Investigation on effects of aggregate roughness on bond strength of aggregate-bitumen systems

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Abstract. It is critical to understand bonding-behavior of aggregate with bitumen. The surface chemistry and roughness of aggregates play an important role to create sufficient bond with bitumen. Usually, asphalt-bond-strength (ABS) test is used to directly quantify bonding-behavior of aggregate-bitumen system, further, surface-free-energy (SFE) approach has also been used by some researchers. AASHTO T-361 recommends to use aggregates polished with 280-silicon-carbide (SiC) powder to determine bond-strength with bitumen. However, increase or decrease in polishing-level can alter aggregate-roughness and may affect bond-strength. Further, there can be numerous roughness-scale for aggregates such as, arithmetic (Ra), root-mean-square (Rq) and box-roughness (Sa), which needs detailed study. Therefore, one of the strong motivations of this study was to evaluate effects of aggregate-roughness on bond-strength using ABS approach. Similarly, aggregate SFE may change with change in its roughness, thereby affecting aggregate-bitumen bonding. The present study evaluates effects of aggregate-roughness on aggregate-bitumen bond-strength using ABS and SFE approaches. Basaltic substrates and viscosity-grade binder (VG30) were selected for this study. To generate different roughness-levels, aggregate substrates were polished with 220SiC and 1000SiC powders. At each polishing-level, Ra and S were parameters were evaluated using zeta-profilometer. The ABS and SFE measurements were conducted on combination of aggregate and bitumen. The results showed that bond-strength increased with increase in aggregate-roughness, indicating better bonding for rough aggregates. Further, S parameter which remained unaddressed in earlier research studies was recommended to quantify aggregate roughness rather than Ra parameters, because it measures roughness over area, which is one of the major contributions of present study.

1. Introduction

Presence of moisture in bituminous mixes results into bonding failure of aggregate-bitumen system. Failure of aggregate-bitumen bonding can lead to cracking, potholes, rutting and raveling distresses in bituminous pavements. Thus, it is crucial to achieve better adhesive bond between aggregate and bitumen. Surface texture of aggregate plays a vital role in developing bond strength between aggregate and bitumen [1-3]. In general, rough textured aggregates make better bond with bitumen [1]. However, aggregate texture changes during crushing, attrition, and abrasion mechanism during production process and during service life. For example, as the pavement ages, the protruding aggregate become polished due to wearing action of vehicular movements, which lowers friction and skid resistance between
pavement and vehicle tires. The reduced friction under wet surface conditions aggravates risk of hydroplaning which is undesirable considering serviceability criteria. Further, polished surface is more likely to undergo bonding failure [1]. Therefore, timely measurement of surface roughness is critical. Further, change in aggregate texture may affect its surface chemistry which influences its bonding ability with bitumen. Therefore, the effect of polishing on the surface chemistry of aggregates also needs to be understood.

The bond strength between aggregate and bitumen can be indirectly evaluated using Surface Free Energy (SFE) approach based on contact angle measurements [4-7]. Koc and Bulut [8] evaluated the SFE components of aggregates polished with silicon carbide (SiC) powder (200, 400, 600, and 1000) and 5-micrometer alumina oxide grit. However, surface roughness values were assumed to be less than 1 µm after polishing with 600SiC grade abrasive powder. Similarly, Kittu et al. [7] evaluated the roughness of unpolished, 400SiC and 600SiC grade polished aggregates using 2-D profilometer. Both studies have reported strong dependence of contact angle on aggregate texture. However, the effect of polishing levels on bond strength was not studied. Recent studies have used Asphalt Bond Strength (ABS) test approach which considers aggregate roughness to determine bond strength of aggregate-bitumen system in accordance with AASHTO T-361 [1, 9-10]. However, standard method recommends aggregates polished with 280SiC grit powder without consideration for magnitude and effect of varying roughness. Hence, it was observed that limited studies were conducted on effect of varying aggregate roughness on bond strength with bitumen. Therefore, the present was undertaken to estimate the effect of aggregate roughness on aggregate-bitumen bond strength.

2. Objective and Scope of study
As discussed, quantification of aggregate roughness was primarily done using 2D profilometer and its effect on bond strength was rarely studied. Roughness of aggregates was usually measured using 2D profiler with arithmetic scale (R_a) [7-8]. However, direction of roughness measurement i.e. along the X-direction (horizontal) or Y-direction (vertical) is not clearly stated which may affect roughness measurements. Further, use of different scale of roughness measurements, for example, root-mean-square (R_q) and box-roughness (S_b) may result in different roughness values. The R_a roughness scale measures roughness over line along horizontal axis (R_a-H) or vertical axis (R_a-V), whereas, S_b measure roughness over the scanned area. Therefore, it will be interesting to study whether the measurement of roughness depends on the choice of scale used. Further, it is important to investigate the impact of higher and lower polishing levels on bonding potential of aggregate-bitumen system.

Therefore, the present study is motivated to determine the roughness of aggregate under different polishing levels using 3D zeta profilometer and identify the effects of aggregate roughness on aggregate-bitumen bond strength. The present study considers measurement of aggregate roughness using line roughness (R_a) and area roughness or box roughness (S_b) scales. Two different levels of aggregate roughness were generated by polishing with 220SiC and 1000SiC grade abrasive powders. Thereafter, the roughness was evaluated using zeta profilometer with different scales of measurement (i.e. R_a and S_b). Further, bond strength of aggregate and bitumen was evaluated using SFE and ABS test approach at different polishing levels.

Thus, the overall objective of the present study was to quantify varying levels of aggregate surface roughness and identify its effect on bond strength with bitumen. To achieve the desired goals, following sub-objectives were formulated:
1. Measurement of aggregate roughness at different polishing levels using 3D profilometer.
2. To estimate the effects of different levels of aggregate roughness on surface chemistry of aggregates and aggregate-bitumen bond strength.

3. Material and Methodology
Basalt aggregate and viscosity grade bitumen (VG-30) were used in the present study. These are the commonly used materials for road construction in India. To determine the SFE of bitumen, water (W), diiodomethane (D) and ethylene glycol (E) were selected as probe liquids due to its lower condition
number (4.47). However, water (W), formamide (F) and ethylene glycol (E) were selected as probe liquids for measuring contact angles of aggregate [5]. The methodology adopted in the present study involves the measurement of aggregate roughness at different polishing stage, evaluation of aggregate surface chemistry and bond strength using SFE approach and evaluation of aggregate-bitumen bond strength using ABS test approach at different roughness levels. Brief discussion of the adopted methodology is presented in the following sub-sections.

3.1 Aggregate Roughness Measurement
The steps in measuring aggregate roughness involves cutting of aggregates using diamond saw cutter, polishing using required grades of SiC powder and cleaning of polished aggregates using ultrasonic water bath. The roughness of aggregate was measured using 3D Zeta profilometer. The main components of zeta profilometer are camera, standard objectives (5x, 10x, 20x and 50x), precision Z-drive mechanism, zeta optics module, control box, substrate holder, and computer system (figure 1a). When a beam of LED bombards the aggregate surface, the X, Y and Z dimensions of a point are measured (figure 1b). Thereafter, using zeta optics at any level of magnification 2D composite image and 3D true color image is obtained. The roughness of aggregate at different scales i.e. $R_a$ along the horizontal axis ($R_a$-H) and vertical axis ($R_a$-V), and $S_a$ is calculated using data analysis software [7, 11]. The $R_a$ is the arithmetic scale which measures line roughness as sum of deviations of measured points from the average peak [11] and is presented in equation (1). On the other hand, $S_a$ is the extension of line roughness scale $R_a$. It measures absolute value of surface roughness measured as the difference in height of each point and arithmetic mean of surface (equation (2)). The line roughness scale i.e. $R_a$-H and $R_a$-V, and area roughness scale i.e. $S_a$ is presented in figure 1c-1e. The measurement of roughness is presented in figure 1f.

$$R_a = \frac{1}{n_r} \sum_{i=1}^{n_r} |z(i) - \bar{z}|$$

(1)

$$S_a = \frac{1}{A} \iint |Z(x, y)| dxdy$$

(2)

where,

$(i)$= local peak height of specimen at $i^{th}$ measurement.

$\bar{z}$= average peak height.

$n_r$= number of measurements on the sampling length $r$.

$A$= scanned area

**Figure 1.** (a) Zeta Profilometer, (b) Roughness measurement using zeta profiler, (c) $R_a$-V profile over line, (d) $R_a$-H profile over line Roughness measurement, (e) $S_a$ profile over surface, (f) Roughness measurement profile
3.2 Surface Free Energy (SFE) approach
The SFE of material (Y) is its intrinsic property, consisting of Lifshitz-van der Waals (\(Y^{LW}\)), Lewis acid (\(Y^+\)) and Lewis base (\(Y^-\)) components [12]. The \(Y^+\) and \(Y^-\) components are together termed as polar component (\(Y^{AB}\)) (equation (3) and (4)). Using contact angle approach, the components of SFE (i.e. \(Y^L_s\)\(^{LW}\), \(Y_s\)\(^{LW}\) and \(Y_s\)\(^L\)) of any substrate ‘S’ can be determined using probe liquids ‘L’ according to acid-base theory using equation (5) [12].

\[
Y = Y^{LW} + 2\sqrt{Y^+Y^-} \\
Y^{AB} = 2\sqrt{Y^+Y^-} \\
Y(1 + \cos\theta) = 2\sqrt{Y^L_sY_s^{LW} + 2\sqrt{Y^L_sY_s^{LW}} + 2\sqrt{Y^L_sY_s^{LW}}} \\
(5)
\]

The SFE components of aggregate and bitumen are useful to determine their bond strength by evaluating energy parameters. Work of dry adhesion (\(W_{AB}\)), work of wet adhesion (\(W_{ABW}\)), cohesion energy (\(W_{BB}\)) and wettability (\(W_{AB} - W_{BB}\)) are regarded as energy parameters. Energy of adhesion in absence of moisture is termed as work of dry adhesion (\(W_{AB}\)), whereas, adhesion energy in presence of moisture is termed as work of wet adhesion (\(W_{ABW}\) (equation (6) and (7))). Cohesion energy is the work required to create unit area crack within bitumen (equation (8)). Combining these energy parameters, the bond strength between aggregate and bitumen can be estimated by determining energy ratio (ER) parameter using equation (9) [6].

\[
W_{AB} = 2\sqrt{Y^L_AY^L_B + 2\sqrt{Y^+_AY^+_B} + 2\sqrt{Y^-_AY^-_B}} \\
W_{ABW} = Y_{AW} + Y_{BW} - Y_{AB} \\
W_{BB} = 2Y_B \\
ER = \left|\frac{W_{AB} - W_{BB}}{W_{ABW}}\right| \\
(6) \\
(7) \\
(8) \\
(9)
\]

3.3 Asphalt Bond Strength (ABS) test approach
ABS test measures the tensile force required to break bonding between aggregate and bitumen in terms of pull-off tensile strength (POTS) as per AASHTO T-361. ABS test set-up comprises of metallic pull-off stub, pressure hose, reaction plate, piston, and pneumatic adhesion tester. The determination of aggregate-bitumen bond strength involves aggregate cutting and polishing with 280SiC grade powder [13]. To prepare test specimens, washed aggregates, binder and pull-off stubs are kept in oven at 150°C for not less than 30 min. Thereafter, the aggregates are kept in another oven maintained at application temperature (60°C). The binder sample is collected in pull-off stub which is then pressed firmly against the aggregate surface preheated at required application temperature. The steps involved in preparing sample is present in figure 2a-2d. The prepared samples were then kept for dry (room temperature, 24 h) and wet conditioning (40°C, 24 h). The POTS of samples after dry conditioning (\(POTS_{dry}\)) and wet conditioning (\(POTS_{wet}\)) can be evaluated using equation (10). Further, to rank different combinations of aggregate and bitumen, bond strength ratio (BSR) parameter can be evaluated using equation (11).

\[
POTS = \frac{(BP \times A_g) - C}{A_p} \\
BSR = \frac{POTS_{dry}}{POTS_{wet}} \\
(10) \\
(11)
\]

where, \(A_g\) is contact area of gasket with reaction plate in mm\(^2\); \(A_p\) is area of pull-off stub in mm\(^2\); C is piston constant; BP is burst pressure in kPa.
4. Results and Discussion

4.1 Effect of polishing levels on aggregate roughness

The roughness of 220SiC and 1000SiC polished aggregates measured at different roughness scales (i.e. R<sub>a</sub>-H, R<sub>a</sub>-V and S<sub>a</sub>) is presented in figure 3. As expected, roughness generated from 220SiC polishing level was found to be higher than roughness of 1000SiC polished aggregates. For example, S<sub>a</sub> value for 220SiC polished aggregate was found to be 2.933 µm, which after progressive polishing to 1000SiC reduces it to 0.610 µm. The reduction in roughness is due to the higher grain size of 220SiC abrasive powder (63 micron) compared with 1000SiC (7 micron). In addition, p-values obtained using students t-test for roughness scales R<sub>a</sub>-H, R<sub>a</sub>-V and S<sub>a</sub> were found to be 0.003, 0.000 and 0.000, respectively, therefore indicating significant difference in the roughness obtained using different polishing levels. Moreover, the difference in polishing levels is clearly evident from the 3D images obtained using zeta profilometer (figure 4). Further, it is to be noted that roughness measured using S<sub>a</sub> scale evaluates higher values of roughness compared with R<sub>a</sub>-H and R<sub>a</sub>-V roughness scale (figure 3).

![Figure 3. Roughness values of polished aggregates using different scales](image)

As discussed, S<sub>a</sub> scale is a surface roughness parameter which measures roughness of aggregate over area whereas R<sub>a</sub> scale measures roughness of aggregate over line. Hence, higher value of S<sub>a</sub> may be expected. However, no significant difference in the roughness measured using R<sub>a</sub>-H, R<sub>a</sub>-V and S<sub>a</sub> was observed. But for a given scanning area, roughness measured over area seems to be more appropriate, hence, use of S<sub>a</sub> parameter is recommended to indicate aggregate roughness. In addition, to substantiate the present study, further experimental study is required to collect roughness data of different aggregates with increased number of observations.
4.2 Variation in contact angles due to change in aggregate roughness

Figure 5 shows the effect of texture on the contact angle of aggregate. The contact angle of aggregates was measured using water (W), formamide (F) and ethylene glycol (E). For each of the probe liquids, higher values of contact angle were observed for aggregate texture generated after polishing with 1000SiC grit powders when compared with texture generated after polishing with 220SiC grit powders. In addition, statistical analysis revealed that surface texture of aggregate has a significant effect (p-value<0.05) on contact angle of aggregate when measured using all the probe liquids (i.e. W, F, and E). Further, significant change in the contact angle may reciprocate in the form of change in SFE of aggregate. Therefore, it will be interesting to known, how significant is the change in the SFE of aggregates due to change in contact angles.

4.3 SFE of aggregate

The SFE components of basalt aggregate is presented in figure 6. It was observed that change in aggregate texture does not affect the acid and base SFE components of basalt aggregate. For example, the base SFE component of basalt aggregate was found to be similar i.e. 17.90 mJ/m² and 17.63 mJ/m² for 220SiC and 1000SiC polished surface, respectively (figure 6). However, significant increase in the dispersive components was observed with change in aggregate texture resulting from 220SiC polishing level to 1000SiC polishing level. Further, the total SFE of 220SiC polished aggregate (76.45 mJ/m²) was found to be higher than SFE of 1000SiC polished aggregates (38.48 mJ/m²). Statistical analysis using independent sample t-test showed significant difference (p-value=0.000) in the total SFE of
220SiC and 1000SiC polished aggregate due change in aggregate texture. Thus, it was observed that polishing of aggregates significantly reduces its SFE.

\[ \text{Figure 6. SFE components of aggregates} \]

**4.4 SFE of bitumen**

The SFE components of bitumen was determined using sessile drop method with set of three different probe liquids namely, W, D and E. The \( \gamma_{\text{LW}} \), \( \gamma^\text{L} \), \( \gamma^\text{B} \) and \( \gamma_0 \) components of binder SFE was found to be 29.15 mJ/m\(^2\), 0.00 mJ/m\(^2\), 2.82 mJ/m\(^2\), and 29.15 mJ/m\(^2\), respectively. The determination of SFE components of bitumen is essential in determining energy parameters related to compatibility with aggregate.

**4.5 Energy parameters and Energy Ratio**

Using the SFE components of aggregate and bitumen, the energy parameters namely, \( W_{\text{AB}} \), \( W_{\text{ABW}} \), and wettability were evaluated (figure 7). Higher value of \( W_{\text{AB}} \) was observed for aggregates polished with 220SiC grade powder compared with aggregates polished with 1000SiC powder, which is favourable for better bond strength. In fact, dry adhesion in case of 220SiC polished surface was found to be 42% higher compared with 1000SiC polished surface. Subsequently, for a particular type of binder used in the present study, the wettability with variedly polished aggregates was evaluated. It was observed that wettability of rough textured aggregate (220SiC) is remarkably higher compared with smooth textured aggregate (1000SiC) (figure 7). Higher wettability indicates better bonding; thus rough textured aggregates were found to be favourable for better bonding compared with smooth textured aggregates.

\[ \text{Figure 7. Energy parameters related to bond strength} \]
Further, comparable values of WABW were observed for aggregates with polishing levels 220SiC and 1000SiC (figure 7). Additionally, to rank the combination of aggregate and bitumen system, ER parameter was evaluated. The ER of rough textured (220SiC) aggregate was found 0.75, while ER of smooth textured (1000SiC) aggregates was found to be 0.18, indicating higher bond strength of 220SiC polished aggregates. Higher ER value for 220SiC polished aggregates was expected due to better coating of binder on rough surface as indicated by higher value of wettability. In addition, ranking criteria characterizes 220SiC polished aggregate as “Fair”, while 1000SiC polished aggregate as “Very poor” [6]. Further, similar level of aggregate polishing can be expected on bituminous pavements due to vehicular movement which is undesirable for aggregate-bitumen bonding. Hence, further study can be conceptualized to correlate the roughness and bond strength of laboratory polished aggregates with the aggregates polished due to vehicular movements.

4.6 Effect of aggregate roughness on POTS and Bond strength ratio (BSR)

Figure 8 shows the POTS<sub>dry</sub> and POTS<sub>wet</sub> of 220SiC and 1000SiC polished aggregates. The POTS of 220SiC polished aggregate was found to be higher than 1000SiC polished aggregate which was expected considering the higher S<sub>a</sub> values of 220SiC polished aggregates (S<sub>a</sub>=2.93) compared with 1000SiC polished aggregates (S<sub>a</sub>=0.61). Increased roughness of aggregate promotes physical interlocking between aggregate surface and bitumen due to presence of summit and valley in aggregate surface (figure 4), resulting in increased bond strength. Further, statistical analysis revealed no significant decrease in the POTS<sub>dry</sub> (p-value=0.102) and POTS<sub>wet</sub> (p-value=0.237) values with increase in polishing from 220SiC to 1000SiC. However, it was noted that POTS<sub>dry</sub> reduces by 7.0% when the polishing level increase from 220SiC to 1000SiC. Similarly, POTS<sub>wet</sub> reduces by 9% when aggregate is polished with 1000SiC grade powder. Hence, wet conditioning regime is detrimental for bond strength of aggregate-bitumen system particularly for highly polished aggregates. Further, it is interesting that aggregate-bitumen combination with higher wettability has highest POTS values. Similar results, i.e. combinations with higher POTS corresponds to higher wettability was reported by Moya et al. [14].

![Figure 8. POTS of aggregate-bitumen system at varying levels of surface roughness](image)

Further, the effect of polishing levels on bond strength was evaluated using BSR parameter (equation (11)). The BSR of 220SiC polished aggregate and 1000SiC polished aggregate was found to 0.92 and 0.90, indicating higher bonding potential of rough textured aggregates. As discussed, the increased bond strength of rough aggregates is due to several summit and valley in the rough textured aggregates generated after polishing with 220SiC grade abrasive powder compared with polishing after 1000SiC powder (figure 4).
5. Concluding Remarks
The present study was primarily focussed on measuring roughness of aggregate at different polishing levels (i.e. 220SiC and 1000SiC) and estimating its effects on bond strength with bitumen. The bond strength was evaluated using SFE and ABS test approaches. Based on the limited studies, following conclusions were drawn:
1. The polishing of aggregate significantly affects its surface roughness properties. However, no significant difference in roughness was observed while selecting different scales (i.e. R_a or S_a) for measurements.
2. Usually, R_a scale of measurement is suitable for 2D profilometer. However, with advance tools capable of measuring 3-dimensions at a point, measurement of roughness over area using S_a scale seems to be more logical.
3. Contact angle measurement was found to be significantly affected by change in aggregate roughness which indicates changes in the unbalanced forces on the surface of aggregate. The unbalanced forces govern the aggregate surface chemistry which was also found to vary significantly with change in aggregate texture.
4. No significant change in POTS values were observed with change in aggregate roughness. However, the POTS decreases with the increase in aggregate polishing level, which is undesirable for bond strength perspective. Hence, it is advisable to check for excessive polishing of aggregate surface in bituminous pavement.
5. Similarly, bond strength evaluated using ER and BSR parameters was found to higher for rough texture aggregates. This may be due to the presence of valley and peaks in rough textured aggregates as observed in 3D images which improved physical interlocking between aggregate and bitumen.

References
[1] Moraes R, Velasquez R, and Bahia H U 2011. Measuring the effect of moisture on asphalt aggregate bond with the bitumen bond strength test. Transportation Research Record, 2209(1), pp 70-81.
[2] Gubler R, Partl M N, Canestrari F, and Grilli A 2005. Influence of water and temperature on mechanical properties of selected asphalt pavements. Materials and structures, 38(5), pp 523-532.
[3] Van Lent D Q, Molenaar A A A, and Van de Ven M F C 2009. Influence treatment in laboratory on the surface roughness. Journal of Testing and Evaluation, 37(5), pp 417-423.
[4] Singh D, and Mishra V 2018. Different methods of selecting probe liquids to measure the surface energy of asphalt binders. Construction and Building Materials, 175, pp 448-457.
[5] Mishra V, and Singh D 2018. Effects of short term aging on aggregate bitumen compatibility. Advances in Materials and Pavement Performance Prediction (AM3P 2018), April 16-18, 2018, Doha, Qatar (p. 425). CRC Press.
[6] Little D N, Bhasin A, and Hefer A 2006. Using surface energy measurements to select materials for asphalt pavement. NCHRP project 9–37. Transportation Research Board (TRB), Washington, DC, USA.
[7] Kittu A T, Bulut R, and Puckette J 2014. Effects of surface roughness on contact angle measurements on a limestone aggregate. Recent Developments in Evaluation of Pavements and Paving Materials, pp 1-8.
[8] Koc M, and Bulut R 2014. Assessment of a sessile drop device and a new testing approach measuring contact angles on aggregates and asphalt binders. Journal of materials in civil engineering, 26(3), pp 391-398.
[9] Habal A, and Singh D 2018. Influence of recycled asphalt pavement on interfacial energy and bond strength of asphalt binder for different types of aggregates. Transportation Research Record, 2672(28), pp 154-166.

[10] Moraes R, Velasquez R, and Bahia H 2017. Using bond strength and surface energy to estimate moisture resistance of asphalt-aggregate systems. Construction and Building Materials, 130, pp 156-170.

[11] Gadelmawla E S, Koura M M, Maksoud T M A, Elewa I M, and Soliman H H 2002. Roughness parameters. Journal of materials processing Technology, 123(1), pp 133-145.

[12] Van Oss C J, Chaudhury M K, and Good R J 1988. Interfacial lifshitz-van der waals and polar interactions in macroscopic systems. Chemical reviews, 88(6), pp 927-941.

[13] TP 91 AASHTO 2011 Standard method of test for determining asphalt binder bond strength by means of the binder bond strength (BBS) test.

[14] Aguiar-Moya J P, Salazar-Delgado J, Garcia A, Baldi-Sevilla A, Bonilla-Mora V, and Loria-Salazar L G 2017. Effect of ageing on micromechanical properties of bitumen by means of atomic force microscopy. Road Materials and Pavement Design, 18(sup2), pp 203-215.

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