

Microscopic Study of the Interaction between Bitumen Emulsion and Aggregate: Effect of Surfactants

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Abstract: The use of cold-mix asphalt is an effective approach to environmental protection. These materials are intended for low- to medium-traffic roads and have significant potential for secondary road networks in African countries. The objective of this article is to study the influence of surfactant use on the bitumen emulsion-aggregate interaction from a microscopic perspective. Two surfactants (designated A and B) and four types of materials (granite, diorite, limestone, and silica) were studied. The tests performed were: emulsion-aggregate compatibility tests, tests to determine the optimal water content of the mixtures, UV-visible adsorption tests by spectrometry, and tests to assess emulsion bond breakdown upon contact with fine minerals. The results show that the surfactant adsorption differed according to the surfactant-substrate pair considered and adsorption tests performed by UV-visible spectrophotometry revealed that surfactant A adsorbed more readily onto the substrates than surfactant B. This could be due to the charge of the respective hydrophilic heads of the surfactants. Adsorption is stronger with surfactant A because its polar charge is greater than that of surfactant B at pH 2. The emulsion – aggregates rupture was all the more rapid as the SiO₂ content increased in aggregates. At the rheological level, the behavior of the emulsion-filler mixtures was influenced by the surfactant nature and content, the specific surface area of the aggregates and the emulsion-filler mass ratio.

Keywords: bitumen emulsion, surfactants, adhesion, fine minerals, UV spectrometry adsorption

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1. Introduction

The various physico-chemical interactions taking place at the microscopic level between the emulsion and the aggregates will manifest themselves at the macroscopic level of the asphalt mix in terms of emulsion-aggregate compatibility, cohesion of the mixtures and adhesion of the residual binder to the aggregates. The effectiveness of the binder-aggregate adhesion is crucial for the water resistance of new and recycled asphalt mixes. The contribution of surfactants to all these manifestations remains to be elucidated in light of the various phenomena at the interfaces of which they are the main agents [1,2]. Numerous studies [3,4,5,6,7] have been conducted in the scientific community to explain the interactions between emulsions and aggregates, the mechanisms of emulsion breakdown on mineral surfaces, and the adsorption of surfactants onto the substrate.

This research has been carried out primarily at the scale of the emulsion and/or the new substrate, and very often within the equilibrium range of the processes. Few studies have been conducted at the scale of cold mix asphalt,

where the mechanisms are assumed to operate in the non-equilibrium range [8], focusing on the interaction of the emulsion and the reconstituted binder with the new aggregate and with the asphalt pavement in the context of recycling. Therefore, various studies on the reactivity of aggregates with emulsions have been conducted in the scientific community. These studies [9,10] have shown that road aggregates can be classified into two categories according to their reactivity to emulsion and acid attack depending on the presence of certain minerals.

Lesueur et al. [4] studied the reactivity of a wide range of aggregates of different petrographic nature and showed that some aggregates, although having a basic tendency, did not cause a significant rise in pH in acidic solution.

Ziyani et al [11] studied the release kinetics of basic elements from gneiss, diorite and limestone aggregates in aqueous solution and showed that calcium ions were the major compounds responsible for the rise in pH. These authors highlighted the influence of specific surface area on the level of pH rise. Moreover, previous studies [12,13] relating to the mechanisms of rupture of emulsions in contact with the mineral surface have been carried out. These studies have shown that, for the most part, three mechanisms of emulsion breakdown that are supposed to

occur when the emulsion is mixed with the aggregates.

This paper deals with the study of the influence of surfactants in the bitumen emulsion-aggregate interaction from a microscopic point of view. The aim is to better understand the mechanisms at play at the interfaces through observations made at the level of the interaction between aggregates and emulsion.

2. Materials and Methods

2.1. Materials

2.1.1. Granular Materials

Four types of granular materials were tested:

- Granite aggregates of grades 0/4 and 4/10
- Diorite aggregates of grade 0/2, 2/6 and 6/10
- Limestone fillers
- Silica fillers.

The particle size distribution curves of the granite and diorite aggregates are shown in Figure 1 and Figure 2.

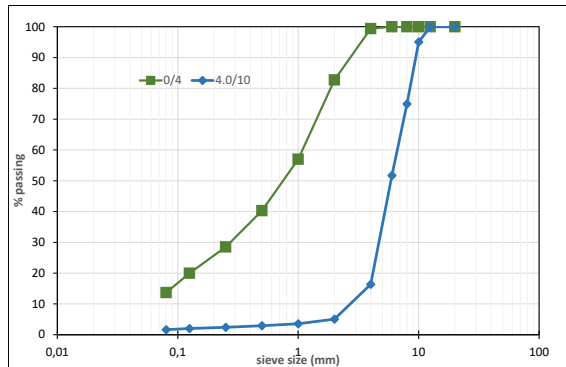


Figure 1. Particle size distribution curves of the different granite fractions

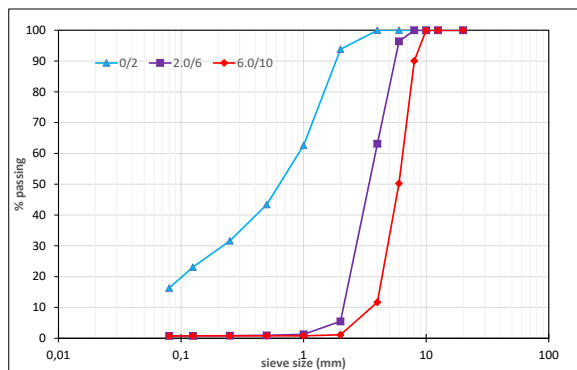


Figure 2. Particle size distribution curves of the different diorite fractions

Table 1 below gives the chemical composition of the four granular materials.

Table 1. Chemical composition of materials used

	Main oxides (%)					
	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	Na ₂ O	SiO ₂
Granite	14.5	1.5	2.1	3.1	8.4	64.3
Diorite	12.6	8.6	14.1	2.1	8.2	44.0
Limestone	1.0	83.2	0.6	0.2	11.7	2.9
Silica	2.3	0.3	0.4	0.1	-	94.8

Physical properties of the granular are given in Table 2.

Table 2. Physical properties of used materials

	Diorite			Granite		Limestone	Silica
	0/2	2/6	6/10	0/4	4/10	63μm	63μm
True density (g/cm ³)	2.90	2.87	2.91	2.75	2.68	-	-
water absorption coefficient (%)	0.30			0.23		-	-
Specific area* (g/cm ²)	12528±575			9475±390		2993±148	474±137

* Realized on fillers for all the aggregates

2.1.2. Bitumen Emulsions

70/100 grade bitumen was used to formulate all the emulsion. Emulsions were manufactured in the laboratory using two cationic surfactant emulsifiers named A and B, by varying the emulsifier content at 0.9, 1.2, 1.5 wt% according to the mass of the bitumen emulsion. The surfactants were mixtures of amines and polyamines in different proportions in A and B. In accordance with the supplier's technical data sheet, B contains a higher proportion of molecules with long hydrocarbon chains than A. In addition, A includes lignin, whereas B is composed of fatty acids.

Tap water was employed to make emulsions and hydrochloric acid (32 %) was added to protonate the aminated bases and to obtain for each aqueous phase a pH of 2.0 ± 0.1 . The emulsions were all slow setting and were named A and B when they contained emulsifiers A and B, respectively. Main characteristics of bitumen emulsion A and B are presented in Table 3.

Table 3. Properties of bitumen emulsion

Emulsifier	A			B		
	0.9%	1.2%	1.5%	0.9%	1.2%	1.5%
Emulsifier content	0.9%	1.2%	1.5%	0.9%	1.2%	1.5%
Binder content (%)	63.7±0.1	65.4±0.0	64.1±0.0	64.9±0.2	64.8±0.0	64.9±0.2
Breaking index	155.1±0.1	157.1±0.1	185.0±0.7	213.6±0.9	228.0±2.9	250.5±1.0
Pseudo-viscosity (s)	37±0	50±1	36±0	38±0	38±1	38±0
Sieve residue (%)	0.02±0.01	0.11±0.05	0.01±0.01	0.04±0.01	0.01±0.01	0.01±0.01
pH	2.1±0.1	2.1±0.1	2.4±0.2	2.6±0.3	2.3±0.2	2.8±0.3

2.2. Tests Methods

2.2.1. Emulsion – aggregates Compatibility Test

The emulsion-aggregate compatibility was evaluated in terms of adhesion of the residual binder on aggregates according to the European standard EN 13614 [14]. The test consisted of mixing 200 g of aggregate (passing through a 10 mm sieve and retained in a 6.3 mm sieve)

with the equivalent of 10 g of bituminous binder from the emulsion. After the complete coating of aggregates and 24 h of curing in an oven at 60°C, these were subjected to the action of water at the same temperature for 20 h. Finally, their surface covered with the residual binder was assessed visually. Due to their covering with aged binder, RAP aggregates do not allow for an estimation of the new binder deposit. Therefore, RAP aggregates were not subjected to this test.

2.2.2. Optimum total Water Content Test

Emulsion-aggregate mixtures were prepared from a total mass of 500 g of dry aggregates, according to the particle size distribution curves shown in Figure 1 and Figure 2. To determine the optimal total water content for each emulsifier concentration (A and B), mixtures containing 5.21% residual binder and 5.21% total mixing water content ranging from 2.9% to 10.7% by weight (relative to the total mass of the mixture) were prepared. The formulation test protocol is based on the European standard EN 12697-55 [15].

2.2.3. UV-visible Spectrophotometry Adsorption Test

To study the adsorption of surfactants on aggregates, the technique used is UV-visible spectrophotometry adsorption test of surfactants on mineral surfaces. For this technique, granite fillers with a diameter of less than 63 µm were used. Adsorption tests were performed using aqueous phases at different concentrations from surfactant solutions A and B prepared at concentrations of 34.6 g/L and 36.3 g/L, respectively. A 10 g quantity of granules was contacted with 100 mL of aqueous phase at different surfactant concentrations in a flask. A solid/liquid mass ratio of 1/10 was adopted in accordance with data found in the literature [16,17]. The minerals fines-aqueous phase contact time was set at 2 hours. This period was selected based on preliminary adsorption tests carried out over durations ranging from one minute to 24 hours. At the end of the contact time, each solution was centrifuged for 10 minutes at 8000 rpm. After recovery, the supernatant fluid was vacuum-filtered using 0.45 µm membrane filters. Finally, the quantity of surfactants present in the supernatant was determined using UV-visible spectrophotometry (Figure 3).



Figure 3. UV-visible spectrophotometer used for adsorption test

2.2.4. Emulsion Rupture Test Upon Contact with Fine Minerals

The phenomenon of emulsion rupture upon contact with aggregates was observed from several perspectives. The influences of parameters such as petrographic nature, emulsion temperature, and the effect of adding sodium hydroxide to the emulsion were studied by performing the conventional cationic emulsion rupture index test according to a procedure adapted from European standard [15,18].

To investigate the influence of petrographic composition, three types of fine minerals were used: silica, granite, and limestone. The 0/4 granite fractions were sieved to extract particles according to the following grain size classes: $D < 63 \mu\text{m}$, $63 \mu\text{m} < D < 125 \mu\text{m}$, $125 \mu\text{m} < D < 250 \mu\text{m}$, and $250 \mu\text{m} < D < 500 \mu\text{m}$, where D is the diameter of the largest grain. The limestone particles were smaller than 63 µm, while the silica particles were divided into two classes ($D < 63 \mu\text{m}$ and $63 \mu\text{m} < D < 125 \mu\text{m}$).

To study the effect of temperature, only silica fillers, conventional materials in the fracture index test [15], were used. The test consisted of heating 100 g of emulsion in a capsule to the desired temperature using a thermostatically controlled bath, and then gradually adding the fillers until the emulsion broke, which was indicated by the formation of a firm paste. The capsule remained in the thermostatically controlled bath throughout the test. The tests were performed three times consecutively for repeatability, and three temperatures were considered: 25, 40, and 60°C.

To study the influence of sodium hydroxide addition on the emulsion-granule interaction, alkaline aqueous phases were prepared by dissolving sodium hydroxide crystals in deionized water at concentrations ranging from 0.2 to 1 mol/L. The protocol consisted of introducing approximately 20 mL of sodium hydroxide solution, at a given concentration, into 100 g of emulsion. After homogenization with a spatula for approximately 30 seconds, the fracture test was performed by adding silica fillers. The rupture index (RI) was calculated using the following formula:

$$RI = \frac{m_f}{m_e + m_s} * 100 \quad (1)$$

where m_f is the mass of fines added in grams, m_e is the mass of emulsion in grams, m_s is the mass of sodium hydroxide solution added in grams.

3. Results and Discussion

3.1. Emulsion-aggregates Compatibility

The results of the emulsion-aggregates compatibility are presented in Figure 4. The results show that granite aggregates exhibit poor binder coverage with surfactant A, while adhesion is excellent with surfactant B. The good affinity of the emulsions prepared with B for the aggregates seems to be due to the lipophilic nature of this surfactant. This is linked to the length of its hydrocarbon chain, which is greater than that of surfactant A. Indeed, a long carbon chain implies a greater affinity for oil than for

water [19,20]. The adsorption of this surfactant onto the substrates leads to better binder-aggregate adhesion [21]. Consequently, the final adhesion of the residual binder remains largely dependent on that of the emulsion, which is generally good for a classic cationic emulsion. It is also strongly influenced by the emulsion-aggregate affinity, itself correlated with the presence of the emulsifier.

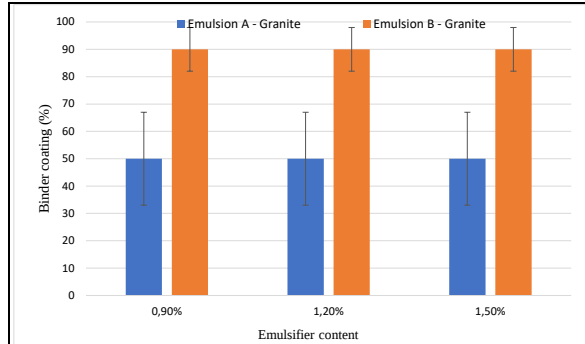


Figure 4. Binder Coating levels of granite aggregates by the residual emulsion binder

3.2. Optimal Total Water Content of Mixtures

Based on consistency tests on emulsion-aggregate mixtures, the optimal total water contents for the respective residual binder contents of 5.21 and 4.76 wt% are shown in Figure 5. A decrease in the optimal total water contents is observed with the increase in surfactant content. This can be explained by the phenomenon of surfactant adsorption on minerals, which tends to make their surface more hydrophobic with the increase in surfactant concentration and thus favor their wetting by the bitumen droplets from the emulsion [10]. Likewise, a difference in the optimum total water content can be noted, depending on the nature of the emulsifier used to manufacture the emulsion. This discrepancy can be explained by the relationship between each surfactant and water. The hydrophilic character of emulsifier A is favorable for the presence of water on the surface of the aggregate. Emulsifier B drives out water more effectively from the aggregate interface, which tends to rewet the mixture. Therefore, less water is required to achieve the optimum formulation conditions, consistency and cohesion.

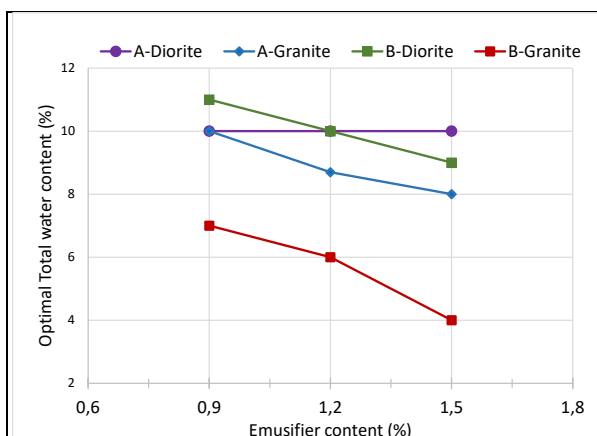


Figure 5. Variation in the optimal total water content of emulsion-aggregate mixtures versus emulsifier content

3.3. Evaluation of Surfactant Adsorption on Substrates by UV-visible Spectrophotometry

Absorbance measurements on samples of the aqueous phases, at different initial concentrations (calibration of the aqueous phases of surfactants A and B at pH 2) and after contact with the aggregates, allow the final concentrations to be determined. The adsorbed quantities are then calculated by subtracting the final concentrations of the samples from the initial concentrations. Figure 6, Figure 7 and Figure 8 respectively show the adsorption isotherms of surfactants A and B on diorite, granite and silica.

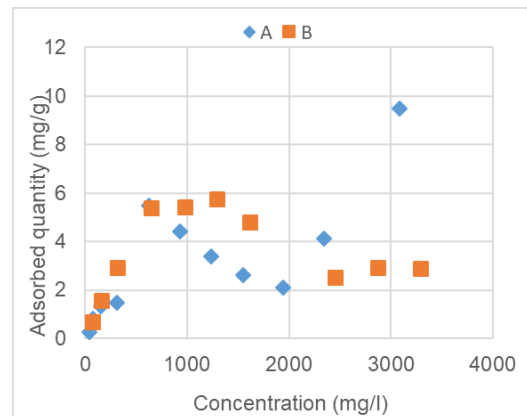


Figure 6. Adsorption isotherms by measuring the absorbance of surfactants A and B on diorite

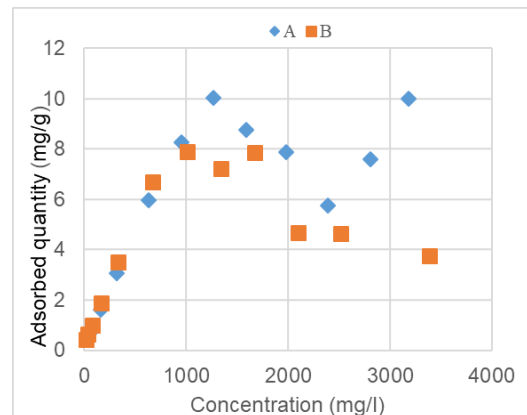


Figure 7. Adsorption isotherms by measuring the absorbance of surfactants A and B on granite

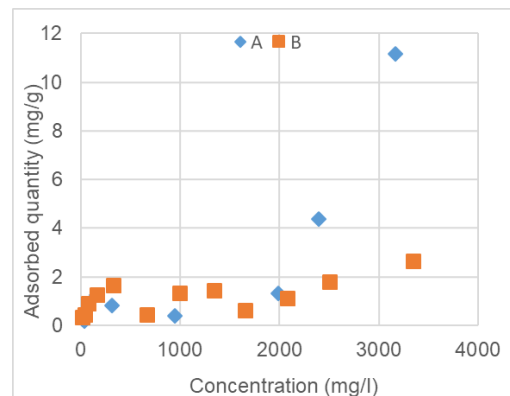


Figure 8. Adsorption isotherms by measuring the absorbance of surfactants A and B on silica

Figure 6, Figure 7, and Figure 8 show that the two surfactants adsorb differently depending on the nature of the aggregate. From the point of view of the nature of the surfactants, the quantities adsorbed at low concentrations (< 200 mg/l) are identical. At high concentrations (> 200 mg/L), surfactant A adsorbs more than surfactant B, regardless of the aggregate type. These figures also indicate that the amount adsorbed is greater with diorite (adsorption values are greater than 8 mg/g), and that adsorbed with granite (values are greater than 4 mg/g) is greater than with silica (adsorption values are less than 4 mg/g). These differences in adsorption quantities can be explained by the specific surface area of the aggregates (see Table 2). Indeed, the order of increase in specific surface area follows the same direction as that of the amount adsorbed. This result is in agreement with those reported by Tanhei et al. [22] and Zaman et al. [23]. The larger the specific surface area, the greater the amount adsorbed.

3.4. Emulsion Rupture upon Contact with Fine Minerals

The results from the emulsion rupture upon contact with fine minerals were presented from several perspectives such as petrographic nature of the aggregates, emulsion temperature, and the effect of adding sodium hydroxide to the emulsion.

3.4.1. influence of the Petrographic Nature of Fine Minerals on the Emulsion Rupture Index

Figure 9 shows the emulsion rupture index vs petrographic nature of fines minerals.

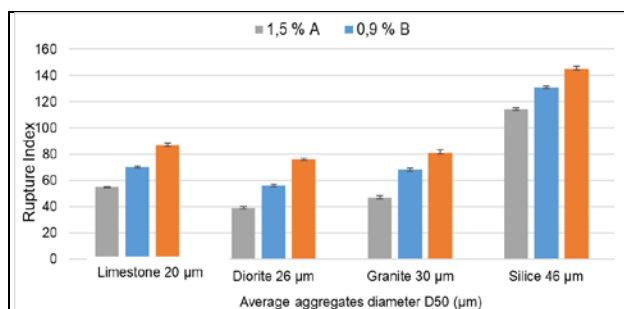


Figure 9. Rupture index vs petrographic nature of the aggregates

The results show that for a given type of aggregates, the emulsion breaks down faster with emulsifier A than with emulsifier B. This trend can be explained by the chemical composition of each surfactant: A is the one that has a hydrophilic head with high polarity (larger than that of B), and the greater the polarity of the hydrophilic head, the less the surfactant forms micelles, as indicated by previous work [20]. Therefore, the emulsifier A has more free molecules in the emulsion than in the case of emulsifier B. In addition, the results show that for the same type of emulsifier, the breakdown of the emulsion is slower when the emulsifier content increases. This finding, consistent with previous work, would be due to the effect, on the one hand, of the increase in electrostatic repulsions and, on the other hand, of the formation of the double layer of surfactants on the surface of the aggregates which delays the rupture of the emulsion [10,24].

3.4.2. Influence of Temperature on the Rupture of the Emulsion upon Contact with Fines Particles

The effect of emulsion temperature on rupture was evaluated.

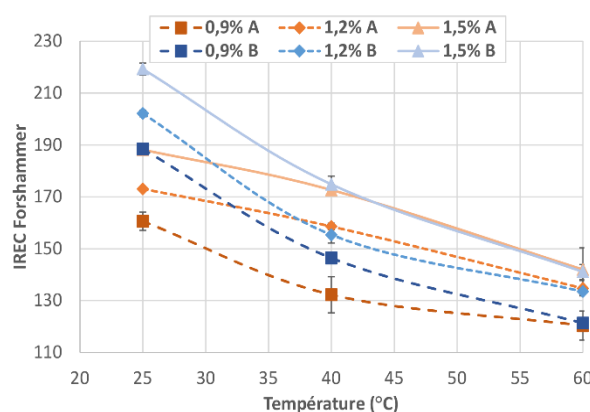


Figure 10. Variation of the rupture index vs the emulsion temperature

The results illustrated in Figure 10 show a decrease in the rupture index with increasing emulsion temperature. This decrease is independent of the emulsifier content. With increasing temperature, the effect of the nature of the emulsifier on rupture decreases; this rupture is a function only of the emulsion content. At 60 °C, with identical emulsifier content, the rupture index is practically the same for both surfactants (A and B). Temperature lowers the surface tension of the droplets as well as the interfacial barriers, which accelerates flocculation and hetero-flocculation. Similar results were reported by Hempoonsert et al. [25] and Khelifa et al. [26] in their work on the effect of temperature on the stabilization of oil droplets by mineral fines.

3.4.3. Influence of Adding Sodium Hydroxide on the Rupture of the Emulsion upon Contact with Fine Particles

The influence of adding a destabilizing agent on emulsion failure upon contact with the mineral was evaluated by adding a sodium hydroxide solution at different concentrations (0 to 1 mol/L) to the emulsion before contact with the siliceous fines. The test results are presented in Figure 11 below.

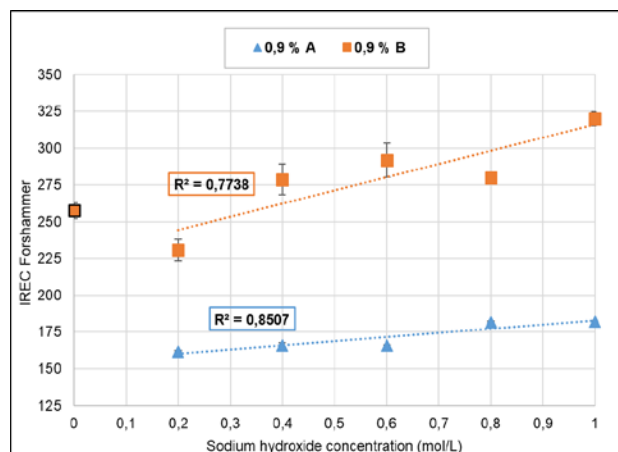


Figure 11. Variation of the breaking strength index vs the amount of sodium hydroxide added

The test was conducted on emulsions A and B at identical concentrations. In both cases, an increase in the breakdown index was observed with increasing sodium hydroxide concentration. This result appears to contradict the work of [27], who showed that breakdown should be faster with the addition of sodium hydroxide. The increase in the breakdown index was smaller for emulsifier A (IREC ranging from 161 to 182) than for emulsifier B (IREC ranging from 230 to 320) when increasing the sodium hydroxide concentration from 0.2 to 1 mol/L. This increase in the mass of fines required to reach fracture, as the amount of sodium hydroxide added increases, can be explained by the reduction in the SiO₂ surface area of the minerals. Indeed, the addition of sodium hydroxide leads to a progressive increase in the pH of the emulsion, from 2.8 to approximately 11 with the addition of a 0.2 mol/L solution, and to approximately 13 with 1 mol/L sodium hydroxide. In a basic medium, silica dissolves via an alkali-silica reaction [28]. The increase in sodium hydroxide concentration causes an increase in the surface area attacked, thus reducing the contact area of the SiO₂ with the emulsion, thereby requiring a greater amount of silica minerals for fracture.

4. Conclusion

Studies carried out to understand the mechanisms of emulsion-substrate interaction have made it possible to address many aspects by taking into account different parameters relating to the nature and content of surfactants and the petrographic nature of aggregates, through several experimental techniques. Adsorption tests performed using UV-visible spectrophotometry revealed that surfactant A was more readily adsorbed onto substrates than surfactant B. This may be due to the charge of the respective hydrophilic heads of the surfactants. Adsorption is stronger with surfactant A because its polar charge is higher than that of surfactant B in the pH 2 range. The emulsion-substrate interaction was studied through the phenomenon of rupture. The results on the rupture of emulsions in contact with different types of fillers are consistent with those obtained in previous work, particularly regarding the correlation between specific surface area and rupture index. Furthermore, this study highlighted the effect of temperature on the rupture mechanism. Increasing the temperature accelerates emulsion rupture.

References

- [1] J. E. Poirier, X. Carboneau, et J. P. Henrat, «les enrobes a froid : des materiaux evolutifs - etude du murissement et de son impact sur les caracteristiques du liant residuel», *revue generale des routes (rgra)*, n° 805, avr. 2002.
- [2] J.-p. Serfass, x. Carboneau, f. Delfosse, et j.-p. Triquigneaux, «enrobés a l'émulsion (2e partie) : comportement et évaluation de graves-émulsion», *rev. Gén. Routes*, n° 889, p. 69-75, 96 [8 p.], 2010.
- [3] B. ECKMANN *et al.*, «Technologies à froid. Les enseignements du projet OPTTEL», *Rev. gén. routes aérod.*, n° 792, p. 68-77, 2001.
- [4] d. Lesueur, f. Delfosse, s. Le bec, b. Duchesne, et c. Such, «étude des interactions emulsion/granulats a l'aide du diasom et du cohesimetre benedict», *revue generale des routes (rgra)*, n° 799, oct. 2001.
- [5] j. J. Potti *et al.*, «slow setting cationic bituminous emulsions for construction and maintenance of roads (optel)», présenté à proceedings of the papers submitted for review at 2nd euraspalt and eurobitume congress, held 20-22 september 2000, barcelona, spain. Book 2 - session 2, 2000.
- [6] j. J. Potti, d. Lesueur, et b. Eckmann, «vers une methode rationnelle de formulation des enrobes a froid : les apports du projet optel», *revue generale des routes (rgra)*, n° 805, avr. 2002.
- [7] k. Van nieuwenhuyze, t. Tanghe, p. Verlhac, et b. Eckmann, «comprehension des proprietes de l'emulsion a partir des caracteristiques du liant et de l'emulsifiant», *revue generale des routes (rgra)*, n° 793, mars 2001.
- [8] c. Deneuilliers et j. E. Poirier, «enrobes a froid : caracterisation et maitrise de la qualite de l'enrobage», *revue generale des routes (rgra)*, n° 803, févr. 2002.
- [9] J.-M. Cases, «Adsorption des tensio-actifs à l'interface solide-liquide : thermodynamique et influence de l'hétérogénéité des adsorbants», 1979.
- [10] R. A. Mercado, V. Sadtler, P. Marchal, L. Choplin, et J. L. Salager, «Heteroflocculation of a Cationic Oil-in-Water Emulsion Resulting from Fontainebleau's Sandstone Powder Addition as a Model for Asphalt Emulsion Breakup», *Ind. Eng. Chem. Res.*, vol. 51, n° 36, p. 11688-11694, sept. 2012.
- [11] L. Ziyani, V. Gaudefroy, V. Ferber, et F. Hammoum, «A predictive and experimental method to assess bitumen emulsion wetting on mineral substrates», *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 489, p. 322-335, janv. 2016.
- [12] T. P. Goloub et L. K. Koopal, «Adsorption of Cationic Surfactants on Silica. Comparison of Experiment and Theory», *Langmuir*, vol. 13, n° 4, p. 673-681, févr. 1997.
- [13] J. Philip, L. Bonakdar, P. Poulin, J. Bibette, et F. Leal-Calderon, «Viscous Sintering Phenomena in Liquid-Liquid Dispersions», *Phys. Rev. Lett.*, vol. 84, n° 9, p. 2018-2021, févr. 2000.
- [14] NF EN 13614. Bitumes et liants bitumineux - Détermination de l'adhésivité des émulsions de bitume par l'essai d'immersion dans l'eau, Collection AFNOR, 2014.
- [15] NF EN 12697-55. Mélanges bitumineux - Méthodes d'essai pour mélange hydrocarboné à chaud - Partie 1 : teneur en liant soluble, Collection AFNOR, 2020.
- [16] A. Fan, P. Somasundaran, et N. J. Turro, «Adsorption of Alkyltrimethylammonium Bromides on Negatively Charged Alumina», *Langmuir*, vol. 13, n° 3, p. 506-510, févr. 1997.
- [17] S. Alila, S. Boufi, M. N. Belgacem, et D. Beneventi, «Adsorption of a Cationic Surfactant onto Cellulosic Fibers I. Surface Charge Effects | *Langmuir*», *Langmuir*, vol. 21, n° 18, p. 8106-8113, juill. 2005.
- [18] Y. Gao, J. Du, et T. Gu, «Hemimicelle formation of cationic surfactants at the silica gel-water interface - Journal of the Chemical Society, Faraday Transactions 1: Physical Chemistry in Condensed Phases (RSC Publishing)», *J. Chem. Soc., Faraday Trans. 1*, vol. 83, n° 8, p. 2671-2679.
- [19] Y. Meng, J. Ouyang, et J. Ou, «Investigation on the wetting behavior of asphalt emulsion on aggregate for asphalt emulsion mixture», *Construction and Building Materials*, vol. 400, p. 132844, oct. 2023.
- [20] j.-l. Salager, *surfactants in aqueous solution*. In firp booklet # e201-a. Escuela de ingenieria quimica, 1993.
- [21] S. Ignatavicius, A. Kavanagh, M. J. Brennan, D. Collieran, J. Sheahan, et S. Newell, «Experimental investigation of optimum adhesion properties for anionic emulsions in road maintenance applications», *Construction and Building Materials*, vol. 304, p. 124678, oct. 2021.
- [22] B. Tanhaei, N. Saghatoleslami, M. P. Chenar, A. Ayati, M. Hesampour, et M. Mänttari, «Experimental Study of CMC Evaluation in Single and Mixed Surfactant Systems, Using the UV-Vis Spectroscopic Method», *J Surfact Deterg*, vol. 16, n° 3, p. 357-362, mai 2013.
- [23] A. C. Zaman, F. Kaya, et C. Kaya, «A study on optimum surfactant to multiwalled carbon nanotube ratio in alcoholic stable suspensions via UV-Vis absorption spectroscopy and zeta potential analysis», *Ceramics International*, vol. 46, n° 18, Part A, p. 29120-29129, déc. 2020.
- [24] A. Khan, P. Redelius, et N. Kringos, «Effects of surfactants and adhesion promoters on the bitumen-minerals interfacial bond during breaking of bitumen emulsions», 2018, Consulté le: 6

novembre 2025. [En ligne]. Disponible sur: [https:// urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-223444](https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-223444).

- [25] J. Hempoonsert, B. Tansel, et S. Laha, «Effect of temperature and pH on droplet aggregation and phase separation characteristics of flocs formed in oil–water emulsions after coagulation», *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 353, n° 1, p. 37-42, janv. 2010.
- [26] A. Khelifa, P. Stoffyn-Egli, P. S. Hill, et K. Lee, «Characteristics of Oil Droplets Stabilized by Mineral Particles: Effects of Oil Type and Temperature», *Spill Science & Technology Bulletin*, vol. 8, n° 1, p. 19-30, févr. 2002.
- [27] L. Boucard, «Déstabilisation des émulsions de bitume et évaluation du comportement à l'interface huile/eau», thesis, Nantes, 2016.
- [28] S. Poyet *et al.*, «Modélisation chimique de la réaction alcali-silice: prise en compte de l'influence de la distribution granulaire réactive», *Revue Française de Génie Civil*, vol. 8, n° 8, p. 905-929, nov. 2004.



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