Debonding location in asphalt concrete associated with moisture damage

Elhussein H. Mohamed

Publisher's version / Version de l'éditeur:
https://doi.org/10.1061/(ASCE)0899-1561(1993)5:4(497)
Journal of Materials in Civil Engineering, 5, 4, pp. 497-509, 1993-11-01

NRC·CNRC Institute for Research in Construction

CNRC·NRC Institut de recherche en construction

http://www.nrc-cnrc.gc.ca/irc

Debonding location in asphalt concrete associated with moisture damage

NRCC-35171

Elhussein H. Mohamed

November 1993

A version of this document is published in / Une version de ce document se trouve dans:
Journal of Materials in Civil Engineering, 5, (4), pp. 497-509, November- 1, 1993, DOI: 10.1061/(ASCE)0899-1561(1993)5:4(497)

National Research Council Canada · Conseil national de recherches Canada

Canada

Debonding Location in Asphalt Concrete Associated with Moisture Damage

By El Hussein H. Mohamed[1]

Abstract: Current adhesion theories fail to explain completely the stripping phenomenon. Quantification of stripping potential prior to mix design, and based on variables described in current adhesion theories, remains difficult. Current laboratory evaluation procedures are not completely reliable and fail to predict, with accuracy, the stripping susceptibility of various asphalt concrete mixes. This paper evaluates the existing adhesion theories and stripping mechanisms suggested in the literature. Factors contributing to the lack of success in predicting stripping susceptibility of asphalt concrete in the laboratory are also discussed. An earlier comprehensive investigation of the stripping phenomenon revealed serious deficiencies in the current approach to the problem. First, the interaction between the different components of the asphalt-concrete mixture under a wide temperature range is neglected. It is proven that differential thermal contraction, as a result of the large difference in the coefficients of thermal contraction, is an important factor. This paper addresses another deficiency, which is the lack of a precise description of the location where debonding associated with moisture occurs. Observations made during the experimental investigation revealed that initial separation in the compacted mix takes place between the asphalt matrix (mix of asphalt cement and fine material) and coated aggregate particles.

INTRODUCTION

The presence of moisture in asphalt concrete is known to cause debonding of the aggregate and asphalt cement in asphalt concrete mixes. Debonding (stripping) is defined in the literature as the physical separation of asphalt cement and aggregate produced by adhesion failure (Majiidzadeh et al. 1968; Lottman et al. 1971). Debonding, as described in the literature, may be understood as the separation between the thin bituminous film, formed during the mixing stage at elevated temperatures, and the aggregate particle. Based on the current definition of the stripping phenomenon, researchers have adopted adhesion theories that describe the bond between asphalt cement and mineral aggregates (Thelen 1958; Peterson et al. 1982; Mack 1957). A number of stripping mechanisms have been suggested to describe the effect that moisture has on the asphalt/aggregate bond ("Bituminous" 1962; Scott 1978; Fromm 1974; Nicholas et al. 1954). Regardless of these findings, quantification of stripping potential prior to the mix-design stage, based on the variables described by the adhesion theories, remains difficult. Laboratory test methods used after the mix-design state are unreliable and fail to predict stripping susceptibility. This paper discusses deficiencies in the current approach, which lead to difficulties in evaluating the stripping susceptibility of asphalt concrete. A major deficiency revealed during the experimental program, part of a comprehensive study investigating stripping (El Hussein 1991), has been the lack of a precise description of the location of debonding associated with stripping.

---

[1]Nat. Res. Council of Canada, Ottawa, Ontario, Canada KlA 0R6.

Note. Discussion open until April 1, 1994. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on March 3, 1992. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 5, No. 4, November, 1993. ©ASCE, ISSN 0899-1561/93/0004-0497/$1.00 + $.15 per page. Paper No. 3594.

PROBLEM

There is general agreement among researchers that existing adhesion theories do not completely explain the stripping phenomenon (Haas et al. 1984; Yoon et al. 1988; El Hussein et al. 1990, 1991). Engineers have not been able to quantify stripping potential prior to the mix-design stage or to predict stripping susceptibility of a prepared mix in the laboratory. Solutions to the problem suggested in the literature include the use of antistrip additives. It is not well known how these additives work or what is their long-term effect on the durability of pavements. Reducing the air voids percentage in the compacted mixture has been suggested as another solution based on known stripping mechanisms. Low air voids failed to limit water circulation inside the pavement (Haas et al. 1984). Moisture-associated damage remains a serious and complex problem with serious economical consequences. There is no widely acceptable and effective solution to the stripping problem.

EVALUATION OF CURRENT ADHESION THEORIES

Based on the current problem definition, debonding takes place between asphalt cement and aggregate due to adhesion failure. This types of debonding may result in changes from the initial condition represented by the idealized asphalt-aggregate system shown in Fig. 1(*a*), to the state represented by Fig. 1(*b*). A great deal of basic and applied research has been conducted over the years to determine the mechanism of stripping. Many stripping mechanisms have been suggested, all of which are based on adhesion failure at the asphalt-aggregate interface caused by water replacing the asphalt film ("Bituminous" 1962; Scott 1978; Fromm 1974; Nicholas et al. 1954). Since all mechanisms are directly or indirectly related to adhesion failure, known adhesion theories will be discussed first. The theories of adhesion cited in literature are mechanical, chemical reaction, molecular attraction, and interfacial energy theory (Thelen 1958; Mach 1957; Peterson et al. 1982). Since the stripping definition specified the asphalt-aggregate interface as the location where debonding occurs, adopted adhesion theories have been used to describe the expected performance of the bond between asphalt cement and mineral aggregate in the presence of moisture.

Laboratory investigations aimed at relating some measurable aggregate and asphalt properties to stripping concluded that a chemical reaction between the components of asphalt cement and aggregate takes place (Stuart 1986). Peterson (1982) suggested a possible reaction between the various chemical functional group types in asphalt cement and aggregate. Mechanical interlock occurs and energy relationships influence the adhesion between asphalt cement and aggregate (Haas 1989). It appears that all the foregoing concepts must be considered together in order to explain the behavioral aspects of a binder aggregate system. However, in spite of the validity of the adhesion theories, quantification of stripping potential prior to the mix-design stage considering variables described in these theories, remains difficult. Researchers and pavement engineers have not always been successful in selecting a mix with high resistance to stripping. Although the chemical reaction theory considers nonacidic aggregate surfaces to promote adhesion with asphalt that is acidic in nature, there are areas where stripping was experienced with limestone aggregate (Haas 1984). Limestone aggregate is not supposed to strip because of its basic nature. Few stripping problems were observed in some areas where granite was used, but not in all cases.

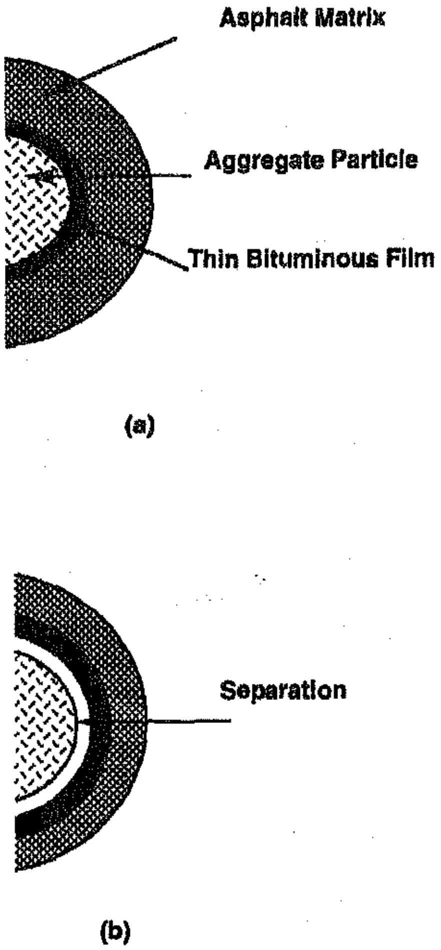


FIG. 1. Idealized Asphalt-Concrete System: (a) Initial Condition; and (b) Separation between Asphalt Cement and Aggregate

Granite, which is acidic in nature, is supposed to strip and not adhere well, as it did in some locations. The variables involved in the interfacial energy theory are difficult to determine experimentally, and, therefore, the theory is not practical to use in material quantification or mix evaluation for stripping susceptibility. However, Yoon and Tarrer (1988) investigated both interfacial energy and mechanical interlock theories. Surface roughness was used to estimate the degree of mechanical interlock. Pore volume and aggregate surface areas were used to scale the interfacial contact. The test results showed no correlation between these physical properties and stripping propensity.

It appears that all of the foregoing concepts cannot by themselves provide a full or definite explanation of the stripping phenomenon, and it is clear that not all the factors governing bond between the asphalt concrete components are known (El Hussein 1991). The fact that quantification of the stripping potential is not yet possible and that no widely accepted moisture conditioning and testing procedure for the prediction of stripping susceptibility exists, makes it clear that additional explanations of the stripping phenomenon are needed.

EVALUATION OF CURRENT LABORATORY STRIPPING PREDICTON METHODS

Many laboratory prediction methods have been suggested, but the indirect tensile strength test, following warm-water soaking (60° C), has gained wide acceptance. Warm-water soaking has been used because past experience indicated that it forces the removal of the thin bituminous film from the surface of aggregate particles while in a loose form or in a compacted mixture. Research work leading to the development of warm-water soaking for moisture conditioning has not linked temperature effects to current adhesion theories or stripping mechanisms. Another deficiency in the current laboratory prediction methods has been the use of laboratory-prepared samples ignoring the influence field compaction may have on the mixture's resistance to stripping. Faults associated with field compaction, such as surface cracks (checks) and aggregate segregation, influence the mix resistance to stripping (El Hussein et al. 1992). The influence of these factors has not been considered in the current laboratory test procedures. Clearly, inability to include most of the factors contributing to the problem during the conditioning stage led to great difficulties in attempting to predict stripping potential in the laboratory. Using these methods in the past resulted in poor correlation between laboratory prediction and field performance. Observations made in the laboratory during the experimental program, part of the aforementioned comprehensive study on stripping (El Hussein 1991), revealed that the most significant deficiency in the current approach is the lack of a precise description of debonding location. Graf (1986) reported similar observations, as will be discussed later.

EXPERIMENTAL INVESTIGATION

The original experimental program was primarily designed to investigate a new mechanistic model that recognizes the problem of thermal incompatibility between the asphalt cement and mineral aggregates (El Hussein 1992). It was hypothesized that differential thermal contraction of the asphalt matrix will influence the strength of the bond between the matrix and aggregate particles. Test results verified the validity of the analytical model and indicated that the response of the asphalt-aggregate system to temperature change significantly influences the mix resistance to stripping.

The current approach to the moisture damage problem is shown in Fig. 2(*a*). The water damage triangle considers: (1) Material susceptibility to stripping; (2) the presence of water; and (3) stress (traffic). There is no indication in the literature to the effect of temperature changes on the strength of the asphalt-aggregate bond. Any drop in the bond strength has been related to other variables assumed to control adhesion. A single conditioning temperature has been adopted that may not be representative of conditions in different regions worldwide. However, the approach adopted in this investigation follows that of an earlier study by El Hussein et al. (1991), and shown in Fig. 2(*b*). The approach considers temperature as an additional factor affecting the strength of the adhesive bond.

Cores from three field-compacted sections were used to study the influence of temperature changes on bond performance. Road sections were constructed on the campus of the National Research Council of Canada

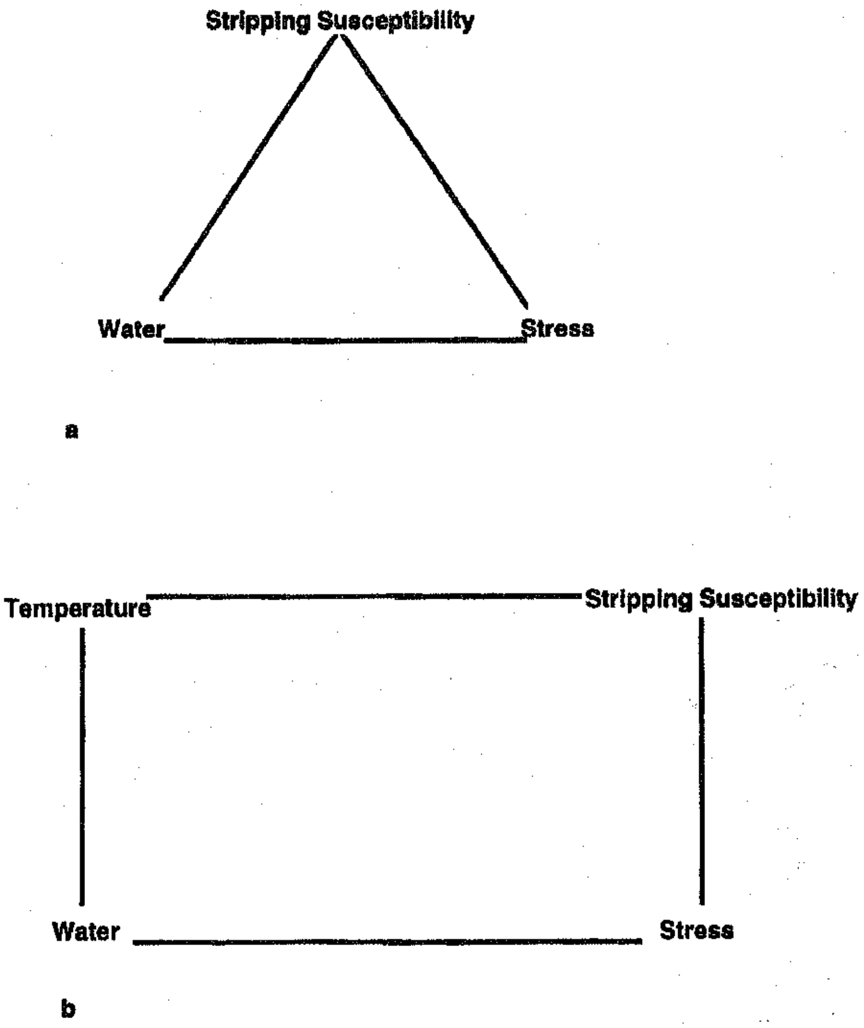


FIG. 2. Factors Considered in Moisture Damage Analysis: (*a*) Current Approach; and (*b*) New Approach

(NRC) (trials 1 and 2), and the third site was constructed in the city of Toronto. Cores recovered from these sites were exposed to a wide range of moisture and temperature conditions for a two-day period. Cores were saturated using a 35-cm vacuum pressure. Water bath temperatures used included −29°, 2°, 18°, 43°, and the conventional 60° C. After soaking at the specified temperature, cores were moved to a water bath at room temperature for a two-hour period prior to indirect tensile strength test. All indirect tensile strength tests were performed at 24° C and the loading rate was 50 mm/min.

TEST RESULTS AND LABORATORY OBSERVATIONS

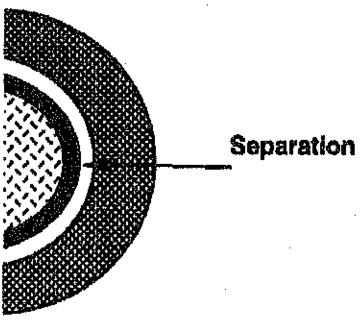
The loading configuration used in the indirect tensile strength test develops a relatively uniform tensile stress perpendicular to the direction of

TABLE 1. Indirect Tensile Strength Test Results (Two-Day Exposure—Tested at 24° C) (NRC Field Trial 1)

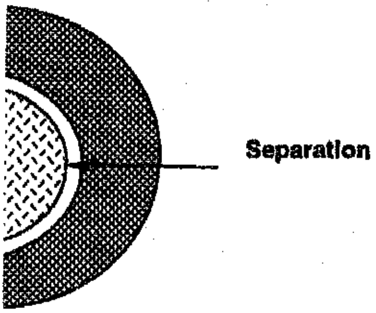
Water bath temperature (° C) (1)	Bulk specific gravity (2)	Permeable voids (%) (3)	Indirect tensile strength (kPa) (4)	Average strength (kPa) (5)
−29	2.380	3–4	649	649
−29	2.401	2–3	584	649
−29	2.414	2–3	715	649
2	2.383	4–5	583	641
2	2.399	4–5	698	641
2	2.412	3–4	644	641
18	2.418	2–3	658	636
18	2.381	3–4	583	636
18	2.396	2–3	668	636
43	2.394	3–4	579	561
43	2.395	2–3	609	561
43	2.404	2–3	495	561
60	2.383	4–5	253	373
60	2.412	2–3	443	373
60	2.400	2–3	424	373
Control Group—Tested Dry				
Not available	2.389	4–5	590	642
Not available	2.395	2–3	659	642
Not available	2.407	2–3	676	642

the applied load and along the vertical diametral plane. Ultimately the specimen fails by splitting along the vertical diameter. Indirect tensile strength test results for NRC trial 1 are given in Table 1. Detailed analysis of these results are given by El Hussein (1991). Visual observations made on the failure surface of cores from NRC field trial 1 related to debonding location are listed as follows:

1. Soaking at relatively low temperatures (lower than 24° C) led to debonding between the asphalt matrix (i.e., mixture of asphalt cement, sand, and other fine materials used as fill) and coated large aggregate particles due to adhesion failure. The aggregate particles retained the thin bituminous film acquired during the mixing stage at elevated temperatures (higher than 150° C). Exposed surfaces were covered with moisture when inspected immediately after failure. Well-identifiable aggregate prints were left on the asphalt matrix, indicating debonding at the interface and not tearing of the matrix. This type of separation is shown by the idealized asphalt concrete system shown in Fig. 3(*a*).
2. Conditioning at mild temperatures did not result in the loss of the thin bituminous film around the aggregate particles even after extended exposure durations, i.e., the separation after failure was not followed by completely bare aggregate particles.
3. Exposure to elevated soaking temperatures for different soaking durations led to one of the following types of separation:



(a)



(b)

FIG. 3. Idealized Asphalt-Concrete System: (*a*) General Case; and (*b*) Structural Changes

- Separation of the asphalt matrix from the coated aggregate particle surface similar to the condition shown by Fig. 3(*a*). No discoloring was observed on the asphalt matrix or the thin bituminous film covering the aggregate.
- Separation between the asphalt matrix and the aggregate particle. In this case part of the aggregate particle was left bare, i.e., without the thin bituminous cover. The degree of the thin bituminous film removal, estimated by the area of exposed aggregate surfaces, depended on conditioning and exposure duraton. Extreme conditions were accompanied by discoloring of the asphalt mixture indicating a high degree of oxidation. Oil spots were observed on the surface of the water bath. This type of separation, i.e., complete or partial disappearance of the bituminous cover, resembles the description offered by the current problem definition. Fig. 3(*b*) shows the idealized failure surface following high-temperature conditioning.

A number of cores from the Toronto field trial were exposed to the same soaking temperatures for a two-day duration. This mixture experienced separation between the asphalt matrix and the coated aggregate. Even after exposure to 60° C soaking temperature for two days, the aggregate particles continued to retain their thin bituminous film. The Toronto mixture has better initial coverage as a result of uniform aggregate distribution within the mix. This condition was a direct result of avoiding vibration during compaction, which limited aggregate segregation. Detailed discussion of these results is given by El Hussein (1991). Test results are given in Table 2.

Cores from NRC field trial 2 were also exposed to a wide range of soaking temperatures for a two-day period. Only cores exposed to 60° C suffered partial loss of the thin bituminous cover. A limited number of aggregate particles exposed at the failure surface, had partially removed film. In other locations, coated aggregate particles separated neatly from the asphalt matrix as indicated by aggregate prints on the failure surface. All groups exposed to lower temperatures showed separation between the asphalt matrix and coated aggregate particles. In spite of the temperature difference between the 60° C and 30° C groups, the observed loss of adhesion was approximately the same in both groups, which was supported by the results of the indirect tensile strength test shown in Table 3. No discoloring was observed in cores from NRC field trial 2 after all exposure conditions. The asphalt material retained its sheen after conditioning. Compaction during low air temperature, below freezing, affected the performance of cores from the Ottawa field trial 2 as indicated by the high decrease in strength at 30° C and by the little change in strength after exposure to 43° C.

TABLE 2. Indirect Tensile Strength Results (Two-Day Exposure—Tested at 24° C) (Toronto Field Trial)

Water bath temperature (° C) (1)	Bulk specific gravity (2)	Permeable voids (%) (3)	Indirect tensile strength (kPa) (4)	Average strength (kPa) (5)
−29	2.373	3–4	581	572
−29	2.350	4–5	595	572
−29	2.337	4–5	539	572
2	2.367	4–5	626	577
2	2.354	4–5	570	577
2	2.337	4–5	535	577
18	2.365	4–5	567	594
18	2.342	4–5	575	594
18	2.343	4–5	639	594
43	2.382	4–5	640	582
43	2.361	4–5	559	582
43	2.291	6–7	546	582
60	2.366	4–5	463	451
60	2.348	4–5	408	451
60	2.341	4–5	481	451
Control Group—Tested Dry				
Not available	2.187	—	—	576
Not available	2.363	—	607	576
Not available	2.240	—	545	576

TABLE 3. Indirect Tensile Strength Test Results (Two-Day Exposure—Tested at 24° C) (NRC Field Trial 2)

Water bath temperature (°C) (1)	Bulk specific gravity (2)	Permeable voids (%) (3)	Indirect tensile strength (kPa) (4)	Average strength (kPa) (5)
−29	2.319	3–4	554	502
−29	2.295	3–4	437	502
−29	2.299	4–5	516	502
2	2.316	5–6	625	549
2	2.283	6–7	484	549
2	2.297	5–6	539	549
18	2.320	4–5	433	394
18	2.278	6–7	389	394
18	2.274	6–7	359	394
30	2.309	5–6	344	374
30	2.303	4–5	411	374
30	2.287	5–6	368	374
43	2.319	5–6	516	456
43	2.289	6–7	432	456
43	2.277	6–7	421	456
60	2.387	3–4	441	371
60	2.285	5–6	361	371
60	2.262	6–7	311	371
Control Group—Tested Dry				
Not available	2.349	3–4	554	477
Not available	2.277	6–7	—	477
Not available	2.247	6–7	401	477

ANALYSIS

Preliminary research efforts aimed at developing a laboratory test method for the prediction of stripping potential adopted existing moisture conditioning procedures. Tests, such as the "Effect of water on cohesion of compacted bituminous mixtures" (ASTM-D1075-76) and the boiling test performed on uncompacted bituminous-coated aggregate (ASTM-D3625-77), are known to produce failure surfaces similar to those of stripped mixes. Warm-water soaking have been used since for conditioning of samples, in order to determine stripping susceptibility of asphalt-concrete mixes. After using freeze-thaw tests for conditioning of samples for moisture damage investigations, the trend now is to abandon freezing since only warm-water soaking is known to produce stripping. This has been suggested in spite of the greater stripping damage reported after freeze-thaw conditioning, and in spite of the fact that pavements in the specific region may be exposed to the effect of freeze-thaw cycles (Parker et al. 1988).

However, observations made during the laboratory investigation left no doubt that debonding caused by adhesion failure occurred mainly between the asphalt matrix and the coated aggregate particles. The disappearance of the thin bituminous films, which occurred at elevated temperatures after extended periods of exposure in some of the investigated mixes, may be the result of disintegration of the thin bituminous film. The thickness of the bituminous film coating the aggregate particle, usually 15–45 μm, appears to be characteristic of the particular asphalt (Haas 1968). Such thin bituminous films acquired during the mixing stage, may experience a structural change if exposed to warm-water soaking similar to that used for conditioning of samples for moisture damage investigations. Oil spots observed on the surface of that water bath are signs of such structural change. Benson (1937) and Mack (1957, 1965) discussed the possibility of structual changes that may lead to segregation of asphalt into two phases—asphaltenes and an oily medium. Such changes have not been considered as part of the suggested damage mechanisms, while most of the damage associated with stripping has been produced in the laboratory through this mechanism. The end result of these changes seems to be complete disintegration of the thin bituminous film, hence, separation of the aggregate from the rest of the mix (the asphalt matrix) i.e., stripping. This type of separation is shown in Fig. 3(*b*).

The aforementioned discussion emphasizes the fact that debonding caused by moisture conditioning occurs between the asphalt matrix and the coated aggregate. Debonding resulting from disintegration of the bituminous cover, as previously described, is an extreme condition where the aggregate particle loses its thin bituminous cover. Peterson's (1982, 1984) description of the chemical adsorption process, which occurs during and after the mixing process, provides an explanation for the performance of the thin film. When asphalt cement initially wets aggregate surfaces, some of the known chemical components in asphalt are usually adsorbed by aggregate followed by a chemical reaction between these groups and aggregate constituents. The adsorbed asphalt must, therefore, be considered part of the aggregate and its removal requires a strong destructive action such as the structural change that follows warm-water soaking.

Graf (1986) reported similar observations where inspection of the failure surface revealed that separation occurred between what has been defined here as the "matrix," and coated aggregate particles. According to Graf, separation after failure was not followed by completely bare aggregate. A-few-micron-thick bituminous film (light-brown stain) was often left on the aggregate surface. Graf concluded that this was a cohesive type of failure, and as in earlier studies, did not distinguish between the thin asphalt-cement film acquired during the mixing process and the rest of the asphalt cement mixed with sand and other fine material. Studies investigating adhesion treat both subsystems as one continuous material. This approach neglects the fact that the very thin bituminous film is usually acquired at elevated temperatures and that preferential adsorption results in a different composition from the rest of the asphalt cement mixed with the fine material (matrix). This concept has been supported by statements in Graf's study, that water-wetted surfaces were observed after failure, indicating that water replaced the adhesive bond between the matrix and coated aggregate.

In the opinion of the writer, maintaining the current description of the debonding location ignores a very serious deficiency in the current approach to the problem and reduces the opportunity to develop a solution to stripping damage. The fact that bitumen comes in contact with large aggregate to form the thin cover and in contact with fine aggregate and fill material to form the matrix at an elevated temperature suggests that wetting, adsorption, and therefore, adhesion may be stronger in these systems than between the two systems. In other words, the temperature when asphalt comes in contact with another system, determines the strength of the bond. Therefore, since the two systems are formed at elevated temperatures but only come in final contact with each other at lower temperatures, the strength of the bond between the two systems is lower than that between the elements of each system. Observations made in the laboratory clearly support that debonding was caused by moisture since all the surfaces after separation were wet.

Cohesive failure is considered insignificant because of the observed smooth nature of the contact surface between the matrix and coated aggregate after debonding. The aggregate print on the matrix surface always remains smooth, showing no sign of tearing. Tearing was clear on this surface when cores were tested without moisture conditioning (dry). At relatively low temperatures, the bituminous film retained during the mixing process remained intact and did not change color. At elevated temperatures the contact surface either suffered slight discoloring while the film was still intact, or partial loss of the film occurred following extensive discoloring. Therefore, it is important to distinguish between the asphalt-cement part of the matrix, and the thin bituminous film that coats aggregate particles. These two components only come into intimate contact at relatively low temperatures during compaction, and their composition is not necessarily the same.

CONSEQUENCES OF RECOMMENDED CHANGE

Realizing that debonding occurs at a location other than that adopted in the current approach, one can explain the lack of success experienced with the use of the existing adhesion theories alone to explain the stripping phenomenon. It may also explain the difficulties associated with the prediction of the stripping potential using current laboratory test methods.

- The failure of current adhesion theories in explaining debonding associated with moisture can be explained by the following arguments:

  1. The chemical reaction theory deals with adhesion of asphalt cement to aggregate surfaces. This type of adhesion does not address debonding between the asphalt matrix and coated aggregate particles that occurs at all temperatures in the presence of moisture. If adhesion occurs due to a chemical reaction between the asphalt matrix and the coated aggregate particle, the details of such a reaction are not known.
  2. Structural changes in the thin bituminous film caused by warm-water soaking are not addressed by any of the stripping mechanisms described in the literature based on the existing adhesion theories. Warm-water soaking produces the observed changes that affect the nature of the thin film, and the subsequent partial or complete disintegration of the thin bituminous film. The details of such structural changes are not yet known.
  3. The theory of interfacial energy also addresses a system that includes aggregate particle surfaces, air, and asphalt cement. Previous efforts made to measure the variables described by the theory do not include a possible interfacial energy relationship at the coated aggregate/matrix/air interface.

- The lack of success experienced with existing laboratory evaluation procedures can be explained considering the new debonding location. Conditioning samples by warm-water soaking helps in evaluating the effect of possible structural changes on the bituminous film. It may also serve to evaluate the influence of warm temperatures on the bond strength (expansion). This test, considering the new debonding location, examines only these two specific types of failure but does not evaluate the adhesive bond performance in general.

CONCLUSION

1. The location where debonding caused by moisture takes place has been reviewed and a new location is suggested for further investigation.
2. In lieu of the new debonding location, existing adhesion theories can only explain a specific type of adhesion failure that does not apply to all conditions.
3. Laboratory evaluation procedures must be designed considering the actual debonding location. The influence of temperature change on bond strength necessitates that the conditioning temperatures cover a wide range.
4. The suggested structural changes of the thin bituminous film require further detailed investigation.
5. The performance of the bond between the matrix and the thin bituminous film requires further investigation. The influence of the compaction temperature must be included in such an investigation.

ACKNOWLEDGMENT

The writer would like to express his deep appreciation for the financial support provided by NSERC during the comprehensive study on stripping; and to A. O. Halim, the Ph.D. thesis supervisor.

APPENDIX. REFERENCES

Benson, J. R. (1937). "Microscopic relations in translucent asphaltic films." *Proc. Association of Asphalt Paving Technologists*, Vol. 9, 102–137.

Bituminous Materials in Road Construction. (1962). Department of Scientific and Industrial Research, Road Research Laboratory, Her Majesty's Stationary Office, London, England, 68–88, 316–333.

El Hussein, H. M. (1991). "Stripping of Asphalt Concrete Surfaces," PhD dissertation, Carleton Univ., Ottawa, Ontario, Canada.

El Hussein, H. M. (1993). "Differential thermal expansion/contraction. A mechanistic approach to adhesion in asphalt concrete." *Can. J. Civ. Engrg.*, 20, 366–373.

El Hussein, H. M., Abd El Hallim, A. O., and Kennepohl, G. J. (1991). "Influence of temperature on the stripping of asphalt concrete mixtures." *Proc. of the 36th Annual Conf. of Canadian Technical Asphalt Association*, Canadian Tech. Asphalt Association, 115–134.

El Hussein, H. M., Abd El Hallim, A. O., and Kennepohl, G. J. (1992). "Influence of construction induced cracks on asphalt concrete resistance to moisture damage." *Transp. Res. Record No. 1353*, 69–72.

Fromm, H. J. (1974). "The mechanisms of asphalt stripping from aggregate surfaces." *Proc., Association of Asphalt Paving Technologists*, 43, 191–223.

Graf, P. E. (1986). "Factors affecting moisture susceptibility of asphalt concrete mixes." *Proc., Association of Asphalt Paving Technologists*, 55, 175–212.

Haas, R. C. G. (1968). "The performance and behaviour of flexible pavements at low temperatures," PhD dissertation Univ. of Waterloo, Waterloo, Canada.

Haas, R., and Joseph, P. (1984). Asphalt stripping and thermal cracking at Canadian airports: Phase 1. Transport Canada, Canadian Air Transport Administration.
Lottman, R. P., and Johnson, D. L. (1971). The moisture mechanism that causes asphalt stripping in asphaltic pavement mixtures. Engineering Experimental Station, Univ. of Idaho.
Mack, C. (1957). "Physical properties of asphalts in thin films." *Ind. Engrg. Chem.*, 10, 422.
Mack, C. (1965). "An appraisal of failure in bituminous pavements." *Proc., Association of Asphalt Paving Technologists*, 34, 234–247.
Majidzadeh, K., and Brovold, F. N. (1968). "State of the art: Effect of water on bitumen-aggregate mixtures." *Highway Res. Board Special Report 98.*
Nicholas, J. W., and Lee, A. R. (1954). "Adhesion in construction and maintenance of roads." *Adhesion and Adhesive, Fundamentals on Practice*, Society of Chemical Industry, London, England.
Parker, F., and Garaybeh, G. A. (1988). "Evaluation of tests to assess stripping potential of asphalt concrete mixtures." *Transp. Res. Record No. 1171*, 18–26.
Peterson, J. C. (1982). "Chemistry of asphalt—Aggregate interactions relationship with pavement moisture damage test." *Transp. Res. Record No. 83*, 95–104.
Peterson, J. C. (1984). "Chemical composition of asphalt as related to asphalt durability: State of the art." *Transp. Res. Record No. 999*, 13–30.
Scott, J. A. N. (1978). "Adhesion and disbonding mechanisms of asphalt used in highway construction and maintenance." *Proc., Association of Asphalt Paving Technologists*, 47, 19–48.
Stuart, K. D. (1986). "Evaluation of procedure used to predict moisture damage in asphalt mixtures." *Report No. RD-81091*, Federal Highway Administration.
Thelen, E. (1958). "Surface energy and adhesion properties in asphalt-aggregate systems." *HRB Bull. 192.*
Yoon, H. H., and Tarrer, A. R. (1988). "Effect of aggregate properties on stripping." *Transp. Res. Record 1171*, 37–43.