x_i^0(k)$ is the largest value of $x_i^0(k)$, $\min x_i^0(k)$ is the smallest value of $x_i^0(k)$.

5.2. Step-II: Calculation of Grey relational coefficient

After the pre-processing of data, the grey relational coefficient can be determined using Eq. (4).

$$\gamma(x_0^*(k), x_i^*(k)) = \frac{[\Delta_{\min}^* + \zeta \Delta_{\max}^*]}{[\Delta_0^*(k) + \zeta \Delta_{\max}^*]}; 0 < \gamma(x_0^*(k), x_i^*(k)) \leq 1 \quad (4)$$

where, $\Delta_0^i(k)$ is the deviation sequence of reference sequence $x_0^*(k)$ and comparability sequence $x_i^*(k)$, $\Delta_0^i(k) = |x_0^*(k) - x_i^*(k)|$; $\Delta_{\max}^* = \max_{\forall k} \max_{\forall i} |x_0^* - x_i^*|$; $\Delta_{\min}^* = \min_{\forall k} \min_{\forall i} |x_0^* - x_i^*|$; ζ is distinguishing or identification coefficient $\zeta \in [0, 1]$, and $\zeta = 0.5$ is generally used [18].

5.3. Step-III: Determination of Grey relational grade

Grey relational grade is the average of the grey relational coefficients and is expressed in Eq. (5).

$$\gamma(x_0^*, x_i^*) = \frac{1}{n} \sum_{k=1}^n \gamma[x_0^*(k), x_i^*(k)] \quad (5)$$

Grey relational grade indicates the correlation level between the reference and comparative sequences. For a specific case, if a comparative sequence is essential to the reference sequence than other comparative sequences, then the grey relational grade for that important comparative sequence is larger than others with the reference sequence [24]. The present study considered SSA, RV, density, and HL or NHL percentage to determine the most influential factor on the bond strength and moisture damage potential of mastic.

6. Results and discussions

6.1. Interfacial Bond Strength of Asphalt Mastic

6.1.1. Influence of B-HL and B-NHL on bond strength in dry condition

Fig. 3(a) and 3(b) shows variations in Pull-Off Tensile Strength (POTS) for asphalt mastic containing B, B-HL, and B-NHL fillers in dry condition. POTS value of asphalt mastic increased with an increase in HL and NHL dosages irrespective of the f/b ratio. For example, the POTS value of asphalt mastic prepared with 0.6 f/b containing 5%HL and 20% HL was 2.45 MPa and 2.278 MPa, respectively. Similarly, the POTS value of asphalt mastic composed of 5%NHL and 20% NHL was observed to be 2.48 MPa

Fig. 3. POTS of asphalt mastics (a) HL mastics, (b) NHL mastics, (c) HL mastics, and (d) NHL mastics.

and 2.97 MPa, respectively. Asphalt mastic composed of B-NHL showed higher POTS than B-HL, inferring better bond strength. Besides, the rate of increase in POTS was higher for asphalt mastic with B-NHL (slope: 0.0318) than B-HL (slope: 0.026). Such an increasing response in POTS value signifies that NHL's contribution is predominant over HL in enhancing the bond strength between asphalt mastic and aggregate. It is believed that the addition of HL to mastic helps in accumulating calcium ions at the aggregate surface, making a bond with acids from asphalt. Consequently, water-insoluble salts are formed, which improves the mastic-aggregate adhesion [8,25]. Similarly, in the present study, the addition of HL and NHL showed an increase in POTS, which indicates improvement in mastic-aggregate adhesion. It is also important to note that NHL's high SSA and potential interaction properties might enhance the bond strength of asphalt mastic to a superior level.

6.1.2. Influence of B-HL and B-NHL on bond strength in wet condition

Fig. 3(c) and 3(d) shows the POTS value of asphalt mastic composed of B, B-HL, and B-NHL filler combinations, tested after 24 hr of moisture conditioning. It can be noticed that POTS values of conditioned asphalt mastic decreased than unconditioned mastic irrespective of HL or NHL dosages, which may be because of the impact of moisture intrusion at the mastic-aggregate interface. However, the POTS values of asphalt mastic increased with an increase in HL and NHL dosage, irrespective of the f/b ratio. For instance, the POTS value of asphalt mastic prepared with 0.6 f/b was found to be 2.04 MPa for 5%HL, which increased to 2.37 MPa for mastic with the addition of 20%HL. Similarly, with 5% to 20% increase in NHL dosage, the POTS value of mastic prepared with 0.6 f/b increased from 2.09 MPa to 2.59 MPa. The rate of increase in POTS value of conditioned asphalt mastic composed of NHL was observed to be higher (slope: 0.029) than HL (slope: 0.021). Thus, POTS of conditioned mastic samples implied NHL's effectiveness over HL in improving the interfacial bond strength and moisture-induced damage resistance. It is reported that HL participates in cation exchange, flocculation, and pozzolanic reactions. Such reactions change the filler characteristics and make the filler to behave as agglomerates and retained together by a

pozzolanic cement. Hence, this process helps to become less susceptible to moisture by increasing the hydrophobic nature [5]. In a similar way, the mastic composed of B-HL and B-NHL combination showed improvement in bond strength (increase in $POTS_{wet}$) than control asphalt mastic (only B filler). Besides, high surface area and more interaction points of NHL might improve the hydrophobic behavior of mastic, which considerably enhanced the resistance to interfacial bond failure due to intrusion of water.

6.1.3. Influence of f/b ratio on bond strength in dry and wet condition

Fig. 4(a) and 4(b) show variations in POTS of asphalt mastics over different f/b ratios for dry and wet conditions. The POTS value increased with an increase in f/b ratio from 0.6 to 1.0, irrespective of HL and NHL dosages. However, an increase in f/b ratio from 1.0 to 1.2 showed a decreasing POTS trend irrespective of HL and NHL dosages. For instance, POTS values of control asphalt mastic (only B filler in dry condition) with 0.6, 0.8, 1.0, and 1.2 f/b ratios were 2.29 MPa, 2.38 MPa, 2.44 MPa, and 2.40 MPa, respectively. The increasing trend in POTS from 0.6 to 1.0 f/b ratio may be due to an increase in stiffness property with an increase in the filler concentration, which might help in developing a better bond between mastic and aggregate. Whereas, the decrease in POTS from 1.0 to 1.2 might be due to the reduction of free asphalt content in mastic (amount of filler concerning binder is high). Thus, a decrease in free asphalt content firmly decreased the bond strength of mastic. A similar response in POTS for conditioned mastic samples was also observed (Fig. 4(b)).

Moreover, the effects of the reduction in particle size of HL were addressed using a comparative analysis between a lower percentage of NHL filler and a higher percentage of HL filler. Interestingly, compared to 15% HL filler, the addition of 10% NHL filler possessed better POTS value (increased by 10% to 25%) for asphalt mastic prepared with 0.6, 0.8, and 1.0 f/b ratios, irrespective of conditioning of samples. Consequently, a comparable trend in POTS values is also evident for 15% NHL with 20% HL for asphalt mastics prepared with 0.6, 0.8 and 1.0 f/b ratios. Such a response implied that a lower percentage of NHL filler can have a predominant effect over a higher HL filler percentage in improving resistance to bond failure and moisture damage of asphalt mastic. However, for asphalt mastic prepared with a 1.2 f/b ratio, a lower percentage of NHL filler did not result in high POTS value than a higher HL filler percentage. As the NHL dosages (5% to 20% by weight of asphalt) are same for all f/b ratio, the concentration of NHL in B filler reduced significantly for 1.2 f/b ratio (Ex; for f/b = 0.6; B = 55%, NHL = 5%; for f/b = 1.2; B = 105%, NHL = 5%). Thus, with fewer interaction points and less free asphalt content, a low percentage of NHL filler did not substantially influence than a higher percentage of HL filler.

Fig. 4. POTS of asphalt mastics over f/b ratios (a) dry condition and (b) wet condition.

6.2. Moisture damage potential of asphalt mastic

6.2.1. Influence of B-HL and B-NHL on bond strength ratio (BSR)

Fig. 5(a)-5(d) shows the BSR of asphalt mastics obtained after moisture conditioning. It can be seen that BSR increased with an increase in HL or NHL dosage from 0% to 20%, irrespective of f/b ratios. For example, the BSR of asphalt mastic prepared with 0.8 f/b was found to be 86%, 87%, 88%, 90% and 91% with the addition of 0%, 5%, 10%, 15% and 20% HL, respectively. Also, BSR of asphalt mastic with 0%, 5%, 10%, 15% and 20% NHL were 86%, 88%, 90%, 92% and 93%, respectively. Though the change in BSR between individual f/b ratios is marginal, POTS' difference was found to be noticeable. In this case, the BSR for NHL was higher than HL (Fig. 5(b)). These results showed that cation exchange, high surface area, and interaction points of NHL might significantly impact the hydrophobic properties of mastic, which firmly enhanced the moisture damage resistance.

Moreover, with an increase in f/b ratio from 0.6 to 1.0, the BSR increased; however, with a further increase in f/b ratio from 1.0 to 1.2, the BSR decreased. Control asphalt mastic (only B filler) resulted in an increase in BSR from 83% to 87% with an increase in f/b ratio from 0.6 to 1.0. Such improvement in BSR indicates that HL filler acts as an antistripping agent, which helps in clogging the intrusion of moisture at the aggregate-asphalt mastic interface. Also, high surface area and low Rigden voids of NHL filler might result in higher interaction points in asphalt, which might help in more accumulation of calcium ions at the aggregate surface and better bond with acids of asphalt. Thus, such a process firmly makes the mastic less susceptible to moisture damage (less intrusion at the mastic-aggregate interface). However, the BSR decreased from 87% to 85% with an increase in f/b ratio from 1.0 to 1.2. Such behavior may be because of the decrease in NHL concentration in B filler for 1.2 f/b ratio, which is due to the increase in B filler concentration to a significant amount with same HL or NHL dosages (Ex; f/b = 0.6; NHL = 5%, B = 55%; for f/b = 1.2, NHL = 5%, B = 115%). Thus, it can be concluded that the addition of HL and NHL fillers can have significant contributions to enhance the bond strength and moisture damage resistance of asphalt mastic prepared with an f/b ratio lower than 1.0.

Fig. 5. BSR of asphalt mastic in dry and wet condition (a) f/b = 0.6 (b) f/b = 0.8 (c) f/b = 1.0 (d) f/b = 1.2.

6.2.2. Influence of B-HL and B-NHL on mode of failure

The mode of failure surface can only be identified by visual inspection of the aggregate surface (Fig. 6). Identification of the mode of failure (cohesive/adhesive) helps in the selection of appropriate filler type and proportion. Fig. 6 shows the photos of the mode of failure for asphalt mastic samples prepared with different B, B-HL, and B-NHL filler combinations for all f/b ratio (0.6 to 1.2). It was observed that the aggregate failure surfaces are of cohesive failure type irrespective of HL and NHL dosages and filler proportion (0.6 to 1.2 f/b, Fig. 6). Such a failure surface indicates that addition of HL and NHL filler can enhance the adhesion property of asphalt mastic. Also, asphalt mastic composed of B-HL and B-NHL filler can reduce the chances of early moisture diffusion and migration at the asphalt mastic-aggregate interface, making the mastic less susceptible to moisture-induced damage.

6.3. Grey relational analysis

POTS_{dry}, POTS_{wet}, and BSR of asphalt mastic were considered reference sequences in this study. RV, SSA, density, and HL and NHL percentage were the corresponding comparative sequences listed in Table 4. The GRA method was applied to analyze the influential degree of the four factors on the bond strength and moisture damage parameter of asphalt mastic prepared for all f/b ratio (0.6-1.2) and all filler combinations of B, B-HL, and B-NHL. Since GRA procedures on POTS_{dry}, POTS_{wet}, and BSR are similar, herein only the worked-out data processing and analysis of GRA on POTS_{dry} for 0.6 f/b and B B-HL, B-NHL combinations are described. As a part of step-I, Table 5 shows the pre-processing of data of the POTS_{dry} parameter for all filler combinations prepared with 0.6 f/b. The grey relational grades with ranking of coefficients are shown in Table 6 (Step-II and III, section Grey Relational Analysis).

Fig. 6. Mode of failure of asphalt mastic.

Table 4
The original sequences of GRA (for 0.6 f/b).

Filler combinations		B	B-5HL	B-10HL	B-15HL	B-20HL	B-5NHL	B-10NHL	B-15NHL	B-20NHL
Reference sequences	POTS _{dry} , MPa	2.29	2.45	2.56	2.67	2.80	2.48	2.64	2.82	2.97
	POTS _{wet} , MPa	1.91	2.04	2.15	2.27	2.37	2.09	2.24	2.42	2.59
	BSR, %	83.0	83.0	84.0	85.0	85.0	84	85.5	86	87
Comparative sequences	RV, %	39.5	41.3	43.33	45.17	46.60	41.3	43.33	45.17	46.60
	SSA, m ² /g	9.2	7.6	6.5	5.7	5.1	7.6	6.5	5.7	5.1
	Density	2.78	2.68	2.68	2.64	2.6	2.68	2.68	2.64	2.6
	HL or NHL, %	0	5	10	15	20	5	10	15	20

Table 5
Data pre-processing for GRA of POTS_{dry} (0.6 f/b).

	B	B-5HL	B-10HL	B-15HL	B-20HL	B-5NHL	B-10NHL	B-15NHL	B-20NHL
x ₀ (k)	83	83	84	85	85	2.48	2.64	2.82	2.97
x ₁ (k)	39.5	41.3	43.33	45.17	46.60	41.3	43.33	45.17	46.60
x ₂ (k)	9.2	7.6	6.5	5.7	5.1	7.6	6.5	5.7	5.1
x ₃ (k)	2.78	2.68	2.68	2.64	2.6	2.68	2.68	2.64	2.6
x ₄ (k)	0	5	10	15	20.0	5	10	15	20.0

Note: x₀(k), x₁(k), x₂(k), x₃(k) and x₄(k) corresponding to POTS dry, RV, SSA, density, and % HL or NHL, respectively.

Table 6
GRA results of POTS_{dry} (0.6 f/b).

Grey relational coefficients	B	B-5HL	B-10HL	B-15HL	B-20HL	B-5NHL	B-10NHL	B-15NHL	B-20NHL	Grey relational grade	Rank -ing
$\gamma(x_0^*(k), x_1^*(k))$	1.000	0.889	0.998	0.901	1.000	0.937	0.950	0.958	1.000	0.959	1
$\gamma(x_0^*(k), x_2^*(k))$	0.833	0.829	0.915	0.855	0.333	0.931	0.873	0.949	1.000	0.835	2
$\gamma(x_0^*(k), x_3^*(k))$	0.333	0.595	0.738	0.489	0.333	0.607	0.743	0.442	0.333	0.513	4
$\gamma(x_0^*(k), x_4^*(k))$	0.333	0.583	0.624	0.787	1.000	0.760	0.878	0.674	0.833	0.719	3

Note: $\gamma(x_0^*(k), x_1^*(k))$, $\gamma(x_0^*(k), x_2^*(k))$, $\gamma(x_0^*(k), x_3^*(k))$ and $\gamma(x_0^*(k), x_4^*(k))$ corresponding grey relational coefficients to RV, SSA, density, and % HL or NHL, respectively.

Fig. 7. Grey relational grade for fillers properties.

As can be seen from Table 6 and Fig. 7, the influential priority of four factors on POTS_{dry}, POTS_{wet}, and BSR is $RV > SSA > HL \text{ or } NHL \% > \text{Density}$. RV was the most influential property of filler with the bond strength and moisture damage potential of asphalt mastic compared with SSA, HL%, and density of filler. Apart from RV, SSA found to have a higher grey relational grade than HL or NHL% and density (Table 6), indicating the second most relevant factor that governs the bond strength and moisture damage potential of mastic. The RV has effective contribution in the asphalt absorption that affects the free asphalt contents and the stiffness properties of mastic and mix. Filler with high RV can result in stiff asphalt mix which becomes less workable, while a filler having low RV would cause asphalt drain-down issue [26,27]. Similarly, fillers with high SSA have more interaction points and absorb more asphalt, which can enhance the stiffening effect. Absorption of asphalt in the mastic influences the amount of free asphalt, affecting the adhesive and cohesive strength between asphalt mastic and aggregate interface. For example, excessive absorption of asphalt enables less free asphalt in the mastic, resulting in mastic-aggregate bond failure (adhesive). Thus, RV and SSA were found to be the two most relevant factors governing the interfacial bond strength and moisture-induced damage potential of asphalt mastic.

7. Conclusions

The laboratory study evaluated the effects of a combination of B, B-HL, and B-NHL fillers on the interfacial bond strength and moisture-induced damage potential of asphalt mastic. The effectiveness of HL and NHL filler on the mastic was addressed using POTS_{dry}, POTS_{wet}, and BSR parameters resulted from the BBS test. The influential filler properties on the bond strength and moisture damage potential of mastic were analyzed using the GRA method. The critical outcomes of the study are as follows.

1. The results of BBS parameters imply that HL and NHL's addition can improve the bond strength and moisture damage resistance of asphalt mastic. Besides, the reduction of HL size from micron to the nanoscale (NHL) was found to intensify the adhesive property of asphalt; hence, it can be more effective in enhancing the moisture damage resistance to a significant degree.
2. The mastic-aggregate failure was cohesive even after wet conditioned for 24 hrs, irrespective of filler type and proportions. This finding indicates moisture damage to the aggregate-mastic system could be due to mastic cohesion rather than adhesive failure.
3. A lower percentage of NHL (10%-15%) filler can have better or equivalent bond strength and moisture damage resistance than a higher percentage of HL filler (15%-20%).
4. Based on the BBS test results, B-HL and B-NHL filler combinations can be more efficient in improving resistance to bond failure and moisture damage of asphalt mastic prepared with an f/b ratio less than 1.0.
5. Moreover, Grey relational analysis between fillers' properties and bond strength and moisture-induced damage potential of asphalt mastics indicates that Rigden voids and specific surface area are the two most relational factors than HL or NHL % and density parameters. Influential priority is: $RV > SSA > HL \% > \text{Density}$.

8. Limitations and recommendations

The present study is limited to comprehensive research on the moisture-induced damage potential of asphalt mastic considering one type of asphalt binder and three mineral fillers. It is recommended that future investigation be conducted on different types of mineral fillers and asphalt binders and validate the results with the performance of asphalt mix for a better understanding.

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Conflicts of interest

There is no conflicts of interest

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