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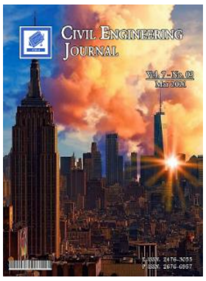
Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 7, No. 03, March, 2021



Influence of Aggregates on Stripping Behavior of Bituminous Mixes

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Received 27 November 2020; Revised 11 February 2021; Accepted 19 February 2021; Published 01 March 2021

Abstract

Moisture damage leads to premature failure of flexible pavements. The removal of bituminous coating from aggregates lead to the disintegration of bituminous mixes and is known as stripping. Various mechanisms and factors have been identified to play a role in the process, properties of aggregates being one of the major factors. This study is an attempt to analyze the influence of chemical, mineralogical and physical properties of aggregates on the stripping propensity of the loose mix. For this purpose, aggregates are chosen from six different quarry sites with diverse chemical compositions used for construction and maintenance of a large network of roads. Stripping tests are thereafter conducted on the aggregates using different percentage of hydrated lime. The amount of hydrated lime required for the prevention of stripping for concerned aggregate sources is determined. The research leads to the findings that the presence of elements such as silicon and potassium leads to a decrease in bond strength whereas the presence of calcium, sodium, iron, magnesium and aluminium enhanced the bond strength. Statistical tools and techniques are used to verify the results. Comparatively softer aggregates showed lesser resistance to stripping which could be inferred from aggregate impact and Los Angeles abrasion tests. The findings of the study can be helpful in the selection of aggregates with different chemical content for bituminous road construction depending upon the sensitivity to stripping.

Keywords: Flexible Pavements; Stripping; Physical Properties; Chemical Properties; Mineralogical Properties; Boil Water Test.

1. Introduction

Hot Mix Asphalt (HMA) is mostly used in top layers of flexible pavements where bitumen is used as principal binding material. These pavements suffer premature failures due to improper construction practices, heavy traffic loadings and environmental factors such as moisture damage and oxidation [1]. Moisture damage is one of the important detrimental cause which leads to premature failure of bituminous mixes where the bond between bitumen and aggregate is affected. These lead to various other distresses such as rutting, raveling, stripping, potholes and fatigue cracking [2].

Presence of moisture within the mix progressively hampers either the cohesive bonding within the binder or the adhesive bond between the aggregate and bitumen resulting in failure of bituminous mix and is termed as moisture damage [3]. Moisture damage often hampers the total integrity of the mix, and thus reduces pavement life by accelerating several other modes of distresses [2]. Moisture damage which involves removal of bituminous film over aggregates and segregation of aggregates leading to disintegration of the bituminous film is termed as stripping.

Few mentionable factors that are responsible for stripping are bituminous binder properties, aggregate chemical and physical properties, construction practices and drainage [1]. The role of improper constructional practice, as well as the

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http://dx.doi.org/10.28991/cej-2021-03091671

influence of drainage layer to drain off rainwater on stripping, has been extensively studied [4, 5]. It is necessary to consider the negative impact of rainfall while selecting constituent materials for bituminous mixes [6]. Bitumen aggregate chemistry has been identified as one of the contributing factors influencing stripping where the chemistry, as well as the mineralogical composition significantly determines the strength of the bitumen-aggregate bond. Mineral and chemical components present in the aggregates are responsible for the polarity, surface charge, surface energy and type of adsorption points thereby affecting the bond between aggregate and bitumen [1]. Aggregates having an affinity towards water are called hydrophilic aggregates which contain a high amount of silica and are generally acidic. On the other hand, aggregates having low silica content are found to repel water and are called hydrophobic aggregates [7]. Correlation between aggregate mineralogy and durability of pavements by conducting experiments on four different aggregate types and one binder was tried to be ascertained by researchers in Norway [8]. Quartz, albite and microcline were found to negatively affect the aggregate-bitumen bond. Peel tests were used to quantify the effect of water on asphalt in the UK [9]. Four different aggregate types were used which includes two granite, one limestone and one marble. It was observed that stripping was greater in case of granite aggregates due to the acidic nature of aggregate which resulted in greater loss of adhesion than the basic aggregates. Moreover, marble is chemically the same as limestone but it turned out to be more water-resistant due to lower porosity. The stripping effect on four types of aggregate using bitumen of two different grades was studied [10]. It was found that bitumen characteristics played a lesser role as compared to aggregate properties as far as stripping is concerned. Clay, anorthite and calcite were the primary minerals in these aggregates. Observations showed that clay and anorthite minerals promote stripping. On the other hand, mineral calcite was found to be resistant to stripping. Apart from mineralogical and chemical structures, other aggregate properties have been observed to influence stripping such as surface texture, aggregate angularity and many other factors influence the bond between bitumen and aggregate [1].

To counter the stripping due to these factors, anti-stripping materials such as lime, liquid anti-stripping (LAS) agents, lime kiln and cement kiln dust are used widely over the world [11]. Different kinds of LAS exist depending upon the active functional groups such as polyphosphoric, amino or silane whose usage depends upon the aggregate type [12]. Fly ash, cement kiln dust, and three types of hydrated lime with different fineness were used. With the application of these materials as filler, it was shown that stripping in HMA had reduced [11]. Different studies showed the effectiveness of hydrated lime to resist stripping [13, 14]. For that reason, it is one of the prefered anti-stripping agent [1]. Use of fly ash as anti stipping agent has been also highlighted [15]. Surface Free Energy (SFE) method and laboratory dynamic modulus test were used to find the stripping potential of Zycosoil as an anti-stripping additive [16]. This test was performed on the two mix one with limestone and other with granite aggregates. . In recent times, research has been carried out considering various nano-materials as anti-stripping agents [17]. In spite of the global increase in the use of anti-stripping agents and the use of various techniques to evaluate stripping, it is observed that stripping propensity remains a concern for bituminous roads.

Many tests have been developed to determine the stripping effects of HMA but the test which bears specific correlation for evaluating this deterioration in the field is yet to be found. There are two types of test methods to find moisture damage: qualitative and quantitative testing methods. In qualitative testing techniques, loose bituminous mixes are used. The percentage of coated aggregate is approximated manually by the visualization. Boil water test was used to determine the effect of fillers of different chemical composition on stripping propensity of aggregates of 5 different types of aggregates using boil water tests [18]. They found that calcium-based fillers performed much better as compared to silica-based glass powder fillers. A digital camera was used to minimize the error and to evaluate the coating percentage more accurately [19]. Examples of qualitative tests are boiling water test and static immersion test. Results revealed that calcium-based fillers improve adhesion whereas silica-based fillers did not. Test of adhesion using boil water test was termed as ‘Passive Adhesion’ [18]. On the other hand, quantitative tests use the change in the mechanical strength of compacted mixes due to the action of moisture to determine moisture sensitivity such as indirect tensile strength and stiffness modulus. In spite of the use of several tools and techniques for the assessment of stripping propensity, the use of conventional tests such as static immersion and boil water tests still provides a low cost and rapid information about the stripping potential of the aggregates.

Tropical countries like India have distributed rainfall with an average rainfall of 1085mm [20]. Bihar, one of the states in India which is located in the eastern part of the country encountering high rainfall (1326 mm) and is one of the most flood-affected state in India. The aggregates used in the present study is used for construction and maintenance of the road network of the state of Bihar and parts of the road network for the state of Jharkhand, West Bengal and Uttar Pradesh amounting to a total network of about 1 million kilometres in length [21]. The high rainfall in the region results in various types of distress including stripping. The huge loss of resources in developing countries like India is a big challenge. The present study tries to identify the stripping potential of the aggregates used in this part of the country for its large road network. Figure 1 depicts the various sources used for the construction of the road network.

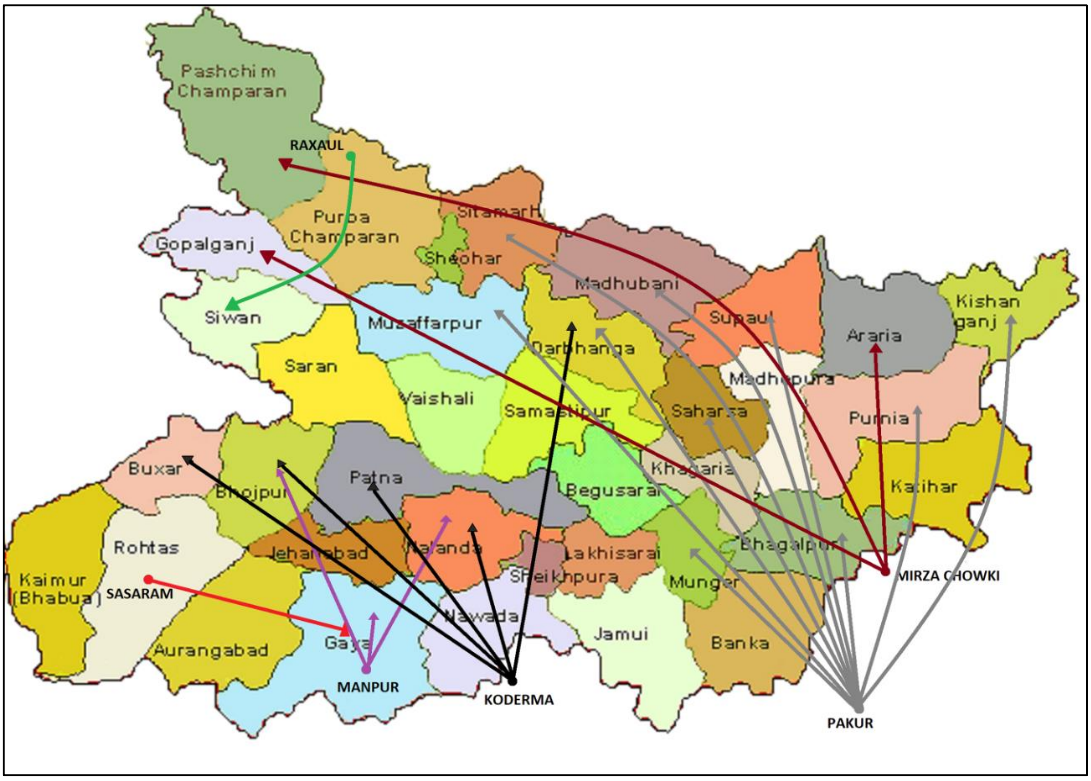


Figure 1. Showing various sources of aggregates in Bihar and Jharkhand and their movement from source to construction sites

The focus of this work is to determine the chemical, mineralogical and physical nature of aggregates obtained from various sources from in and around the region and determine a correlation between the chemical contents of the aggregates and the stripping propensity. Also, the effect of hydrated lime on stripping propensity is studied.

2. Materials

2.1. Bitumen

Bitumen of Viscosity Grade (VG 30) was used from Barauni IOCL refinery, Bihar, India. Penetration test, softening point, viscosity tests were done for identifying the physical properties and grade determination of the binder and is presented in Table 1.

2.2. Aggregates

The aggregates used in this study were selected from six different sources that are identified to be used in the region. The source quarries were namely Koderma (Jharkhand), Sasaram (Bihar), Pakur (Jharkhand), Gaya (Bihar), Raxaul (Bihar) and Mirza Chowki (Jharkhand). Physical tests were conducted to determine the construction properties required for the bituminous mix. Moreover, the elemental and mineralogical properties were determined.

2.3. Additive

Hydrated lime (Purity 90%) was used in this research work as an anti-stripping additive to the bituminous mix. Application dosage of hydrated lime has been increased gradually from 1 to 2% by weight of aggregate to investigate the stripping propensity. The maximum value of hydrated lime to be used is specified as 2% by Ministry of Road Transport & Highways (MoRTH), (2013), and hence, these quantities were considered for further research.

3. Methodology

The stripping propensity of aggregates of different sources of aggregate was evaluated by conducting tests on the bituminous binder and aggregates of various sources in the region. The physical characteristics of the aggregates were determined according to ASTM standards which were followed by the determination of chemical and mineralogical characteristics. The chemical analysis for determination of elemental composition was done in National Test House, Kolkata and the mineral composition was determined by X-ray diffraction technique performed by Sophisticated Test and Instrumentation Centre (STIC), Cochin. Thereafter, boil water test and static immersion test were used to determine the stripping propensity of the aggregates from these sources. To determine the influence of hydrated lime (HL) in resisting stripping, tests were also conducted using HL. Thus, an effort was made to draw a correlation between the aggregates' physical properties and elemental and mineralogical composition with stripping propensity.

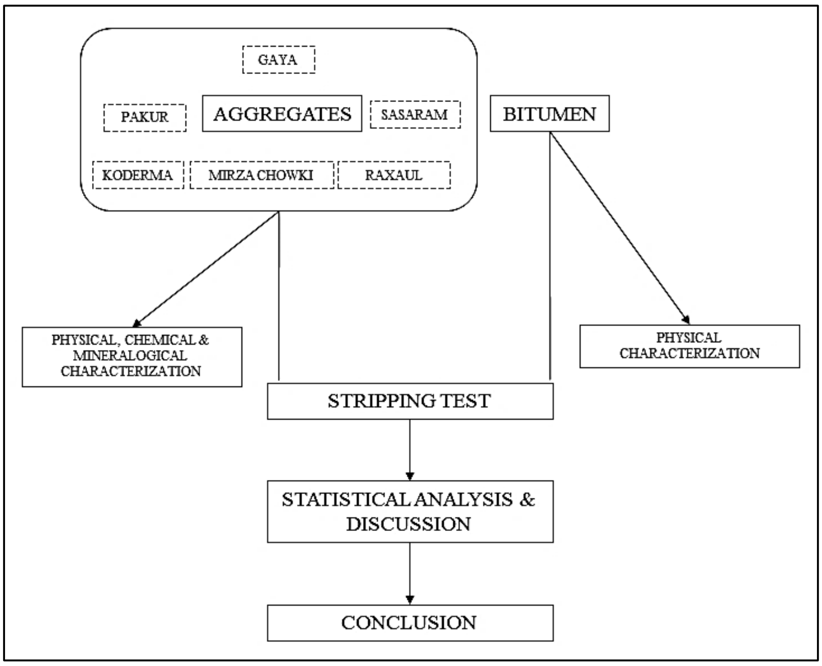


Figure 2. The planned flow chart for conducting the research

3.1. Stripping Measurements

The aggregate-bitumen loose mix was prepared and subjected to static immersions tests (AASHTO T182) and boil water test (ASTM D3625) to assess the extent of stripping of these aggregates. The tests were performed with aggregates and subsequently with the addition of incremental quantities of hydrated lime.

4. Results

4.1. Bitumen

Penetration and softening point were performed on bitumen of grade VG-30 and the results were compared to the specification as per IS 73:2006. The results were within permissible limits and are tabulated below:

Table 1. Viscosity grade (VG-30) bitumen specification as per IS 73:2006

Test	Standard Method	Result	Specification Limit
Penetration Value	ASTM D5	52	50-70
Softening Point (°C)	ASTM D36	64	Above 47
Viscosity at 60°C (in Poises)	IS 73: 2013	2592	2400-3600

4.2. Aggregates

Physical characterization of aggregates was performed according to IS: 2386. The specified limits according to MoRTH (2013) and the acquired results are mentioned as under in Table 2.

Table 2. Physical Properties of Aggregates

S. No	Test	Test Method	Pakur	Gaya	Sasaram	Koderma	Raxaul	Mirza Chowki	Specified Limit
1	Aggregate impact Value	BS 812-112: 1990	12.50	12.88	13.33	15.00	24.23	9.35	Max 24%
2	Loss Angeles Abrasion Value	ASTM C131	15.00	16.70	18.74	17.68	39.40	7.36	Max 30%
3	Combined Flakiness	ASTM D4791-10	12.85	14.97	9.40	10.34	10.01	6.77	Max 35%
4	And Elongation Index		13.36	16.80	8.79	14.56	12.35	14.22	
5	Soundness With Sodium Sulphate	ASTM C88	1.85	1.23	0.29	2.25	0.032	1.12	Max 12%
6	Water Absorption	ASTM C127	0.65	0.20	1.18	0.85	0.97	0.60	Max 2%

National Test House (NTH), Kolkata performed chemical tests to determine the elemental composition of the aggregates. The table below gives the prominent elements present in the aggregates and is compared with the stripping values obtained from the boil water test without the addition of lime.

Table 3. Elemental composition of aggregates obtained from various sources

Aggregate Source	Chemical Composition of Aggregate (% by Weight)							Stripping Without Lime
	Ca	Si	Na	K	Fe	Mg	Al	
Pakur	7.84	24.31	0.32	0.75	7.75	3.12	7.08	90
Gaya	3.37	30.35	0.12	2.06	2.99	0.91	8.81	72
Sasaram	0.54	41.04	0.08	2.10	1.17	0.23	3.07	68
Koderma	7.16	24.57	0.22	1.75	6.67	3.55	7.94	75
Raxaul	0.66	39.46	0.02	4.98	2.46	0.23	1.72	60
Mirza Chowki	7.06	25.25	0.12	1.39	5.52	3.69	7.83	87

The mineralogical compositions of the aggregates from six (6) different sources were determined using XRD peaks and are presented under in Table 4.

Table 4. Mineralogical composition of the aggregates

Source	Percentage of Minerals									Stripping Without Lime
	Quartz Low	Magnesium Calcite	Trikalsilikate	Albite Low, Calcian	Vaterite	Zeolite	Diopside, Aluminium	Anthracite	Potassium Aluminium Silicate	
	SiO_2	$(Ca, Mg)CO_3$	$3CaO.SiO_2$	$(Na,Ca)AlSi_3O_8$	Polymorph of $CaCO_3$	$Na_2Al_2Si_3O.2H_2O$	$CaAlSi_2O_6$	$C_{240}H_{90}O_4NS$	$AlKO_6Si_2$	
Pakur	0	0	0	57.01	0	9.57	27.62	5.80	0	90
Gaya	50.84	0	0	49.16	0	0	0	0	0	72
Sasaram	18.08	0	0	81.92	0	0	0	0	0	68
Koderma	0	0	0	92.23	0	0	0	0	7.77	75
Raxaul	82.98	7.74	9.27	0	0	0	0	0	0	60
Mirza Chowki	2.23	0	0	54.66	0	10.03	33.07	0	0	87

4.3. Boil Water Test

This is a quick laboratory test to determine the susceptibility of aggregate coated with bitumen against stripping in which visual examination of the aggregates are made after boiling loose bituminous mix according to ASTM D3625. Initially, the test was conducted on sample mix with no additive. The result showed maximum adhesive failure with least coating area. By the increase in the concentration of hydrated lime, the stripped area was improved. This verifies that hydrated lime improves the water-resistant of asphalt mix. With further increase in the concentration of hydrated lime coating percentage of mastic asphalt mix was maximized up-to 100%.

Table 5. Coating Percentage of aggregates determined using Boil Water test

Sources	Without lime	Lime (1%)	Lime (1.5%)	Lime (2%)
Pakur	90	93	95	100
Gaya	72	82	90	100
Sasaram	68	80	87	95
Koderma	75	88	90	100
Raxaul	60	73	82	90
Mirza Chowki	87	93	95	100

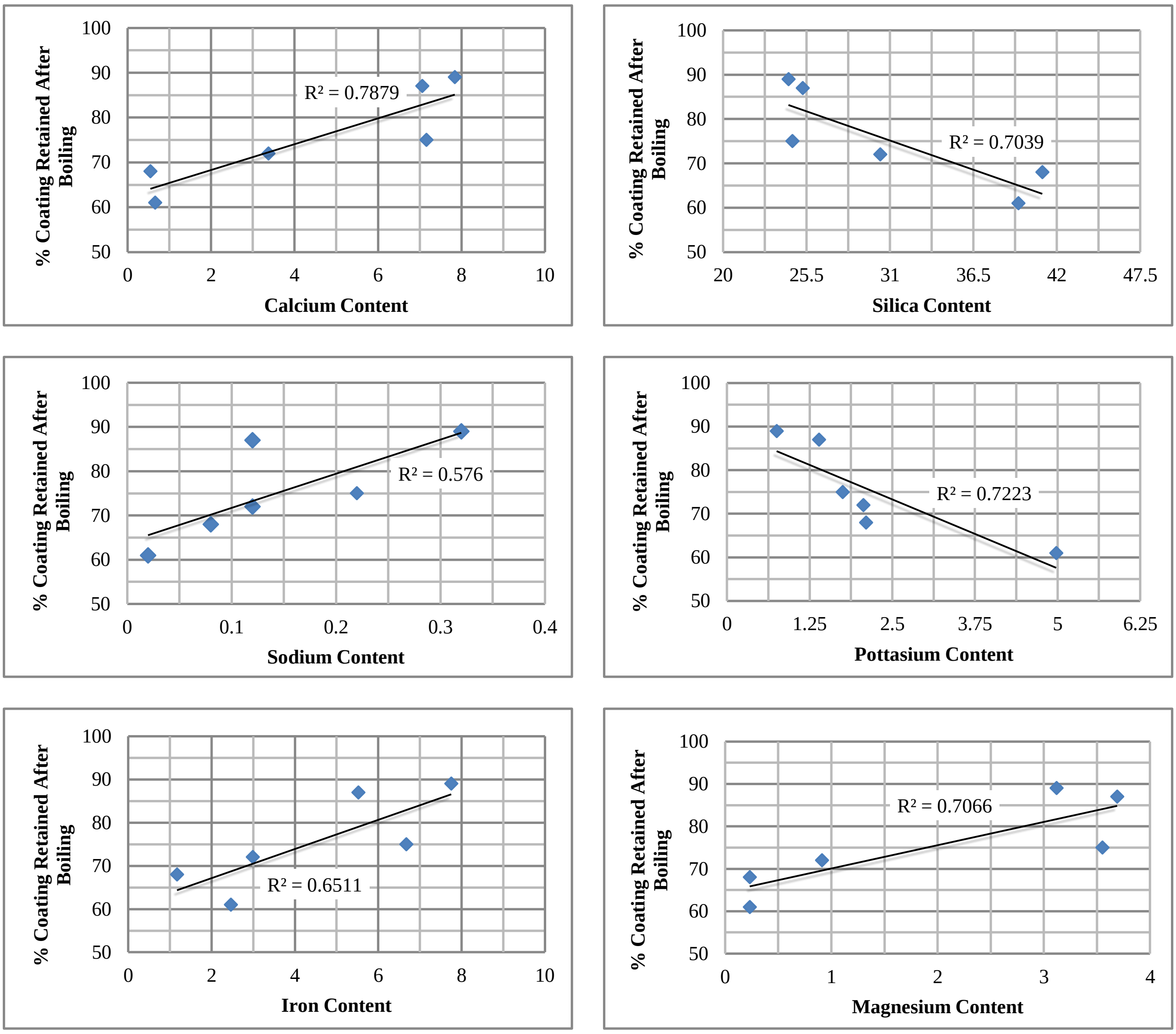
Figure 3. Representative image of aggregate stripping using the Boiling Water Test

4.4. Static Immersion Test

Static immersion test was conducted on the aggregates. No stripping was observed for any aggregate even after absorption in water under 40ºC for 24 hours even without the addition of lime. No tests were thereafter conducted using lime as because boil water tests showed a decrement effect of stripping using lime. Therefore, this test was rendered as an insignificant test to study stripping for these sources.

5. Discussion

Aggregate chemical composition influences the behaviour of aggregate surface and stripping relies on the aggregate surface chemistry. Metallic element such as iron, aluminium, magnesium and calcium were found to strengthen the interfacial bond that opposed the harmful effects of water molecules. On the other hand, the presence of silicon and potassium was observed to be unfavourable for the bonding between the aggregate and bituminous material.



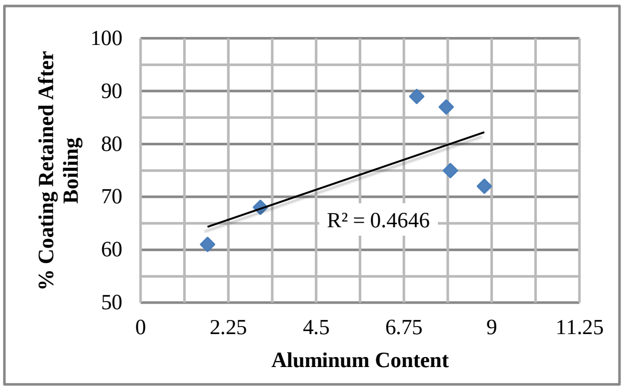


Figure 4. Correlation between aggregates' elemental composition and boil water test results

The correlation between the elemental composition and the coating retained after boil water test in percentage was determined in the study by two statistical parameters namely coefficient of determination (R^2) and P-value. The coefficient of determination (R^2) value determines the level of fit of the proposed curve with the actual data depicted by the points in the graphs whereas P-value determines the significance of a hypothesis. P-value of less than 0.05 is considered considerably significant for a confidence level of 95% and therefore, the null hypothesis of no significant correlation should be rejected. These statistical parameters obtained for the elements studied are mentioned under in Table 6.

Table 6. Statistical parameters depicting the correlation between elemental compositions and stripping propensity.

Sl. No.	Element	R^2	P-value
1	Calcium	0.7879	0.0182
2	Silicon	0.7039	0.0368
3	Sodium	0.5760	0.0800
4	Potassium	0.7223	0.0321
5	Iron	0.6511	0.0510
6	Magnesium	0.7066	0.0360
7	Aluminium	0.4646	0.1360

Increase in calcium content was seen to positively and significantly influence resistance to stripping with an R^2 value of 0.7879 and P-value of 0.018. Increase in sodium content also influenced the stripping resistance of the material. Table 6 however predicts a weak correlation of sodium content with stripping propensity with an R^2 value of 0.5760 and P-value of 0.08. Iron content was observed to provide resistive behaviour to moisture-induced stripping with an R^2 and P-value of 0.6511 and 0.0510 respectively. Increase in magnesium was found to positively affect the resistance to stripping. A good correlation was observed in this regard with an R^2 value of 0.7066 and P-value of 0.036. Increased aluminium content too showed to resist moisture-induced damage. However, the correlation obtained could not be considered significant with an R^2 value 0.4646 and P-value of 0.136. Whereas, the resistance to stripping was found to decrease with increase in silica content, suggesting a negative influence of silica content on the stripping resistance. The relation can be considered significant with R^2 and P-value of 0.7039 and 0.037 respectively. Potassium is also observed to negatively influence the stripping resistance potential. With the increase in the potassium content, a significant increase in stripping is observed having a good correlation with an R^2 value of 0.7223 and P-value of 0.032.

Presence of calcium ions (Ca) in aggregate surface improved the bonding between aggregates and bitumen. It was explained that both anionic and cationic surfactants that exist naturally in bitumen form a strong bond with the calcareous aggregate surface [22]. However, only the cationic portion of bitumen forms a bond with siliceous (Si) aggregates which leads to easy displacement of anionic surfactants by water for siliceous aggregates. Thus, it can be seen that as aggregates containing Ca ions increases, the bonding increases which is opposite to the trend seen for siliceous aggregates, signifying negative influence of Si ions on bonding strength as depicted in earlier studies [7, 18]. The results obtained from this study follow similar trends. Moreover, aggregate containing Si and Al react to form insoluble salts that are detrimental for stripping. Aluminium (Al) has less role to play in stripping. Whereas K forms soluble salts due to which it is easily washed by water molecules and hence, decreases the bond strength. It was stated that alkali earth metals (sodium and potassium) are detrimental for adhesion because of the higher surface area which provides more active sites for interaction [23]. The correlation observed for element potassium in this study is in line with the earlier findings. However, for the element sodium, an opposite trend was observed in this study.

Co-relation graph between mineralogical composition and resistance to stripping obtained from boil water test was obtained for albite low (calcian). Apart from albite low (calcian), correlation graphs could not be obtained because of the absence of the other minerals studied from most of the aggregates, thereby, limiting the development of such co-relation. However, albite low (calcian) was not found to be significantly correlated to the stripping propensity of the material.

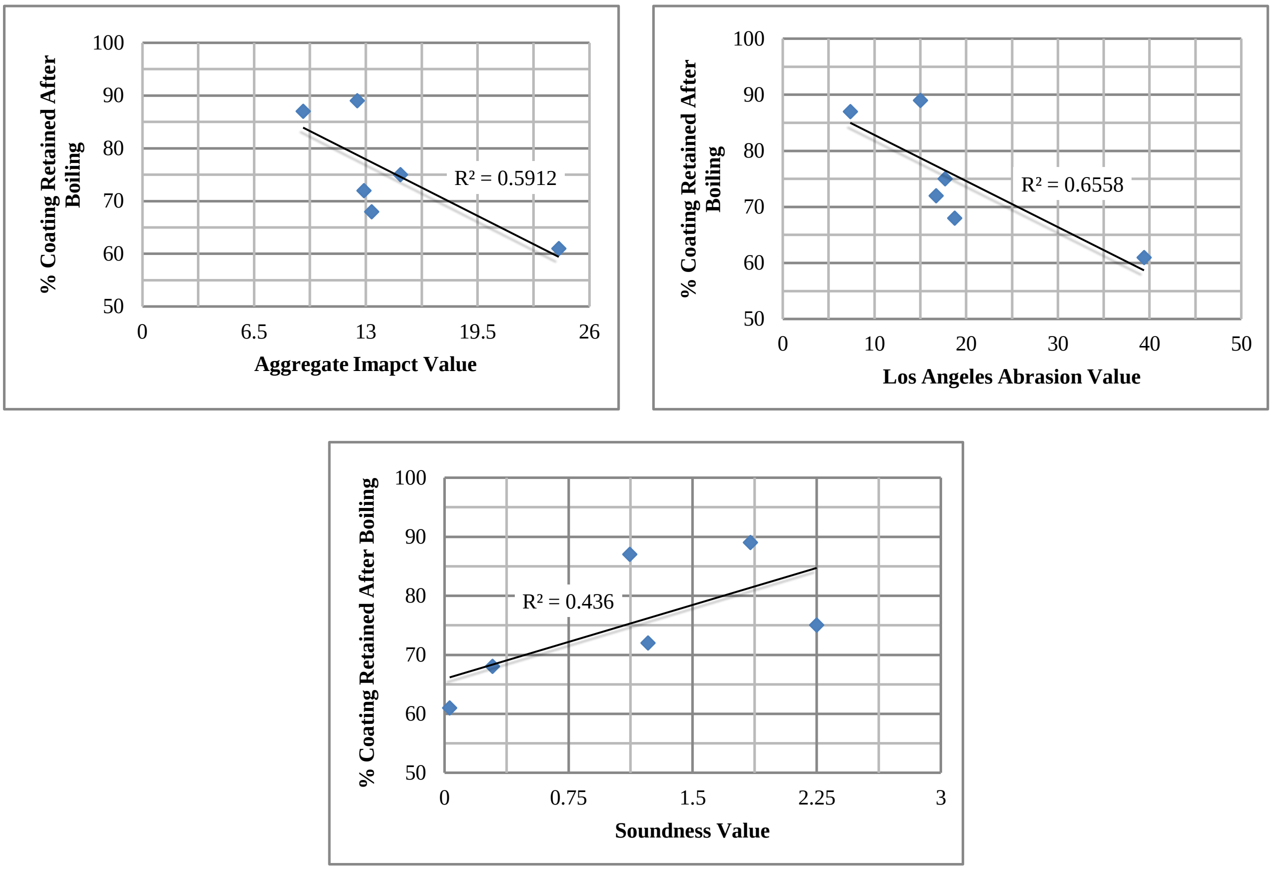


Figure 5. Correlation between aggregates' physical properties and boil water test results

With an increase in aggregate impact value (AIV), the stripping resistivity was found to decrease. The R^2 value was observed to be 0.5912. However, with a P-value of 0.07, the correlation seemed to be weak. Similar trends were also seen for Los Angeles Abrasion (LAA) value. The correlation obtained here was better than AIV with an R^2 value of 0.6558 and significant with 0.05.

Table 7. Statistical parameters depicting the correlation between the physical properties of aggregates and stripping propensity

Sl. No.	Physical property of Aggregates	R^2	P-value
1	Aggregate Impact Value	0.5912	0.0740
2	Los Angeles' Abrasion Value	0.6558	0.0500
3	Soundness Value	0.4360	0.1530

AIV and LAA value is an indication of aggregate toughness and resistance to wear and tear respectively. Higher value signifies softer and wearable aggregates. Thus, it could be concluded that softer aggregates are susceptible to stripping. It can be attributed to the fact that moisture easily softens and damages the interfacial bond between aggregates and bitumen leading to damage.

Moreover, the increase in soundness value depicted an increase in stripping showing that more the aggregate is chemically active, more it reacts with moisture leading to stripping.

6. Conclusion

The present study is an attempt to investigate the stripping propensity of aggregates used for road construction and maintenance of about 1 million km road network for the state of Bihar and adjoining parts of states of Jharkhand, Uttar Pradesh and West Bengal in India. Elemental, mineralogical and physical properties of the aggregates obtained from six different sources were determined, and these values were co-related with the stripping results. The aggregates were obtained from quarry sites of Gaya, Sasaram, Raxaul, Pakur, Mirza Chowki and Koderma. As observed from experiments, aggregates from Pakur and Mirza Chowki having higher calcium content require lesser hydrated lime to ensure anti-stripping behaviour. On the other hand, the aggregates from the other four sources require a higher dosage of HL content (2% by weight) to reduce stripping propensity.

The degree of correlation was ascertained by two statistical parameters namely the coefficient of correlation (R^2) and p-value. The elemental results could be well correlated with stripping values from boil water test. Calcium, sodium, iron, magnesium positively influenced the bonding between aggregates and bitumen. However, it was found that the presence of silicon and potassium showed to decrease the bond strength. Except for sodium, the trend fitted well with the literature mentioned in the study. Apart from albite low (calcian), the mineralogical composition obtained from these aggregates were not similar. Hence, no correlation could be obtained using mineralogical data. Albite low (calcian) showed poor correlation with stripping results. The physical properties also showed correlation with the stripping propensity. Increase in aggregate impact value and Los Angles abrasion value resulted in a decrease in stripping resistance showing the vulnerability of softer aggregates to stripping. Moreover, aggregates with higher soundness value being chemically more interactive showed significantly less stripping resistance. In spite of having several qualitative and quantitative methods for the assessment of stripping propensity, the limitation of the experiment is that boil water test and static immersion tests were only used for assessment which needs to be supplemented by other quantitative tests. In-depth study of the mineralogical composition of the aggregates should be taken up in the future studies to set forth the norms for construction of this large road network.

7. Declarations

7.1. Author Contributions

Conceptualization, H.C., and S.S.; methodology, H.C.; investigation, G.K.; resources, S.S.; data curation, H.C.; writing—original draft preparation, H.C.; writing—review and editing, S.S.; supervision, S.S. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in article.

7.3. Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

7.4. Acknowledgements

The authors would like to thank National Test House (NTH), Kolkata for carrying out the elemental analysis and Sophisticated Test and Instrumentation Centre (STIC), Cochin for carrying out the mineralogical analysis.

7.5. Conflicts of Interest

The authors declare no conflict of interest.

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