Transportation Association of Canada

# Moisture Damage of Asphalt Pavements and Antistripping Additives

## Causes, Identification, Testing and Mitigation

December 1997

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| Author(s) | Corporate Affiliation(s) |
|---|---|
| John Emery<br>Hoda Seddik | John Emery Geotechnical Engineering Limited |


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| Research and Development Council<br>Transportation Association of Canada<br>2323 St. Laurent Blvd., Ottawa, Canada K1G 4J8 | John Emery Geotechnical Engineering Limited<br>#1, 109 Woodbine Downs Boulevard<br>Etobicoke, Ontario M9W 6Y1 |


Abstract

Moisture damage to asphalt pavements is a serious durability problem throughout Canada. Stripping resistance (moisture susceptibility) testing for specific aggregate-asphalt cement combinations should be an integral part of asphalt mix design procedures. This manual provides guidance on the mitigation of moisture damage of asphalt pavements, with focus on stripping potential testing and the appropriate use of antistripping additives. The manual is based on: a technical literature review; questionnaires to highway materials engineers and asphalt cement suppliers; and a comprehensive laboratory evaluation of stripping potential test methods, use of antistripping additives (typical liquid and hydrated lime), testing a number of aggregate-asphalt cement-antistripping additive combinations and testing to determine the field efficacy of antistripping additive use.

The manual covers: causes of moisture damage (stripping); methods to mitigate moisture damage in the asphalt pavement structure (adequate drainage, proper compaction, selection of aggregates, type of asphalt mix, waterproofing membranes, stockpile storage time, antistripping additive, quality and maintenance); identification of moisture damage of asphalt pavements in the field; basics of antistripping additives; laboratory evaluation of stripping potential; and a good practices check list.

Three laboratory stripping potential test methods are recommended: Modified Lottman (AASHTO 283); Ontario Ministry of Transportation Immersion Marshall (MTO LS-283); and Tunnicliff-Root (ASTM D 4867). The ASTM D 4867 stripping potential test method appears to be the most practical and reliable, with the MTO LS-283 test being quite comparable. The visual assessment of the conditioned asphalt mix samples to determine a stripping rating is very important.

The use of antistripping additives, when required, significantly improves the stripping resistance of asphalt mixes. Guidance is provided on the appropriate use of antistripping additives, including possible problems and safety aspects. The importance of adopting all of the methods to mitigate moisture damage (stripping) to asphalt pavements, particularly proper asphalt mix compaction and good asphalt pavement structure drainage, cannot be overemphasized.

A Background Document covering the information to to develop the Manual is available from the Transportation Association of Canada.



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| Auteur(s) | Affiliation(s) |
|---|---|
| John Emery<br>Hoda Seddik | John Emery Geotechnical Engineering Limited |

| Nom et adresse de l'organisme parrain | Nom et adresse de l'organisme exécutant |
|---|---|
| Conseil de la recherche et du développement<br>Association des transports du Canada<br>2323, boul. St-Laurent, Ottawa, Canada K1G 4J8 | John Emery Geotechnical Engineering Limited<br>#1, 109 Woodbine Downs Boulevard<br>Etobicoke, Ontario M9W 6Y1 |


Résumé

La détérioration des chaussées bitumées en raison de l'humidité représente un sérieux problème de durabilité des routes au Canada. Les essais de résistance au décollement (sensibilité à l'humidité) pour certaines combinaisons de granulats et de bétons bitumineux devraient être intégrés aux méthodes de calcul des mélanges asphaltiques. Le présent manuel fournit des directives quant aux méthodes permettant d'atténuer la détérioration par l'humidité des chaussées bitumées, en mettant l'accent sur des essais de la résistance au décollement et sur l'utilisation appropriée d'adjuvants antidécollement. Le manuel se fonde sur une analyse bibliographique d'ouvrages techniques et des questionnaires distribués aux ingénieurs des chaussées et aux fournisseurs de béton bitumineux. Il comprend également une évaluation exhaustive des méthodes d'essai en laboratoire de la résistance au décollement, de l'utilisation d'adjuvants antidécollement (en général, des adjuvants liquides et de la chaux hydratée), des essais de diverses combinaisons d'adjuvants antidécollement, de granulats et de bétons bitumineux ainsi que des essais pour déterminer l'efficacité sur le terrain de l'utilisation d'adjuvants antidécollement.

Le manuel traite des sujets suivants : causes de la dégradation des chaussées par l'humidité (décollement); méthodes d'atténuation de la dégradation de la fondation des chaussées bitumées en raison de l'humidité (drainage adéquat, compactage approprié, choix des granulats, types de mélanges d'asphalte, membranes hydrofuges, temps d'entreposage en tas, adjuvants antidécollement, qualité et entretien); reconnaissance sur le terrain des dommages causés par l'humidité aux chaussées bitumées; notions fondamentales sur les adjuvants antidécollement; évaluation en laboratoire de la résistance au décollement; et liste de contrôle des bonnes pratiques.

Trois méthodes d'essai en laboratoire de la résistance au décollement ont été recommandées : l'essai modifié de Lottman (AASHTO T 283); l'essai par immersion de Marshall du ministère des Transports de l'Ontario (MTO LS-283); et l'essai d'enracinement de Tunnicliff (ASTM D 4867). L'essai de la résistance au décollement ASTM D 4867 s'est révélé le plus pratique et le plus fiable, quoique l'essai MTO LS-283 ait donné des résultats assez comparables. L'examen visuel des échantillons de mélanges d'asphalte conditionné est très important pour déterminer le taux de résistance au décollement.

L'utilisation d'adjuvants antidécollement, au besoin, a amélioré considérablement la résistance au décollement des mélanges asphaltiques. Des directives sont données pour une utilisation adéquate des adjuvants antidécollement, y compris comment régler des problèmes éventuels et certains aspects liés à la sécurité. On n'insistera jamais trop sur l'importance d'avoir recours à toutes ces méthodes pour atténuer les dommages (décollement) causés par l'humidité aux chaussées bitumées, plus particulièrement un compactage adéquat des mélanges asphaltiques et un bon drainage de la fondation de la chaussée bitumée.

Un document de référence portant sur les données ayant servi à l'élaboration du manuel est disponible auprès de l'Association des transports du Canada.



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# SUMMARY

Moisture damage to asphalt pavements is a serious durability problem throughout Canada. This manual, dealing with the causes, identification, testing and overall mitigation of asphalt pavement moisture damage (stripping), will be of assistance to agencies in improving the long-term durability of their asphalt pavements. All asphalt mixes should be tested for stripping resistance (moisture susceptibility), unless satisfactory laboratory and field performance for the same mix type and components (aggregates, asphalt cement and antistripping additive, if any) has already been documented. Stripping resistance testing for specific aggregate-asphalt cement combinations should be an integral part of agency asphalt mix design procedures.

This manual provides guidance on an overall strategy to minimize asphalt pavement moisture damage through a range of actions, from providing adequate asphalt pavement structure drainage, through to using antistripping additives. The manual is based on: a technical review of some 400 articles on asphalt concrete stripping, including recent SHRP activities; questionnaires on asphalt concrete moisture damage and antistripping additives completed by highway materials engineers and asphalt cement suppliers; and a comprehensive laboratory evaluation involving assessment of asphalt mix stripping potential test methods, use of antistripping additives (typical liquid and hydrated lime), testing a number of aggregate-asphalt-cement-antistripping additive combinations and testing of field asphalt mixes to determine the efficacy of antistripping additive use. This background information is summarized in a supplementary Information Document available from TAC.

This manual covers: causes of moisture damage (stripping); methods to mitigate moisture damage in the asphalt pavement structure (adequate pavement drainage, proper asphalt mix compaction, selection of aggregates, type of asphalt mix, waterproofing membranes, stockpile storage time, use of antistripping additives, quality of asphalt mix production, placement and compaction, and systematic asphalt pavement maintenance); identification of moisture damage of asphalt pavements in the field; basics of antistripping additives technology; laboratory evaluation of stripping potential, and a good practices check list for asphalt pavement moisture damage mitigation. The importance of adopting all of the methods to mitigate moisture damage, particularly proper asphalt mix compaction and good asphalt pavement structure drainage, is emphasized.

Three laboratory stripping potential (moisture susceptibility) test methods involving accelerated conditions to simulate field conditions (high compacted air voids, various levels of vacuum saturation and elevated temperature, typically 60°C) are recommended: Modified Lottman, which also involves a freeze-thaw cycle (AASHTO

T 283); Ontario Ministry of Transportation (MTO LS-283); and Tunnicliff-Root (ASTM D 4867). The ASTM D 4867 stripping potential test method appears to be the most practical and reliable, with the MTO LS-283 test being quite comparable. The visual assessment of the conditioned asphalt mix samples, to determine a stripping rating, is considered a very important component of the laboratory stripping potential evaluation. A detailed stripping potential evaluation methodology is provided with recommended retained strength and stripping rating requirements.

The use of antistripping additives, when required, significantly improves the stripping resistance of asphalt mixes. Technical guidance is provided on the appropriate use of liquid and hydrated lime antistripping additives, including possible problems, and particularly safety aspects. Further research on the use of hydrated lime as an antistripping additive, particularly cost-effective addition methods and quality assurance procedures to check field efficacy, is recommended.

It is recommended that all asphalt mixes should be tested for stripping resistance, unless satisfactory performance for the specific aggregate-asphalt cement-antistripping additive, if any, combination has been documented. Stripping resistance testing should be an integral part of every agency's asphalt mix design procedures.

# RÉSUMÉ

La détérioration des chaussées bitumées sous l'effet de l'humidité compromet sérieusement la durabilité de ces dernières, partout au Canada. Le présent manuel traite des causes et de la nature des dommages (décollement) qui sont ainsi occasionnés aux chaussées bitumées ainsi que des méthodes d'analyse en laboratoire et des techniques d'atténuation de ces problèmes. Ce manuel saura se révéler utile aux administrations routières qui souhaitent améliorer la durabilité à long terme des chaussées bitumées dont elles ont la responsabilité. La résistance au décollement (sensibilité à l'humidité) de tous les mélanges bitumineux devrait toujours être mesurée, à moins que pour un mélange donné et ses composants (granulats, béton bitumineux et adjuvant antidécollement, s'il y a lieu) on ne dispose déjà de résultats détaillés d'essais de rendement en laboratoire et en conditions réelles. De fait, l'exécution d'essais de résistance au décollement de compositions spécifiques de granulats et de béton bitumineux devrait faire partie intégrante de la méthodologie de conception des mélanges bitumineux de toute administration routière.

Le présent manuel énonce les principes directeurs d'une stratégie globale visant à réduire le plus possible les dommages causés par l'humidité aux chaussées bitumées, le tout à la faveur de la mise en oeuvre de différentes mesures, depuis l'application de méthodes appropriées de drainage des fondations de chaussées à l'emploi d'adjuvants antidécollement. Ce manuel a été élaboré en se fondant sur une analyse technique de quelque 400 documents traitant du décollement des couches de béton bitumineux, y compris des rapports récents d'activités menées dans le cadre du SHRP, les résultats d'une enquête auprès d'experts en génie des matériaux de voirie et de fournisseurs de béton bitumineux - enquête portant particulièrement sur les dommages causés par l'humidité aux chaussées bitumées et sur les adjuvants antidécollement - ainsi que les résultats d'un programme exhaustif d'évaluation en laboratoire. Ce dernier programme était plus précisément axé sur les volets ci-après de la conception des chaussées : méthodes d'essai de résistance au décollement des mélanges bitumineux, utilisation d'adjuvants antidécollement (notamment de chaux liquide et hydratée), l'essai de certaines compositions spécifiques de granulats, de béton bitumineux et d'adjuvants antidécollement ainsi que l'essai en conditions réelles de mélange bitumineux aux fins de déterminer l'efficacité des adjuvants antidécollement. À ce sujet, les intéressés pourront également obtenir auprès de l'ATC un document d'information complémentaire résumant ces travaux.

Plus spécifiquement, le présent manuel traite des points suivants : causes des dommages attribuables à l'humidité (décollement); méthodes d'atténuation des dommages causés par l'humidité à la structure des chaussées bitumées (drainage adéquat des fondations de chaussées, compaction appropriée des mélanges bitumineux, choix des granulats, type de mélange bitumineux, membranes hydrofuges, durée de l'entreposage en tas, emploi d'adjuvants antidécollement, qualité des techniques de préparation des mélanges bitumineux, application et compaction des mélanges, entretien systématique des chaussées bitumées); dépistage des dommages causés aux chaussées bitumées exposées à des conditions réelles d'humidité;

principes fondamentaux de la technologie des adjuvants antidécollement; évaluation en laboratoire de la résistance au décollement, et liste de vérification des bonnes pratiques d'atténuation des dommages causés par l'humidité aux chaussées bitumineuses. Le manuel souligne également l'importance d'appliquer toutes les méthodes d'atténuation des dommages attribuables à l'humidité, notamment en ce qui concerne la compaction appropriée des mélanges bitumineux et le drainage adéquat des fondations de chaussées.

Ce manuel recommande en outre trois méthodes d'essai en laboratoire de la résistance au décollement. Ces méthodes prévoient une simulation, en accéléré, des conditions réelles auxquelles peuvent être exposées les chaussées (compaction élevée des vides intergranulaires, divers niveaux de saturation à vide et température élevée, principalement à 60º C). Les trois méthodes ainsi recommandées sont : l'essai modifié de Lottman avec exposition à un cycle de gel-dégel (AASHTO T 283), l'essai du ministère des Transports de l'Ontario (MTO LS-283) et l'essai de Tunnicliff-Root (ASTM D 4867). L'essai ASTM D 4867 de résistance au décollement s'est révélé à la fois le plus commode et le plus fiable, bien que l'essai MTO LS-283 ait donné des résultats assez comparables. Ceci dit, l'examen visuel des échantillons de mélanges bitumineux conditionnés s'est avéré, aux fins du calcul du ratio de délaminage, un élément déterminant de l'évaluation en laboratoire de la résistance au décollement des mélanges bitumineux. À cet égard, une méthode détaillée d'évaluation est préconisée dans le manuel, ratios de résistance rémanente et de délaminage à l'appui.

L'utilisation d'adjuvants antidécollement, lorsqu'une telle pratique s'impose, permet d'améliorer considérablement la résistance au décollement des mélanges bitumineux. Dès lors, le manuel propose des lignes directrices techniques sur l'utilisation appropriée d'adjuvants à base de chaux liquide et hydratée et il expose également certains problèmes connexes, en particulier au chapitre de la sécurité. Il convient cependant de préciser ici que les auteurs du manuel recommandent de poursuivre les recherches au sujet de l'utilisation de chaux hydratée à titre d'adjuvant antidécollement, notamment au regard de la rentabilité des méthodes qui s'offrent dans ce contexte et des techniques d'assurance de la qualité du rendement des chaussées en conditions réelles.

Enfin, précisons en guise de rappel que le manuel recommande de soumettre tous les mélanges bitumineux à des essais de résistance au décollement, à moins qu'on ne dispose déjà de données témoignant du rendement satisfaisant de mélanges donnés (granulats - béton bitumineux - adjuvants antidécollement). L'exécution d'essais de résistance au décollement devrait faire partie intégrante de la méthodologie de conception des mélanges bitumineux appliquée par toute administration routière.

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## Project Steering Committee

| | |
|---|---|
| Don MacLeod (Chairman) | Public Works Government Services Canada |
| Andaleeb Qayyum (Project Manager/ Secretary) | Transportation Association of Canada |
| Keith Foster | Newfoundland Department of Works, Services and Transportation [currently with John Emery Geotechnical Engineering Limited] |
| Daryl MacLeod | Saskatchewan Highways and Transportation [currently with Husky Oil Marketing Company] |
| Lyle Moran | Imperial Oil Ltd., Products and Chemicals Division |
| Kai Tam | Ontario Ministry of Transportation |
| Allan Widger | Saskatchewan Highways and Transportation |

## Principal Consultants

John Emery
Hoda Seddik
John Emery Geotechnical Engineering Limited

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# MOISTURE DAMAGE OF ASPHALT PAVEMENTS AND ANTISTRIPPING ADDITIVES

## 1.0 INTRODUCTION

### 1.1 PURPOSE OF THIS MANUAL

Moisture damage to asphalt pavements is a serious durability problem throughout Canada, particularly with the generally severe weather conditions involved [1][1]. Asphalt pavements deteriorate with time due to the combined actions of traffic and weather, which continuously subject the pavement to changes in stress, temperature and moisture conditions. It is imperative that the design, construction and maintenance of asphalt pavements give the most cost-effective life-cycle performance by minimizing the rate of serviceability deterioration. Even high performance asphalt pavement types with premium aggregates and asphalt cements, such as heavy duty base (binder) course and stone mastic asphalt mixes, will not serve their intended purpose if they are susceptible to stripping in the presence of water. It is imperative that the stripping potential (moisture susceptibility) of aggregate-asphalt cement combinations be assessed as part of an overall strategy to minimize asphalt pavement moisture damage through a range of actions from providing adequate pavement drainage systems through to using antistripping additives [2-5].

All asphalt mixes should be tested for stripping resistance, unless satisfactory performance has already been documented. Only in the case of known good field performance, with previous stripping test validation for the same mix type and components (aggregates, asphalt cement and antistripping additive, if any), should a mix be assumed to be satisfactory in stripping resistance (moisture susceptibility). Stripping resistance testing should be a part of every agency's mix design procedures [6,7]. The purpose of this manual is to provide overall guidance on the mitigation of moisture damage of asphalt pavements, with focus on the laboratory evaluation of hot-mix aggregate-asphalt cement stripping potential and the appropriate use of antistripping additives.

### 1.2 PERFORMANCE REQUIREMENTS FOR ASPHALT MIXES

It is important that the design of any hot-mix asphalt mix reflects the wide range of performance requirements for asphalt pavements. For instance, the development of permanent deformation resistant (rutting resistant) mixes through somewhat harsh, high stability mix designs raises durability concerns related to ravelling, wear, aging and cracking. Base course and surface course

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1. See the list of references at the end.

dense graded hot-mix asphalt concrete must fulfil a wide range of engineering requirements for the specific site geotechnical, drainage, weather and traffic conditions [8]:

1. be workable during placement and compaction;
2. contribute to the strength of the pavement structure;
3. resist permanent deformation (rutting);
4. resist fatigue cracking;
5. resist thermal cracking;
6. resist the effects of air and water (durability);
7. be impermeable to protect the pavement structure from water; and
8. be easily and cost-effectively maintained.

In addition, surface course asphalt concrete must also fulfil several tire-pavement interaction requirements:

1. adequate frictional properties (skid resistance) for all weather conditions;
2. acceptable level of tire-pavement noise for the traffic and location conditions; and
3. acceptable riding quality (smoothness).

This is a rather formidable list of asphalt pavement engineering requirements that clearly indicates the need to design asphalt mixes for optimal service and economic performance. For instance, a balance must be achieved between low asphalt cement contents (high air voids) for stability and high asphalt cement contents (low air voids) for durability. A stripping resistance test on compacted hot-mix asphalt concrete representative of field air voids and moisture levels must be coupled with mix design procedures such as the Marshall method and Superpave. It is also important to check the effectiveness of any antistripping additive use through field compliance testing of the actual asphalt mix produced.

It should be noted that open graded asphalt mixes, such as asphalt treated permeable base (asphalt treated open graded drainage layer, OGDL) and open friction course (porous asphalt, OFC), have a high water permeability design requirement [9]. This high permeability raises durability concerns due to the very high design air voids and presence of water. These asphalt mixes must also be checked for potential stripping problems and antistripping additives incorporated as necessary.

## 1.3 ADHESION OF ASPHALT CEMENT TO AGGREGATES

Asphalt cement has generally proven to be an excellent adhesive and waterproofing agent to bind together the aggregate particles in hot-mix asphalt concrete. The asphalt cement adheres very well to most aggregates provided that they are clean, dry and not coated with dust. However, the presence of

water can result in problems because aggregates are 'wetted' more readily by water than asphalt cement. Adhesion problems in the presence of water can occur either during the initial coating of the aggregate or after the asphalt mix has been placed.

Failure of the asphalt cement-aggregate bond already formed is referred to as stripping; the displacement of the asphalt cement from the aggregate surface by water [8].

The types of aggregates have a considerable influence on asphalt cement adhesion due to differences in their affinity for asphalt cement. Aggregate types with a high silica content ('acidic' aggregates) are more difficult to coat with asphalt cement (higher stripping potential) than aggregate types with a high carbonate content ('basic' aggregates). These concepts are shown in a somewhat simplified form in Figure 1 [10]. The role of antistripping additives is essentially to improve the asphalt cement coating's adhesion to the aggregate and resist moisture action.

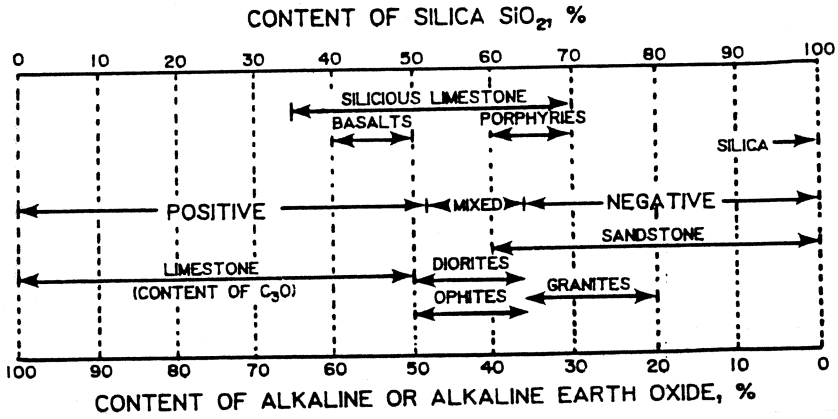


**FIGURE 1 CLASSIFICATION OF AGGREGATES BY SURFACE CHARGES [10]**

The stripping of asphalt cement from the aggregate is generally associated with mixes that are permeable to water. There is a much reduced risk of stripping in properly compacted, dense-graded asphalt mixes [11]. Many aggregates offer adequate resistance to the asphalt cement displacing effect (stripping) of water. It is important to identify those asphalt cement-aggregate combinations that do not have such adequate stripping resistance.

## 1.4 BACKGROUND INFORMATION

A considerable study effort was completed to develop the background information for this manual. This background information is available as a supplementary volume from the Transportation Association of Canada (TAC). The study involved: a technical literature review of moisture damage of asphalt pavements and antistripping additives; a questionnaire "Moisture Damage and

Antistripping Additives" to agencies; a questionnaire "The Use of Liquid Antistripping Additives in Hot-Mix Asphalt" to asphalt cement suppliers; comprehensive laboratory evaluation of stripping potential test methods and use of antistripping additives (typical liquid and hydrated lime); and a field efficacy evaluation, including Superpave Level 1 asphalt technology [7].

The key references from the technical literature review are listed in the References Section. It should be noted that there is considerable on-going research and development work on the moisture susceptibility of hot-mix asphalt. The National Cooperative Highway Research Program, for instance, is currently evaluating AASHTO T 283 [12] in order to recommend changes to make the testing compatible with the Superpave system and to develop field correlations. The extensive stripping resistance testing program, mainly for Ontario aggregates, is summarized in the Appendix Section.

Some of the background conclusions from the supplementary volume include:

1. There is a wide range of experience across Canada with moisture damage to asphalt pavements, mitigation of moisture damage, testing asphalt cement-aggregate combinations for stripping potential and the use of antistripping additives. Some agencies have developed comprehensive programs to deal with asphalt pavement moisture damage, particularly through stripping tests and the use of antistripping additives, while some agencies do not appear to recognize the problem. It is clear that a Canadian manual dealing with the causes, identification, testing and overall mitigation of asphalt pavement moisture damage will be of considerable assistance to agencies in improving the durability of asphalt pavements.

2. The source, grade and type of asphalt cement/binder, as well as aggregate type(s) can influence the stripping resistance of a mix.

3. The effectiveness of hydrated lime as an antistripping additive added to moist aggregate was equal or better compared to its addition to dry aggregate. Hydrated lime was generally more effective in improving the stripping resistance of a mix than the 'low odour' liquid antistripping additive studied.

4. The use of antistripping additives clearly improved the bonding mechanisms between asphalt cements and aggregate surfaces and is generally effective in increasing the stripping resistance of mixes.

5. The most convenient and reliable test method to predict the stripping resistance of asphalt mixes in the laboratory and field was generally found to be the Tunnicliff-Root ASTM D 4867 procedure [13]. The MTO LS-283 immersion Marshall procedure [14] was also found to be

satisfactory, with the stripping rating adding considerable assessment information. The modified Lottman AASHTO T 283 procedure (freeze-thaw cycle) [12] was found to be more time-consuming, and generally not as consistent in results.

6. Reheating an asphalt mix in a microwave oven appears to reduce the apparent effectiveness of liquid antistripping additives. Great care must be taken with the reheating and/or oven retention of asphalt mixes during any testing procedure to ensure that the results are not affected.

7. Lower viscosity asphalt cements appear to result in less stripping resistant asphalt mixes than higher viscosity asphalt cements of the same origin. This effect seems to be more pronounced with the liquid antistripping additive compared to hydrated lime.

8. The use of liquid antistripping additives with performance graded (PG) asphalt binders (cements) should be evaluated as there have been some problems with the treated asphalt binder grading not being achieved.

Conclusion one reflects the questionnaire responses while conclusions two through eight reflect mainly the comprehensive laboratory evaluation.

It is clear that all hot-mix asphalt mixes should be tested for stripping resistance, unless satisfactory performance has been demonstrated. Only in the case of known good field performance with previous stripping test validation for the same mix and components should a mix be assumed to be satisfactory in stripping resistance.

## 2.0 CAUSES OF STRIPPING

The factors responsible for inducing stripping of asphalt cement from aggregate surfaces include [2,5,8,11,15]:

1. Moisture In, or On, the Dried Aggregate

   High water absorption and/or adsorption makes drying more difficult, and fine aggregates dry preferentially which may leave some moisture in the coarse aggregate, particularly under the partial vacuum conditions of the dryer/drum.

2. Aggregate Type

   'Siliceous' aggregates are more prone to stripping than 'carbonate' aggregates.

3. Aggregate Surface Texture

   A 'smooth' aggregate surface texture is less resistant to asphalt cement stripping than a rough surface texture. The effect of aggregate surface texture on asphalt cement adhesion is shown in Figure 2 [8].

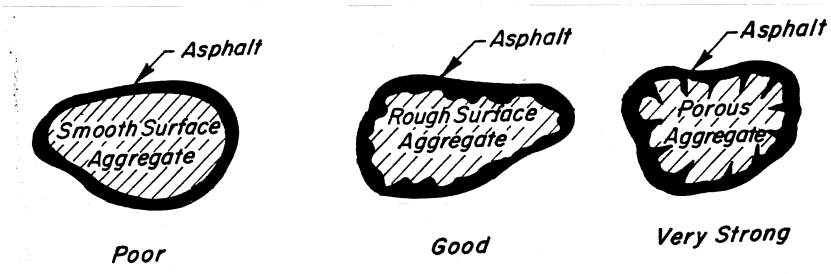


**FIGURE 2 EFFECT OF AGGREGATE SURFACE TEXTURE ON ADHESION [8]**

4. Weak and/or Friable Aggregates

   Degradation during hot-mix asphalt mix compaction and heavy traffic action exposes uncoated aggregate surfaces that can absorb water and initiate stripping.

5. Dust-Coated Aggregate (also combustion products coating)

   Dust coated aggregate does not allow asphalt cement to adhere and dust creates film defects (pinholes). The effect of surface films such as dust, water or combustion products on asphalt cement wetting (coverage) of the aggregate is shown in Figure 3 [8].

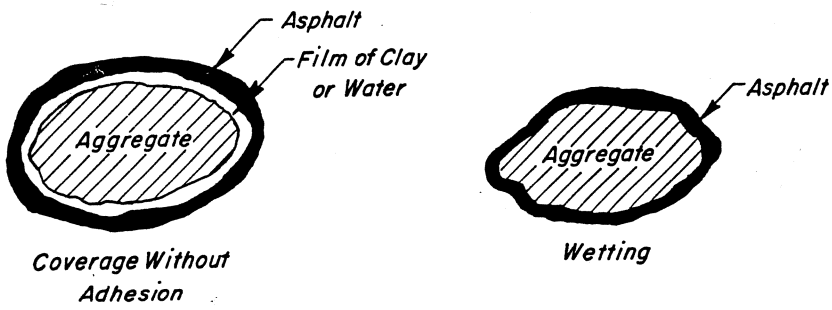


**FIGURE 3 EFFECT OF SURFACE FILMS ON AGGREGATE COVERAGE [8]**

6. Stockpile Age

   Some newly crushed aggregates exhibit poor resistance to asphalt cement stripping.

7. Spontaneous Emulsification

   Liquid antistripping agents can become stripping agents under certain conditions (excess addition rate for example).

8. Asphalt Cement Properties

   The chemical and physical properties of each asphalt cement are unique and can dramatically influence the stripping behaviour of an asphalt mix.

9. Hot-Mix Asphalt Mix Design, Production, Placement and Compaction

   The overall quality of the paving is critical to the performance of the asphalt concrete. High in-place air voids, for instance, can promote water movement.

10. Presence of Asphalt Prime or Tack Coat Incorporating Solvent (cutback, that was not fully cured prior to hot-mix asphalt placement)

    The potential solvent action on asphalt cement films can cause significant asphalt concrete damage and induce stripping.

11. Free Water Availability to Asphalt Pavement Structure

    The presence of water, or moisture, impacts on the overall durability performance of the asphalt pavement, particularly with respect to asphalt cement stripping potential and moisture damage.

# 3.0 METHODS TO MITIGATE MOISTURE DAMAGE IN THE ASPHALT PAVEMENT STRUCTURE

1. Adequate Pavement Drainage System

Water or moisture vapour in the asphalt pavement structure is the prime factor responsible for inducing stripping in hot-mix asphalt pavements. Water enters the pavement structure in different ways: from the surface through cracks or seepage from the shoulder; ditches; a high water table or cut area; or subsurface by capillarity and vapour action. The asphalt pavement structure must be properly drained and systematically maintained to minimize the ingress of water [5].

2. Compaction

Poor compaction of hot-mix asphalt concrete is probably the most common construction-related factor related to stripping. A dense graded asphalt mix should be designed, produced, placed and compacted to avoid the 'pessimum voids content'[2] range in place, and have a maximum air-voids content of 8 percent (compacted to at least 92 percent of the maximum theoretical density). Figure 4 illustrates the pessimum voids content concept [16]. The asphalt concrete should densify to the design air voids content after two to three years under heavy traffic.

Compaction testing is generally the last major quality control activity performed by the contractor before agency acceptance of the completed asphalt pavement. Poor compaction can result in a pavement's performance being much worse than material properties alone would indicate. Too little compaction can permit moisture and air to enter the pavement and prematurely age the asphalt concrete. The intrusion of water can also, of course, result in stripping in a moisture-sensitive asphalt mix [5,16].

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2. 'Pessimum voids content' for stripping can be defined as a relationship between in-situ air voids and retained strength of hot-mix asphalt mixes following conditioning [16]. The amount of strength loss depends on the amount and nature of the voids. The mix can fall within three ranges:

a) Impermeable range - a mix with low air voids (< ~4 percent) is impermeable to water. Impermeable or low air voids asphalt mixes are made with high asphalt cement contents, or are mastics. To offset the lower stability expected from higher asphalt cement contents, the aggregate quality and/or gradation is modified (with manufactured sand for instance), and/or an improved asphalt binder containing polymers and/or fibres can be used;

b) 'Pessimum voids range' - unfortunately, many asphalt pavements are constructed at the mid air voids range (>8 percent), opposite to optimum voids, due to an inadequate mix design, poor compaction and/or poor quality control procedures; and

c) Free draining or open-graded range - asphalt mix is designed as an open graded drainage layer (OGDL) or open friction course (OFC). With the use of polymer-modified asphalt cement, OFC mixes can be designed with higher binder contents (thicker films) to remain open, stable and durable under traffic.

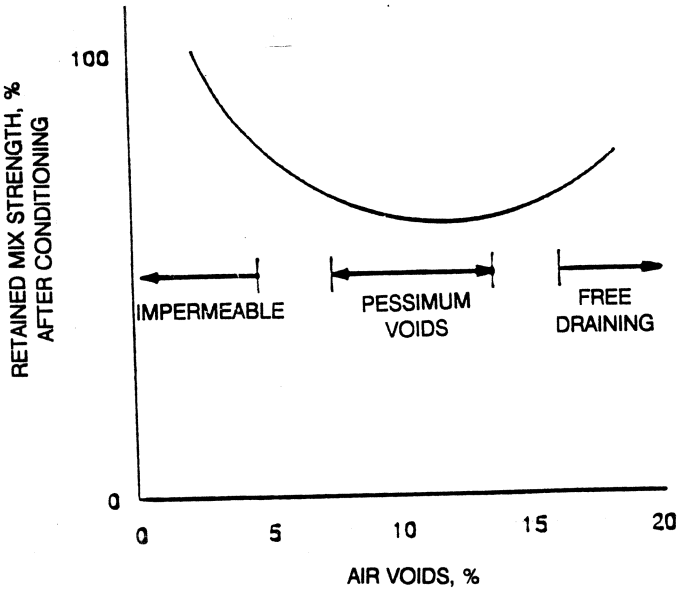



**FIGURE 4 RELATION OF ASPHALT CONCRETE AIR VOIDS AND RETAINED STRENGTH [16]**

3. Proper Selection of Aggregates

Dust free, durable, dry aggregates having a rough surface texture, to enable the aggregate particles to be covered completely with a well adhered asphalt cement film, are least susceptible to moisture-related damage [8,15]. Some aggregates are inherently very susceptible to stripping. Siliceous aggregates (sandstone for instance) have been classified as hydrophillic, and tend to strip much more readily than carbonate aggregates (limestone and dolostone for instance). Another selection method classifies the aggregate as 'electro-positive' (positively charged) for carbonate aggregates and 'electronegative' (negatively charged) for siliceous aggregates as shown previously in Figure 1. The Zeta Potential[3] of the aggregate surface and/or the pH of the water imparted by the aggregate can also be used to measure the stripping potential. The higher the Zeta Potential, the higher the probability of stripping [15].

---

3. Zeta Potential (electrokinetic potential) is the potential across the interface of all solids and liquids (can be calculated from electrophoretic mobilities; rate of migration towards electrode of charge opposite to that of particle).

The presence of dust and clay coatings, moisture and/or combustion products on the aggregate prevents adequate adhesion between the aggregate and asphalt cement (Figure 3). This can generally be eliminated by washing and properly drying the aggregate. The use of clean, dry aggregates in the production of hot-mix asphalt mixes is fundamental to satisfactory asphalt pavement performance. It would appear that many agency specifications permit too high a moisture content, typically 0.5 to 1.5 percent, during hot-mix production. A more appropriate level would be 0.1 to 0.2 percent in order to minimize potential stripping, particularly of the coarse aggregate fraction [17].

Smooth textured aggregates minimize the ability of the aggregate and the asphalt cement to develop sufficient adhesion (Figure 2). This can generally be eliminated by adequately crushing the aggregate to produce surfaces with more texture. Some antistripping additives improve the adhesion of asphalt cement to smooth textured aggregates.

4. Gradation/Type of Asphalt Mix

Dense graded asphalt concretes are less susceptible to stripping than open graded asphalt concretes (see pessimum voids concepts). Special attention must be taken during the asphalt mix design (stripping test for instance), production, placement and compaction of OGDL and OFC if the desired performance is to be obtained [9].

5. Use of Waterproofing Membranes and Seal Coats

Stripping can be exacerbated in the asphalt pavement layers overlying waterproofing membranes and seal coats (trapped water vapour) if the main source of water is not determined correctly [5]. If a major source of moisture is from beneath the asphalt pavement (typical case), then sealing of the road surface can be detrimental in terms of potential stripping. Waterproofing membranes (such as stress-absorbing membranes to minimize reflecting cracking) and seal coats between pavement courses, or at the asphalt pavement surface, can act as a vapour seal or barrier. If the main source of water is from the pavement surface, then the ingress of water can be somewhat reduced by sealing or reducing the asphalt concrete air voids. This can be done by spraying a light emulsified asphalt 'fog seal' or other commercial seal on the pavement surface. However, this is a rather short-term remedy.

6. Stockpile Storage Time for Crushed Aggregates (some Trap Rocks for Instance)

   For aggregates exhibiting 'surface charge' (piezoelectric) properties, aging (stockpile storage time) is required prior to use in hot-mix asphalt mixes to enable any induced electrical surface charges to dissipate and hence improve the performance of the aggregate with respect to stripping resistance.

7. Treatment of the Aggregate and/or Asphalt Cement

   Antistripping additives should be used as necessary to strengthen the bond between the asphalt cement and the aggregate, noting that the compatibility of the specific asphalt cement-aggregate-antistripping additive combination must be considered.

8. Quality Control (QC) and Quality Assurance (QA)

   Good contractor quality control (QC) during all stages of asphalt pavement construction, and monitoring through agency quality assurance (QA) (end result specifications for instance), are imperative to overall asphalt pavement performance.

These asphalt pavement design, materials, hot-mix asphalt mix design (antistripping additive need, if any, for instance), construction (particularly compaction) and quality factors must all be considered in the production of a durable, stripping resistant asphalt pavement. Subsequent systematic asphalt pavement maintenance is, of course, also important to satisfactory performance.

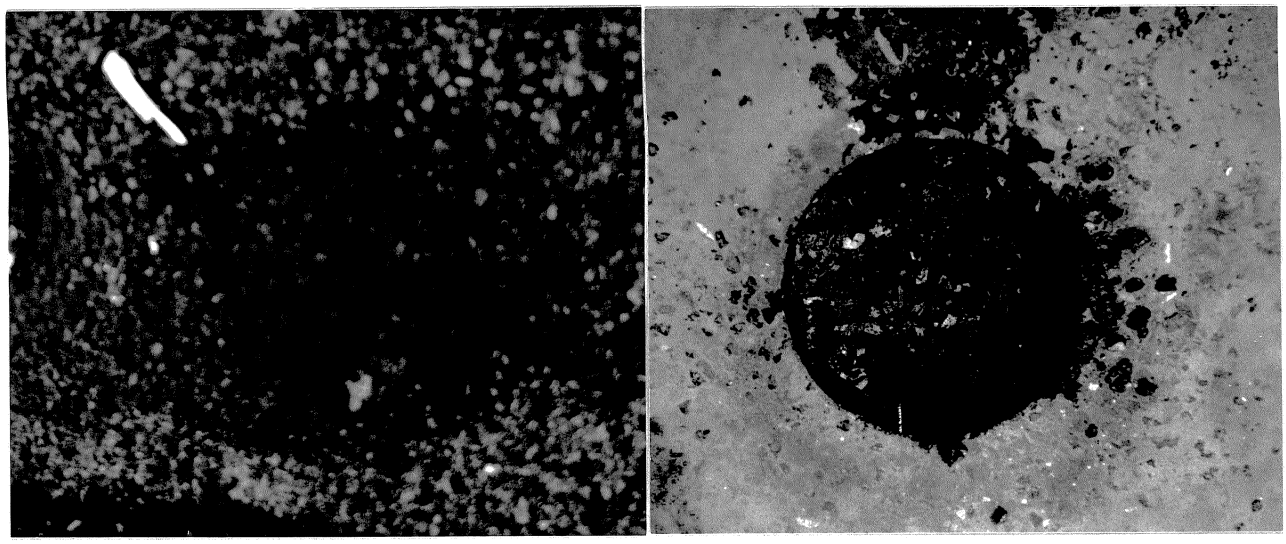
# 4.0 IDENTIFICATION OF MOISTURE DAMAGE OF ASPHALT PAVEMENTS IN THE FIELD

The identification of stripping of in-service asphalt pavements is important in determining if asphalt pavement distresses such as ravelling and potholing are due to moisture damage, and in checking the performance of specific asphalt cement-aggregate combinations, including the effectiveness of antistripping additives. Moisture damage deterioration of asphalt pavements can be at the surface and/or within the pavement structure [5,18].

## 4.1 SURFACE AND INTERNAL STRIPPING

The stripping of asphalt cement from aggregates in the upper surface of asphalt pavements is quite easy to detect visually through its effects ('symptoms') of severe ravelling, potholing and pavement disintegration (Photograph 1A). Areas where such surface stripping starts are typically more open ('porous') due to low compaction, segregation, poor joints and/or cracking. These areas are often the last to dry after periods of rain and provide the contacting water necessary to initiate stripping of moisture susceptible asphalt concrete. There is considerable laboratory and practical experience that confirms deicing chemicals, typically sodium chloride for highways and urea for airfields, can accelerate the stripping of cracked, poorly compacted and/or ravelled asphalt concrete [18]. These deicing chemicals do not 'damage' intact, quality asphalt concrete, but in prolonged contact with deteriorated asphalt concrete, will certainly contribute to moisture damage.

It appears that much stripping of moisture susceptible asphalt concrete starts below the pavement surface and is more serious as its presence is not evident at early stages and the pavement slowly loses its integrity (Photograph 1B). This internal stripping typically starts at the interface of wet granular base and lower course asphalt concrete, or at cracks where water is trapped, and then progresses upwards through the other asphalt concrete courses [18]. In some cases, the amount of debonded asphalt cement is large enough to cause bleeding of free asphalt cement [5]. The loss of asphalt pavement structural integrity can be severe enough to cause instability rutting before the asphalt concrete actually disintegrates.



A. SURFACE STRIPPING B. INTERNAL STRIPPING

**PHOTOGRAPH 1 EXAMPLES OF SURFACE AND INTERNAL STRIPPING OF ASPHALT CEMENT FROM AGGREGATES**

## 4.2 INVESTIGATION OF STRIPPING

The visual inspection of an asphalt pavement is not adequate to establish if stripping is a problem, as much asphalt concrete stripping is internal and distress symptoms such as ravelling, bleeding, rutting, potholing and disintegration can be caused by other mix problems, and in combination with moisture damage. A combined pavement inspection, sampling and testing program is recommended to determine if stripping is the cause of unsatisfactory asphalt concrete performance or to assess the performance of a specific asphalt cement-aggregate(s) combination. The sampling of asphalt pavements to assess moisture damage is quite 'tricky', as it is important that the pavement cutting or coring method adopted not damage the asphalt concrete or mask any evidence of stripping. The investigation of stripping can be on a localized problem area, project or network level, and form a pavement management system component.

A suggested methodology for the identification of stripping of in-service asphalt pavements, based on practical experience [5,18], has the following components:

1. Visual Inspection

The asphalt pavement area of interest is evaluated in accordance with the agency's visual condition (surface distress) survey method. All of the asphalt pavement distresses are categorized by type, severity and extent (length or area), and the distress details recorded on asphalt pavement condition forms. Ravelling, potholing, disintegration, bleeding and rutting are of particular concern with regard to moisture damage. Photographs, with a date, identifier and scale, should be taken of typical distress areas. The widely used American Public Works Association PAVER system can be readily implemented by agencies that do not have a visual condition survey method. It is also important to consider the 'history' of the asphalt pavement area in terms of construction and maintenance records.

2. Sampling

The asphalt pavement sampling program is generally established from the visual inspection evaluation and/or construction records of asphalt mix types, and generally includes a control area with no (minimal) distresses. Practical experience has indicated that stripping of asphalt concrete may be more evident during spring wet conditions. It is necessary to dry core the pavement (no water coolant/lubricant) so that the sample moisture content is not changed. (A block of dry ice can be used to pre-chill the asphalt pavement to avoid core drill overheating and damage. Alternatively, wet coring can be used with an adjacent separate piece of asphalt concrete removed by jack hammer for moisture content determination [5].) The cores should be taken at least 500 mm away from any cracks in the asphalt pavement, unless the stripping of cracked areas is of specific interest. This is important as trapped water in cracks can cause severe stripping in cracked areas that is not representative of the general condition of the area. The cores must be placed and stored in sealed containers to preserve their field moisture condition.

The following information should be recorded for each asphalt concrete core sample:

a. location of sample - station, lane, distance from pavement edge and reference to condition form;
b. thickness of asphalt pavement;
c. number of asphalt concrete layers (courses) - thickness, mix type and interface condition for each layer;
d. moisture condition of the granular base and/or presence of asphalt prime at the bottom of the hole from which the dry cut sample was removed;
e. appearance of asphalt pavement surface - tight or open, ravelling, bleeding, rutting, cracking nearby, etc;

f. local drainage conditions - surface drainage conditions, full width granular, depth of ditches, maintenance, etc.; and
g. asphalt pavement maintenance activities in the area.

The number and size of asphalt core samples taken randomly for each distress or control area of interest depend on the testing program adopted:

a. visual assessment (stripping rating) only
   - three, 150 mm diameter (6 in. nominal) cores for each area (preferably dry cut); or
b. visual assessment (stripping rating) and testing (moisture content and retained strength for instance)
   - three, 150 mm diameter (6 in. nominal) cores for each area for visual assessment (preferably dry cut)
   - retained strength of core samples - six, 102 mm diameter (4 in.) cores for each area (preferably dry cut)
   - retained strength of recompacted samples - six, 150 mm diameter (6 in. nominal) cores for each area (preferably dry cut).

3. Testing of Asphalt Core Samples

a. visual assessment to determine the stripping rating - the Ontario Ministry of Transportation (MTO) method is recommended [18]:
   1. split each 150 mm diameter asphalt core sample to separate the layers for individual visual assessment;
   2. break each layer in half, and using an illuminating-magnifying glass, examine the freshly broken faces of the samples for: evidence of stripping; depth stripping has progressed (generally from bottom upwards or from top downwards); percent stripping (within 10 percent) of coarse aggregate (plus 4.75 mm); and percent stripping of fine aggregate (minus 4.75 mm);
   3. assign a stripping rating, R, using the 'formula':

$$R = P_F + C + F$$

where R is the stripping rating;
$P_F$ is the stripping penetration factor;
C is the coarse aggregate stripping factor (disregard sawn or fractured coarse aggregate particles); and
F is the fine aggregate stripping factor.

These factors are determined as follows:

| $P_F$ | Stripping Penetration, mm |
|---|---|
| 1 | 0 |
| 2 | 0 to 12.5 |
| 3 | 12.5 to 25 |
| 4 | 25 to 75 |
| 5 | greater than 75 |

| C | Coarse Aggregate Stripping, % |
|---|---|
| 0 | less than 10 |
| 1 | 10 to 30 |
| 2 | 31 to 60 |
| 3 | greater than 60 |

| F | Fine Aggregate Stripping, % |
|---|---|
| 0 | less than 10 |
| 1 | 10 to 30 |
| 2 | greater than 30 |

4. report the average (three cores) R, $P_F$, C and F for the asphalt concrete layer (course). (The visual assessment procedure for laboratory prepared samples is given in Table 2.)

b. visual assessment and testing to determine retained strength (stripping potential):
   1. visual assessment as given above (retain sample pieces);
   2. determine in-situ moisture content of sample pieces from visual assessment;
   3. determine the bulk specific gravity of the cores after drying to constant mass (preferred method is to dry cores at laboratory ambient temperature with a fan);
   4. complete retained strength (stripping potential) testing on asphalt core samples or recompacted asphalt samples in accordance with selected stripping test procedure (see Section 6);
   5. determine the maximum theoretical specific gravity for a composite sample following retained strength testing;
   6. determine the mix composition (asphalt content and gradation) with an extraction test on a composite sample following retained strength testing (Marshall properties can also be determined); and
   7. report visual assessment results and testing results.

The laboratory evaluation of stripping potential is described in Section 6. The asphalt concrete cores, or laboratory prepared samples, are the starting point for the testing involved.

# 5. BASICS OF ANTISTRIPPING ADDITIVES

Antistripping additives, typically a liquid polyamine (0.5 to 1.5 percent by mass of asphalt cement) or dry hydrated lime (0.5 to 2.0 percent by mass of mix), are used to strengthen the bond between the asphalt cement and the aggregate in mixes with a stripping potential [4,19-24]. The need for an antistripping additive, if any, and its type and dosage, are determined through laboratory stripping potential testing (Section 6) at the specific asphalt cement-aggregate(s) combination. While the use of antistripping additives is an important, cost-effective method to mitigate moisture damage in an asphalt pavement, such use must still be in conjunction with the other moisture damage mitigation methods previously emphasized in Section 3 [5]. It is also important to consider the overall compatibility of the specific asphalt cement-aggregate-antistripping additive combination. Generally speaking, hydrated lime can be considered to be compatible with all asphalt cement-aggregate combinations [19]. Liquid antistripping additives are compatible with asphalt cement-acidic (siliceous) aggregate combinations (Figure 1), but should not be used with basic (carbonate) aggregates or mixed (siliceous/carbonate) aggregates where stripping can actually be induced [4].

## 5.1 ANTISTRIPPING ADDITIVES

### 5.1.1 Liquid (Chemical) Antistripping Additives

Liquid (chemical) antistripping additives are designed to decrease the surface tension between the asphalt cement and aggregate surface, thus improving the aggregate coating and reducing the stripping potential (moisture damage) of asphalt pavements. Chemical antistripping additives can be divided into two categories: fatty amidoamines; and polyamines. Polyamines, added to the asphalt cement, are mostly used in hot-mix asphalt mixes (new or recycled). Fatty amidoamines are mostly used in cutback asphalt cements and in asphalt emulsions. Most of the liquid antistripping additives are classified as being 'heat stable' by their manufacturers. This indicates that the liquid antistripping additive does not contain components that might react at high temperature with some elements of the asphalt cement and make the additive less effective and/or be lost by 'evaporation'. There does not appear to be a standard heat stability test, but maintained antistripping effectiveness after 96 hours storage at 155°C (asphalt cement with liquid antistripping additive at selected dosage) is considered adequate by some agencies. It is also important that the liquid antistripping additive is blended in uniformly with the asphalt cement.

Liquid antistripping additives can also affect the physical properties (consistency and viscosity) of asphalt cements; they can interact with polar compounds and viscosity building components that could affect the peptization or dispersion of asphaltene-like constituents, and alter the asphalt cement consistency. Liquid antistripping additives can soften an asphalt cement and change its aging characteristics and temperature susceptibility. Significant problems can develop

with liquid antistripping additives when used in excess; a moisture-susceptible shear plane can be formed which may accelerate stripping in the long term, and the antistripping additive actually becomes a stripping additive [5]. It is clearly very important to not put in too much liquid antistripping additive.

Recent experience in Metro Toronto with two sources of performance graded (PG) asphalt binder (70-28) has shown that the use of liquid antistripping additives can reduce the grading (70-28 down to 64-28) at higher addition levels and/or when the grading is close to the specification limits.

The odour of liquid antistripping additives and safe handling procedures are of concern to both contractors and agencies, as discussed in Section 5.3.

### 5.1.2 Chemical Lime (Hydrated Lime) Additives

Many studies have recommended the use of hydrated lime as an antistripping additive to improve the stripping resistance and stability of hot-mix asphalt concrete, and to reduce the age hardening of the asphalt cement [19,25]. Some agencies regularly specify hydrated lime in their asphalt mixes to provide resistance to stripping and to improve the performance of asphalt concrete. Chemical lime is manufactured from either high-calcium or dolomitic limestone. Limestone (calcium carbonate) is calcined (burned) to produce quicklime. Quicklime and water react to produce hydrated lime.

Several theories have been developed to explain why chemical lime (hydrated lime) is so effective as an antistripping additive: it improves the bonding of calcium with silicate in aggregates; it reduces the interfacial tension between the asphalt cement and water; and aggregates with clay coatings undergo ion exchange between the calcium in the lime and the silica in the clay. Essentially, the hydrated lime provides a favourable physical-chemical surface condition for asphalt cement adhesion to the aggregate.

Mechanistic studies of chemical lime treatment have shown positive effects such as: reduce the asphalt cement viscosity; stiffen the asphalt cement; remove reactive polar compounds; reduce the formation of carbonyl-type oxidation products upon aging; reduce the ratio of asphaltenes formed to oxidation products formed upon aging; and reduce asphaltene formation [25].

### 5.1.3 By-Product Antistripping Additives

Two promising by-products that have been used as antistripping additives are:

a. cement kiln dust (CKD) which is the fine, dry mineral dust from the air pollution control system for rotary kilns;
b. tall oil pitch (TOP) which is a by-product of the pulp and paper industry. The British Columbia Ministry of Transportation has conducted several studies and field trials with TOP, and concluded that TOP can be an

alternative for softer asphalts and liquid antistripping additives [26].

The use of either CKD or TOP as antistripping additives requires a detailed evaluation of their effectiveness for the specific asphalt cement-aggregate-CKD or TOP combination involved.

## 5.2 ANTISTRIPPING ADDITIVE INCORPORATION

There are two methods by which antistripping additives are added to asphalt mixes:

a. a relatively simple and economic application method is to introduce a selected liquid antistripping additive ('low odour' polyamine generally) to the asphalt cement, at the supplier, terminal or asphalt plant, and thoroughly mix the additive with the asphalt cement prior to mixing the asphalt cement with the aggregate in the hot-mix plant. Although this method is commonly used, it becomes less effective as the mixture cools and the viscosity of the asphalt cement increases. This is due to the reduced amount of antistripping additive reaching the aggregate-asphalt cement interface due to slow migration; or

b. apply the antistripping additive directly to the aggregate surface. The use of hydrated lime, both in dry or slurry form, has been shown to be an effective means to reduce stripping when applied directly to the aggregate [19,27].

### 5.2.1 Methods Used To Add Hydrated Lime

There are several ways of adding hydrated lime to aggregates or asphalt mixes to improve their stripping resistance [19,27].

#### Dry Hydrated Lime Added to Dry Aggregate

The main problem with dry hydrated lime is maintaining the lime on the surface of the dry aggregate until it is coated with asphalt cement. Hydrated lime can be added to the aggregate in a batch or drum plant. Some asphalt paving technologists feel this method is not consistently effective.

#### Hydrated Lime Slurry

Adding hydrated lime in a slurry form requires additional water to be added to the aggregates, which results in an increase in fuel costs (drying costs) and reduced hot-mix asphalt mix production rates (longer retention/mixing time required).

#### Dry Hydrated Lime Added to Damp Aggregate

Dry hydrated lime is added to the damp aggregate (3 to 5 percent water) to

prevent the lime being washed off the surface, or dry hydrated lime is added to the damp aggregate using a premixing pugmill or tumble mixer. Unless the amount of water added is low, increased fuel costs and a reduction in hot-mix asphalt mix production rates will result.

### Hot Lime Slurry (Quicklime)

It may be cost (less transportation cost) and temperature (raised) advantageous to use quicklime which is slaked or slurried at the job site. This is not commonly done for handling reasons.

### Dry Hydrated Lime Added During Aggregates Production Stockpiling

An interesting and cost-effective approach appears to be hydrated lime addition during aggregates production stockpiling. There is some concern with potential carbonation of the hydrated lime (loss of effectiveness) with this approach. This was evaluated for a Meta-Arkose dense friction course aggregates source during the study (Appendix) and excellent stripping resistance, with improved effectiveness, was actually found.

A summary of the methods of introducing hydrated lime is given in Table 1. Each contractor and agency must assess the most technically acceptable, cost-effective method for the specific project and hot-mix plant equipment involved.

**TABLE 1 METHODS OF INTRODUCING DRY HYDRATED LIME***

| METHOD | ADVANTAGES | DISADVANTAGES |
|---|---|---|
| During aggregates production and stockpiling operations at pit or quarry (moist aggregates**) | - Good coating of aggregates (excellent coating if mixing unit involved)<br>- Aggregate producer takes responsibility | - Potential for lime washing off stockpile and/or leaching to groundwater<br>- Potential for lime carbonation<br>- Some lime loss due to handling (dusting) |
| Premixing with aggregates as part of stockpiling at asphalt plant site (moist aggregates**) | - Good coating of aggregates (excellent coating if mixing unit involved) | - Potential for lime washing off stockpile and/or leaching to groundwater<br>- Some lime loss due to handling (dusting) |
| Addition to cold feed of asphalt plant (moist aggregates**) | - Lowest cost for handling lime | - Least effective aggregate coating<br>- Some lime loss due to handling (dusting) |
| Addition through a mixing unit as part of asphalt plant cold feed (moist aggregate**) | - Excellent coating of aggregates<br>- Most effective coating method | - Some lime loss due to handling (dusting, probably minor) |
| Hot-Mix Batch Plant<br>Addition to pugmill mixing unit (dry aggregate) | - Good coating of aggregates<br>- Cost effective method | - Some lime loss to dust control system<br>- Some lime loss to asphalt cement |
| Hot-Mix Drum Plant<br>Addition to drum mixing unit (dry aggregate) | - Good coating of aggregates<br>- Cost effective method | - Potential for significant lime loss to dust control system unless special equipment used |

* It is also possible to use hydrated lime slurry, but this is not a common method of lime addition due to: slurry mixing equipment required; and increased fuel costs during hot-mix asphalt mix production (or reduced production rates) to remove the additional moisture. Quicklime slurry has also been used (similar cost to hydrated lime), but requires special slaking equipment and care with handling due to heat generation.

** Some specifications require a moisture content of typically 3 to 5 percent to apparently ensure coating and increased lime effectiveness. This can result in increased fuel costs for drying during hot-mix asphalt mix production.

## 5.3 SAFETY ASPECTS OF ANTISTRIPPING ADDITIVES

The safety aspects of using antistripping additives can be summarized as:

a. both hydrated lime and liquid (amine) antistripping additives can be a health hazard if not properly selected and handled;
b. most liquid antistripping additives have a strong, obnoxious odour that is a health concern:
    1. health concern symptoms can be eye, nose and throat irritation, nausea, dizziness and headaches;
    2. health concern is exacerbated by diluent solvents; and
    3. trend in North America is to use 'low-odour' amines which have higher boiling point diluents and/or higher molecular weight active compounds requiring no solvent, with low odour, low vapour, low irritation and no longer-term effects.
c. important to train and inform all asphalt personnel (contractors, suppliers, testers, carriers, truckers, unions and agency) on proper selection and application of antistripping additives; and
d. preconstruction meeting is important to develop work practices, protective equipment and clothing requirements, and a clear understanding of each parties responsibility, especially protection of 'sensitive' workers (asthmatics for instance).

The selection of nonhazardous antistripping additives overall practices is clearly the first proactive safety action. Beyond this, personnel information and training is the key to establishing a safe work action plan.

## 5.4 RESEARCH NEEDS FOR ANTISTRIPPING ADDITIVES

During the technical literature review on moisture damage of asphalt pavements and antistripping additives, there were a number of references found on the comparative efficacy of chemical lime (typically hydrated lime) as an antistripping agent, its regular use by many agencies, and apparent additional benefits of increased asphalt concrete stiffness and reduced age hardening of asphalt cement. For instance, it would appear that hydrated lime has been found to be more effective as an antistripping agent than commercial heat-stable liquid antistripping agents [19]. For this reason, it would appear that research on the cost-effective addition of hydrated lime, quality assurance procedures to check the efficacy of hydrated lime addition at hot-mix plants, use of hydrated lime with performance graded (PG) asphalt binders, and use of hydrated lime in open graded asphalt mixes (OFC and OGDL) to reduce moisture damage, may provide significant benefits through improved asphalt pavement durability.

# 6.0 LABORATORY EVALUATION OF STRIPPING POTENTIAL

The focus of tests for moisture damage in asphalt concrete has been a range of laboratory procedures that have the purposes of:

1. assessing the potential for stripping in an asphalt concrete at the mix design stage;
2. determining the effectiveness of antistripping additives;
3. identifying the component(s) (typically considered to be aggregates) 'responsible' for stripping; and
4. establishing the extent of moisture damage (stripping) with service life (simulated and/or field samples, Section 4).

Testing for stripping in asphalt concrete is, of course, made difficult by the many interacting factors that may influence moisture damage, such as:

1. asphalt cement and aggregate (filler, fine and coarse) properties and characteristics;
2. hot-mix asphalt mix design;
3. hot-mix asphalt mix production, placement and compaction; and
4. service conditions, particularly the availability of moisture (water or vapour).

No single test method has gained general acceptance to date, probably due to the difficulty of establishing a clear relationship between laboratory and field performance. The tests can be divided into two categories: qualitative (or subjective) tests run on loose, hot-mixed samples of asphalt cement coated aggregate; and quantitative tests run on compacted asphalt concrete samples or cores from asphalt pavements.

1. Qualitative or Subjective Tests

These tests are based on the visual observation and qualitative evaluation of the percentage of retained asphalt cement coating the aggregate. They are not widely used.

2. Quantitative Strength Tests

These tests, on compacted asphalt concrete samples or asphalt pavement cores, are based on comparing a property such as tensile strength before and after moisture conditioning. Moisture damage in asphalt concrete results in a substantial reduction in tensile strength from asphalt cement adhesion loss due to stripping. A ratio is computed by dividing the strength result for the 'conditioned' (wet) specimen(s) by the strength result for the 'unconditioned' (dry) specimen(s). Parameters such as Marshall stability (indirect indicator of tensile strength), diametral tensile strength (Figure 5), diametral resilient modulus, etc. have been used. If the ratio is less than a specified value, the

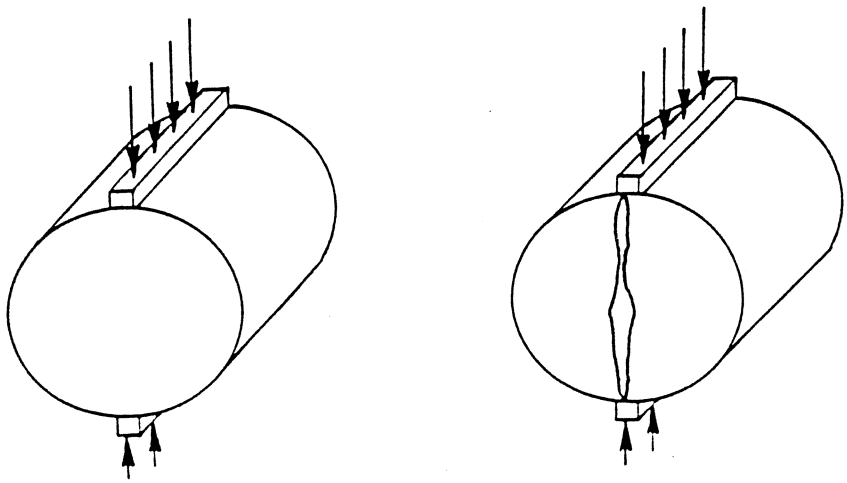



**FIGURE 5 INDIRECT TENSILE TEST DURING LOADING (A.) AND AT FAILURE (B.) [10]**

mix is considered to be moisture susceptible and treatment with an antistripping additive is required. The appearance of the mix and aggregates (coating and stripped aggregate particles) is also typically considered.

The indirect tensile test procedures (Figure 5) with moisture conditioning ('Lottman procedure' (NCHRP 246) and 'Tunnicliff-Root procedure' (NCHRP 274)) have become the most widely used test methods for hot-mix asphalt moisture susceptibility. The Modified Lottman Test (AASHTO T 283) has been adopted by AASHTO and SHRP, and the Tunnicliff Root Test (ASTM D 4867) by ASTM [20,21,23,27-31]. Recently, some states have found that aggregates known to be susceptible to stripping pass AASHTO T 283 without antistripping additive treatment. As a result, a current NCHRP project involves the evaluation of AASHTO T 283 in order to develop correlations between laboratory moisture damage tests and asphalt pavement field performance. This project will also include recommended changes to make the testing compatible with the Superpave mix design system.

The earlier, widely used, immersion compression and immersion Marshall testing procedures have not proved effective in predicting moisture damage in asphalt concrete, unless the air voids (saturation) in the compacted specimens are representative of those anticipated in the field under service conditions. For instance, laboratory compaction procedure specimen air voids of 8 to 10 percent, representative of field air voids, are adopted in the Ontario (MTO) immersion Marshall procedure that is the 'required' Ontario test [14]. There is now considerable positive Ontario and Newfoundland experience with the MTO immersion Marshall testing procedure for a number of hot-mix asphalts (mix types, aggregates, asphalt cements and antistripping additives).

While there is on-going research and debate between the supporters of various testing procedures for stripping (moisture susceptibility), it would appear that the FHWA, AASHTO and SHRP are generally satisfied with the applicability of the Lottman procedure for predicting and monitoring moisture damage in asphalt concrete [31].

## 6.1 RECOMMENDED TEST METHODS

Three stripping resistance testing methods (procedures) are recommended for agency consideration:

1. Ontario Ministry of Transportation 'MTO LS-283 - Method of Test for Resistance to Stripping of Asphalt Cement in Bituminous Mixtures by Immersion Marshall' (Immersion Marshall Test) [14].

2. ASTM D 4867 'Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures' (Tunnicliff-Root Test) [13].

3. AASHTO T 283 'Standard Method of Test for Resistance of Compacted Bituminous Mixture to Moisture Induced Damage' (Modified Lottman Test) [12].

### 6.1.1 Immersion Marshall Test (MTO LS-283) [14]

The Ontario Ministry of Transportation and Metro Toronto Transportation Department have good experience with this method to determine the stripping resistance of hot-mix asphalt. The Newfoundland and Labrador Department of Works, Services and Transportation also uses MTO LS-283. The procedure followed is outlined in Table 2. This method is used to determine the resistance to stripping of compacted asphalt cement-aggregate mixes (specimens (briquettes) compacted by the double plunger method to fairly high air voids level) when immersed in hot water. The Marshall stability values of hot-water cured specimens are compared to the stability values for air-cured control specimens, thus producing an index of retained stability. A minimum Marshall retained stability (MRS) of 70 percent is required by the MTO:

$$\text{Marshall Retained Stability (Percent)} = \frac{\text{Marshall Stability at 25°C (Hot-Water Cured)}}{\text{Marshall Stability at 25°C (Air-Cured Control)}} \times 100$$

A visual coating rating (heavy, medium, light, heavy stain, medium stain and light stain) is given for the air-cured control specimens, and a visual stripping factor is given for the hot-water cured specimens based on the degree of asphalt cement stripping from the surface of the coarse and fine aggregate particles when the briquettes are tested (broken open) after curing in air and water (similar to MTO field stripping rating, Section 4).

## TABLE 2 IMMERSION MARSHALL TEST (MTO LS-283)

| | |
|---|---|
| SPECIMENS | 6 specimens divided into 2 groups<br>Size: Marshall briquettes prepared by double plunger compaction method (about 8 to 12 percent air voids) |
| Curing | Compacted specimens are placed in air bath @ 60°C for 16 to 18 hrs (overnight) |
| Procedure | - Remove the specimens from the air bath and leave them to cool<br>- Determine bulk relative density (BRD) of specimens<br>- Sort the specimens into two groups, such that the average BRD of each group is approximately equal<br><br>Group 1 (air-cured):<br>- Place the specimens in a water bath at 25°C for 1 hr; remove and test for stability and flow<br>- Break open the specimens and allow to sit overnight<br><br>Group 2 (water-cured):<br>- Place the specimens in a vacuum cell containing distilled water at 25°C and reduce the pressure to 30 mm Hg (absolute pressure) for about 1 hr, then immerse saturated specimens in a water bath at 60°C for 24 hrs<br>- After 24 hrs, remove the specimens and place them in a water bath at 25°C for 1 hr; test for stability and flow<br>- Break open the specimens and allow to sit overnight |
| Damage Analysis (Stripping Resistance) | - Marshall Retained Stability (Percent) = [Stability Group 2]/[Stability Group 1] x 100<br>- Visual examination of the broken surfaces of the specimens using an illuminating magnifying glass, and note any swelling<br><br>Group 1 (air-cured):<br>- Coarse aggregate is examined for coating and assigned a coating rating<br>Group 2 (water-cured):<br>- Coarse and fine aggregates are examined for percent of stripping<br>- Assigned a stripping rating using the following formula:<br>Rating = $P_L$ + C + F<br>where: $P_L$ = 3 when no stripping is evident<br>= 4 when stripping is evident<br>C = coarse aggregate factor [0 for less than 10%, 1 from 10 to 30%, 2 for 31 to 60%, 3 for greater than 60% stripping)<br>F = fine aggregate factor [0 for less than 10%, 1 from 10 to 30%, 2 for greater than 30% stripping) |
| Advantages | - Can be conducted on laboratory mixes, field mixes, or cores from existing pavements<br>- Testing time required is moderate<br>- Severe test<br>- Good correlation with field performance<br>- Involves a visual examination of the broken specimen (aggregates) to determine the extent of stripping |
| Disadvantages | - May require trial specimens to obtain desired air voids level<br>- Degree of saturation is not determined<br>- Requires the use of a compression machine |

### 6.1.2 Tunnicliff-Root Test (NCHRP 274/ASTM D 4867), Indirect Tensile Test with Tunnicliff and Root 1984 Conditioning [13]

The procedure followed is outlined in Table 3. Six specimens are compacted to 6 to 8 percent air voids. These specimens are then divided into two groups of three specimens each. The Group 1 specimens are treated as a control without conditioning. The Group 2 specimens are vacuum saturated (500 mm Hg) with water for 5 minutes to attain a saturation level of 55 to 80 percent. Specimens saturated more than 80 percent are disregarded (considered to be damaged). The saturated specimens are then conditioned in water at 60°C (140°F) for 24 hours. All specimens are tested for indirect tensile strength (ITS) at 25°C (77°F) using a loading rate of 51 mm/min (2 in./min). A minimum tensile strength ratio (TSR) of 70 to 80 percent is usually specified. The use of a freeze-thaw cycle is not required in ASTM D 4867 which is based on the Tunnicliff-Root test. (The freeze-thaw cycle is optional.)

**TABLE 3 TUNNICLIFF-ROOT TEST (NCHRP 274/ASTM D 4867)**

| | |
|---|---|
| SPECIMENS | 6 specimens divided into 2 groups<br>Size: Marshall briquettes for aggregate ≤ 25.4 mm |
| Curing | Mix cured in an oven at the required compaction temperature for 1 to 2 hrs |
| Compaction | ASTM D 1559, D 1561 or D 3387 |
| Air Voids (%) | 6 to 8 percent (anticipated voids in place) |
| Procedure | - Test for BRD and air voids<br>- Sort the specimens into 2 groups, such that the average air voids are approximately equal<br><br>Group 1 (unconditioned):<br>- Store dry at room temperature<br>- Soak for 20 minutes at 25°C. Test for indirect (diametral) tensile strength (ITS)<br>Group 2 (conditioned):<br>- Obtain a 55 to 80 percent saturation level (partial vacuum of 500 mm Hg for about 5 minutes in distilled water)<br>- Test for BRD and saturation level<br>- Reject if saturation is > 80 percent<br>- Soak for 24 hrs at 60°C<br>- Soak for 1 hr at 25°C. Test for ITS |
| Damage Analysis (Stripping Resistance) | - Indirect (Diametral) Tensile Strengths (ASTM D 4123) of Groups 1 and 2<br>- Tensile Strength Ratio (Percent) = $\frac{\text{ITS Group 2}}{\text{ITS Group 1}} \times 100$<br>- Average swell<br>- Visual appearance |
| Advantages | - Can be conducted on laboratory mixes, field mixes or cores from existing pavements<br>- Testing time required is moderate<br>- Good correlation with field performance (based on 80 percent TSR) |
| Disadvantage | - May require trial specimens to obtain desired air voids level or degree of saturation |

### 6.1.3 Modified Lottman Test (AASHTO T 283), Combined Features of NCHRP 246 and 274 [12]

This stripping resistance test method was adopted by AASHTO in 1985. The procedure followed is outlined in Table 4. Six specimens are compacted to 7 ± 1 percent air voids. Specimens are divided into two groups of three specimens each. The Group 1 specimens are treated as a control without conditioning. The Group 2 specimens are partially vacuum saturated (500 mm Hg) in water for 5 minutes to attain a saturation level of 55 to 80 percent. The specimens are then subjected to one freeze-thaw cycle as proposed by Lottman. All specimens are tested for ITS at 25°C using a loading rate of 51 mm/min. A minimum TSR of 70 to 80 percent is usually specified. This method is gaining wider acceptance by agencies and is also used to evaluate the stripping resistance for the SHRP Superpave volumetric mix design method.

**TABLE 4 MODIFIED LOTTMAN TEST (AASHTO T 283)**

| | |
|---|---|
| Specimens | 6 specimens divided into 2 groups<br>Size: Marshall briquettes for aggregate ≤ 25.4 mm |
| Curing | Mix cooled at room temperature for 2 hrs, then placed in an oven at 60°C for 16 hrs, for curing<br>After curing, the mix is placed in an oven at 135°C for 2 hrs, prior to compaction |
| Compaction | ASTM D 1559, D 1561 or D 3387<br>After compaction, the specimens are stored at room temperature for 72 to 96 hrs |
| Air Voids | 6 to 8 percent (anticipated voids in place) |
| Procedure | - Test for BRD and air voids<br>- Sort the specimens into 2 groups, such that the average air voids are approximately equal<br><br>Group 1 (unconditioned):<br>- Store dry at room temperature<br>- Place in water bath at 25°C for 2 hrs. Test for ITS<br><br>Group 2 (conditioned):<br>- Obtain a 55 to 80 percent saturation level (partial vacuum of 500 mm Hg for about 5 minutes in distilled water)<br>- Soak for 30 minutes, test for BRD and saturation level<br>- Reject if saturation is > 80 percent<br>- Freeze at -18°C for 16 hrs in sealed bags<br>- Soak in a water bath at 60°C for 24 hrs<br>- Remove and place in water bath at 25°C for 2 hrs. Test for ITS |
| Damage Analysis (Stripping Resistance) | - Indirect (Diametral) Tensile Strengths (ASTM D 4123) of Groups 1 and 2<br>- Tensile Strength Ratio (Percent) = $\frac{\text{ITS Group 2}}{\text{ITS Group 1}} \times 100$<br>- Visual appearance |
| Advantages | - Can be conducted on laboratory mixes, field mixes or cores from existing pavements<br>- Severe test<br>- Can differentiate between antistripping additive levels<br>- Good correlation with field performance |
| Disadvantages | - Time-consuming (about 7 days to finish the stripping resistance evaluation for a mix)<br>- May require trial specimens to obtain desired air voids level or degree of saturation |

The generally accepted minimum criteria for evaluating stripping resistance (moisture susceptibility) by the three test methods are given in Table 5.

**TABLE 5 MINIMUM TEST CRITERIA**

| TEST METHOD | CRITERIA FOR EVALUATION |
|---|---|
| MTO LS-283 | Minimum Marshall retained stability (MRS) of 70 percent* |
| ASTM D 4867 | Minimum tensile strength ratio (TSR) of 75 percent |
| AASHTO T 283 | Minimum tensile strength ratio (TSR) of 75 percent |
| * Appearance (extent of stripping) also considered. | |

## 6.2 QUICK STRIPPING TEST

A preliminary 'quick' stripping test was developed during the study that has proven helpful in 'ranking' project aggregates. This quick test involves mixing a sample of the project aggregate with the project asphalt cement at 4, 5 and 6 percent asphalt cement content for coarse aggregate, screenings and asphalt sand, respectively, batched, heated and mixed in accordance with the standard mix design method. The loose mix is then allowed to sit overnight at room temperature. About 0.25 kg of the loose mix is removed to be used as an appearance control, and the remaining loose mix is placed in a plastic bag and filled with water. This loose mix (submerged in the plastic bag) is immersed in a water bath at 60°C for 24, 48 and 72 hours. The appearance and percentage of stripping is then observed at each time interval using the MTO visual examination procedures summarized in Table 2.

## 6.3 RECOMMENDED TESTING PROCEDURE

The following testing procedure is recommended for the assessment of an asphalt cement-aggregate combination's stripping potential and the selection of an antistripping additive, if needed:

a. Select a Stripping Test Method from the Three Recommended, Noting the Limitations on Each:

   1. Immersion Marshall Test (MTO LS-283) - Table 2.
   2. Tunnicliff-Root Test (ASTM D 4867) - Table 3.
   3. Modified Lottman Test (AASHTO T 283) - Table 4.

b. Always Complete a Visual Stripping Rating in Accordance with MTO LS-283 - Table 2.

c. Complete the Stripping Test and Visual Stripping Rating for the Asphalt Cement-Aggregate Combination at the Mix Design (JMF) Asphalt Cement Content.

d. Compare the Stripping Test Result and Stripping Rating to the Minimum Test Criteria in Table 6.

**TABLE 6 MINIMUM STRIPPING TEST (PERCENT) AND STRIPPING RATING CRITERIA FOR SINGLE TEST***

| TEST METHOD | PASS | COMPLETE TWO MORE TESTS | FAIL |
|---|---|---|---|
| MTO LS-283 | MRS ≥ 75 and R ≤ 5 | MRS 65 to 74 and R ≤ 7 | MRS ≤ 65 or R ≤ 8 |
| ASTM D 4867 | TSR ≥ 80 and R ≤ 5 | TSR 65 to 79 and R ≤ 7 | TSR ≤ 65 or R ≤ 8 |
| AASHTO T 283 | TSR ≥ 80 and R ≤ 5 | TSR 65 to 79 and R ≤ 7 | TSR ≤ 65 or R ≤ 8 |
| * This table reflects the typical qualified interlaboratory range of single stripping tests (MTO LS-283) of 10 percent. | | | |

e. Complete Further Testing in Accordance with Table 6, as Necessary.

1. Pass - asphalt cement-aggregate combination is acceptable for stripping resistance.

2. Complete two more tests - complete two more stripping tests to supplement first test, and check average of three test results (total of nine conditioned specimens and nine unconditioned specimens) and stripping ratings to minimum test criteria in Table 7.

3. Fail - complete stripping test with selected antistripping additive:

   i. 0.5, 1.0 and 1.5 percent by mass of asphalt cement content for liquid antistripping additive; or
   ii. 0.5, 1.0 and 2.0 percent by mass of asphalt mix for hydrated lime (added to moist aggregate).

f. Compare the Stripping Test Result(s) and Stripping Rating(s) to the Minimum Test Criteria:

1. Average of three stripping test results and stripping ratings to minimum test criteria in Table 7.

2. Use of antistripping additive stripping test results and stripping ratings to minimum test criteria in Table 6.

**TABLE 7 MINIMUM STRIPPING TEST (PERCENT) AND STRIPPING RATING CRITERIA FOR AVERAGE OF THREE TESTS**

| TEST METHOD | PASS | FAIL |
|---|---|---|
| MTO LS-283 | MRS ≥ 70 and R ≤ 6 | MRS ≤ 70 or R ≥ 7 |
| ASTM D 4867 | TSR ≥ 75 and R ≤ 6 | TSR ≤ 75 or R ≥ 7 |
| AASHTO T 283 | TSR ≥ 75 and R ≤ 6 | TSR ≤ 75 or R ≥ 7 |

g. Complete Further Testing in Accordance with Tables 7 and 6, as Necessary.

1. Table 7 (f.1. - average of three stripping tests)

i. Pass - asphalt cement-aggregate combination is acceptable for stripping resistance.

ii. Fail - complete stripping test with selected antistripping additive. Combination is not acceptable.

2. Table 6 (f.2. - use of antistripping additive)

i. Pass - asphalt cement-aggregate-antistripping additive combination is acceptable for stripping resistance (select at minimum antistripping additive level that passes).

ii. Complete two more tests - complete two more stripping tests at the most favourable antistripping additive level to supplement first test with antistripping additive.

iii. Fail - asphalt cement-aggregate-antistripping additive combination is not acceptable (change asphalt cement source, aggregates and/or antistripping additive and repeat testing).

h. Report the Stripping Test Results and Provide Recommendations for Acceptance or Rejection of the Asphalt Cement-Aggregate-Antistripping Additive (if any) Combination.

## 7.0 GOOD PRACTICES CHECK LIST

The following good practices should be followed by agencies in order to minimize the moisture damage of asphalt pavements.

1. Complete a network level ravelling, potholing, disintegration, bleeding and rutting distress survey to determine if stripping is a problem (none to little, local, general).

2. Complete a field evaluation program to assess the causes of the stripping if it is a problem.

3. Continue to take steps to mitigate moisture damage of all asphalt pavements:

    a. adequate pavement drainage;
    b. proper selection and use of aggregates;
    c. mix design (Marshall method or Superpave) optimized for rutting resistance, fatigue endurance; thermal cracking resistance and durability;
    d. use of antistripping additives as necessary to provide adequate stripping resistance; and
    e. quality control and assurance at all stages of asphalt pavement construction.

4. Systematic maintenance to 'preserve' the asphalt pavements.

# 8.0 RECOMMENDATIONS

All asphalt mixes should be tested for stripping resistance, unless satisfactory performance has already been documented. Only in the case of known good field performance, with previous stripping test validation for the same mix type and components (aggregates, asphalt cement and antistripping additive, if any), should a mix be assumed to be satisfactory in stripping resistance (moisture susceptibility). Stripping resistance testing should be a part of every agency's mix design procedures.

There is still a research need to establish the relationship between laboratory stripping resistance results and the field performance rating of asphalt pavement moisture susceptibility.

The importance of adopting all of the methods to mitigate moisture damage to asphalt pavements, particularly proper asphalt mix compaction and good asphalt pavement structure drainage, cannot be overemphasized.

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# APPENDIX

## LABORATORY EVALUATION OF STRIPPING POTENTIAL TEST METHODS AND USE OF ANTISTRIPPING ADDITIVES (TYPICAL LIQUID AND HYDRATED LIME)

### TABLES


TABLE A1 Job Mix Formula - Gradation (Percent Passing) and Asphalt Cement (AC) Content (Percent)
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### FIGURES


FIGURE A1 Phase 1 - Standard Mixes, Strength Ratio for Base (Binder) Course Mixes
FIGURE A2 Phase 2 - Standard Mixes, Strength Ratio for Surface Course Mixes
FIGURE A3 Phase 2 - Strength Ratio for Additional Surface Course Mixes
FIGURE A4 Phase 3 - Stage 1 - Standard Mixes, Strength Ratio for Base Course Mixes

FIGURE A5 Phase 3 - Stage 2 Special Mixes, Strength Ratio for Worst Performance Mix (HL 4 (M))

## TABLE A1 JOB MIX FORMULA (JMF) - GRADATION (PERCENT PASSING*) AND ASPHALT CEMENT (AC) CONTENT (PERCENT)

JMF for Standard Mixes

| SIEVE SIZE | 26.5 | 19.0 | 16.0 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 | 600 | 300 | 150 | 75 | AC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HL 4 (G) | 100 | 100 | 98.4 | 93.7 | 78.8 | 55.0 | 42.1 | 32.0 | 22.4 | 12.8 | 6.2 | 3.6 | 5.2 |
| HL 4 (M) | 100 | 100 | 99.2 | 92.8 | 77.3 | 55.0 | 44.9 | 32.9 | 19.2 | 10.2 | 5.6 | 4.5 | 5.0 |
| HL 4 (P1) | 100 | 100 | 98.7 | 86.7 | 70.5 | 55.0 | 47.4 | 40.7 | 33.3 | 20.3 | 7.9 | 3.6 | 5.3 |
| HL 4 (P2) | 100 | 100 | 99.1 | 92.3 | 75.7 | 55.0 | 46.6 | 40.1 | 32.9 | 19.9 | 7.6 | 3.5 | 5.2 |
| HL 1 (G) | 100 | 100 | 100 | 100 | 81.8 | 47.8 | 36.9 | 28.5 | 19.8 | 11.0 | 5.0 | 2.7 | 5.0 |
| HL 1 (M) | 100 | 100 | 100 | 99.4 | 79.3 | 47.0 | 40.2 | 30.1 | 17.6 | 9.3 | 5.10 | 4.2 | 5.0 |
| HL 1 (P1) | 100 | 100 | 100 | 99.2 | 79.4 | 50.5 | 45.9 | 41.3 | 34.7 | 20.4 | 6.6 | 2.3 | 5.5 |
| HL 1 (P2) | 100 | 100 | 100 | 99.4 | 78.8 | 47.7 | 42.5 | 37.9 | 31.6 | 18.7 | 6.2 | 2.5 | 5.1 |
| JMF for HL 1 Additional Mixes | | | | | | | | | | | | | |
| HL 1 (G′) | 100 | 100 | 100 | 100 | 81.2 | 47.9 | 42.2 | 36.0 | 23.9 | 9.7 | 4.7 | 2.9 | 5.0 |
| HL 1 (M) | 100 | 100 | 100 | 99.4 | 79.3 | 47.0 | 40.2 | 30.1 | 17.6 | 9.3 | 5.1 | 4.2 | 5.0 |
| HL 1 (P1′) | 100 | 100 | 100 | 100 | 81.8 | 47.8 | 36.9 | 28.5 | 19.8 | 11.0 | 5.0 | 2.7 | 5.0 |
| HL 1 (P2′) | 100 | 100 | 100 | 99.4 | 78.7 | 47.4 | 41.1 | 34.9 | 23.2 | 9.7 | 4.9 | 3.1 | 5.0 |

Good performance** (G): HL 4 (G) Dufferin-Milton (Dolostone), Dufferin-Milton Screenings (Dolostone), Caledon Asphalt Sand.
HL 1 (G) Armbro Trap Rock (aged), Caledon Asphalt Sand.
HL 1 (G′) Armbro Trap Rock (aged), New Dundee Asphalt Sand.

Medium performance (M): HL 4 (M) Nelson-Uhtoff (Dolostone), Dufferin-Milton Screenings, Caledon Asphalt Sand.
HL 1 (M) 3M Trap Rock (aged), Sherman Asphalt Sand.

Poor performance (P1): HL 4 (P1) Villeneuve-Esker (Granitic), Villeneuve-Esker Screenings (Granitic), Hutcheson Asphalt Sand.
HL 1 (P1) Permanent Lafarge Dolomitic Sandstone, Hutcheson Asphalt Sand.
HL 1 (P1′) Permanent Lafarge Dolomitic Sandstone, Sherman Asphalt Sand.

Medium performance CA and poor performance FA (P2): HL 4 (P2) Nelson-Uhtoff, Villeneuve-Esker Screenings, Hutcheson Asphalt Sand
HL 1 (P2) 3M Trap Rock (aged), Hutcheson Asphalt Sand.
HL 1 (P2′) 3M Trap Rock (aged), New Dundee Asphalt Sand.

* Fines returned to the mix (1.0%). ** Performance was ' assumed ' prior to laboratory evaluation.

## TABLE A2 JOB MIX FORMULA (JMF) - GRADATION (PERCENT PASSING) AND ASPHALT CEMENT (AC) CONTENT (PERCENT)

Newfoundland Aggregates*

| SIEVE SIZE | 25.4 | 22.0 | 19.0 | 12.7 | 4.76 | 2.0 | .425 | .075 | % AC |
|---|---|---|---|---|---|---|---|---|---|
| Percent Passing | 100 | 100 | 100 | 77.9 | 50.0 | 29.5 | 12.5 | 5.0 | 6.0 |

* Unclassified crushed quarry aggregate.

## TABLE A3 AGGREGATES AND COMPACTED MIX PROPERTIES FOR BASE (BINDER) COURSE MIXES

| BASE COURSE (HL 4) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Classification | Aggregate Properties | | | | | Properties of Compacted Mix | | |
| | Coarse and Fine Aggregate (CA) (FA) | | Moisture Content (%) | Absorption (%) | BSG of Aggregate | BRD | MRD | Marshall Properties |
| G | CA | Dufferin | 1.41 | 1.355 | 2.695 | 2.422 | 2.522 | Air Voids (%) 4.0<br>Flow (0.25 mm) 10.5<br>Stability (N) 9126<br>VMA (%) 14.3 |
| | FA | Dufferin Screenings | 1.96 | 1.355 | 2.765 | | | |
| | FA | Caledon Asphalt Sand | 4.85 | 0.933 | 2.648 | | | |
| M | CA | Uhtoff | 0.23 | 0.770 | 2.670 | 2.389 | 2.485 | Air Voids (%) 3.9<br>Flow (0.25 mm) 9.3<br>Stability (N) 7409<br>VMA (%) 13.9 |
| | FA | Uhtoff Screenings | 2.39 | 1.350 | 2.650 | | | |
| | FA | Sherman Asphalt Sand | 6.02 | 1.671 | 2.603 | | | |
| P1 | CA | Villeneuve-Esker | 0.29 | 0.652 | 2.740 | 2.417 | 2.515 | Air Voids (%) 3.9<br>Flow (0.25 mm) 8.4<br>Stability (N) 6194<br>VMA (%) 15.7 |
| | FA | Villeneuve-Esker Screenings | 0.40 | 0.742 | 2.684 | | | |
| | FA | Hutcheson Asphalt Sand | 2.62 | 0.300 | 2.693 | | | |
| P2 | CA | Uhtoff | 0.23 | 0.770 | 2.670 | 2.394 | 2.496 | Air Voids (%) 4.1<br>Flow (0.25 mm) 8.3<br>Stability (N) 5995<br>VMA (%) 15.2 |
| | FA | Villeneuve-Esker Screenings | 0.40 | 1.35 | 2.650 | | | |
| | FA | Hutcheson Asphalt Sand | 2.62 | 0.3 | 2.693 | | | |

BSG is the bulk specific gravity of aggregates.
MRD is the maximum relative density and BRD is the bulk relative density of mix.

## TABLE A4 AGGREGATES AND COMPACTED MIX PROPERTIES FOR SURFACE COURSE MIXES

| SURFACE COURSE (HL 1) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Classification | Aggregate Properties | | | | | Properties of Compacted Mix | | |
| | Coarse and Fine Aggregate (CA) (FA) | | Moisture Content (%) | Absorption (%) | BSG of Aggregate | BRD | MRD | Marshall Properties |
| G | CA | Armbro Trap Rock | 0.60 | 0.493 | 2.914 | 2.524 | 2.597 | Air Voids (%) 2.8<br>Flow (0.25 mm) 9.2<br>Stability (N) 8091<br>VMA (%) 13.8 |
| | FA | Caledon Asphalt Sand | 4.85 | 0.933 | 2.648 | | | |
| M | CA | 3M Trap Rock | 0.14 | 0.357 | 2.981 | 2.521 | 2.613 | Air Voids (%) 3.5<br>Flow (0.25 mm) 9.2<br>Stability (N) 8995<br>VMA (%) 14.4 |
| | FA | Sherman Asphalt Sand | 6.02 | 1.671 | 2.603 | | | |
| P1 | CA | Permanent Lafarge Dolomitic Sandstone | 0.14 | 1.053 | 2.640 | 2.362 | 2.463 | Air Voids (%) 4.1<br>Flow (0.25 mm) 7.8<br>Stability (N) 5622<br>VMA (%) 16.2 |
| | FA | Hutcheson Asphalt Sand | 2.62 | 0.300 | 2.693 | | | |
| P2 | CA | 3M Trap Rock | 0.14 | 0.357 | 2.981 | 2.514 | 2.620 | Air Voids (%) 4.0<br>Flow (0.25 mm) 7.5<br>Stability (N) 5244<br>VMA (%) 16.2 |
| | FA | Hutcheson Asphalt Sand | 2.62 | 0.300 | 2.693 | | | |
| G′ | CA | Armbro Trap Rock | 0.60 | 0.493 | 2.914 | 2.513 | 2.606 | Air Voids (%) 3.6<br>Flow (0.25 mm) 9.0<br>Stability (N) 9760<br>VMA (%) 14.6 |
| | FA | New Dundee Asphalt Sand | 4.33 | 1.217 | 2.664 | | | |
| M ✓ | CA | 3M Trap Rock* | 0.14 | 0.357 | 2.981 | 2.521 | 2.613 | Air Voids (%) 3.5<br>Flow (0.25 mm) 9.2<br>Stability (N) 8995<br>VMA (%) 14.4 |
| | FA | Sherman Asphalt Sand | 6.02 | 1.671 | 2.603 | | | |
| P1′ | CA | Dolomitic Lafarge Sandstone | 0.14 | 1.053 | 2.640 | 2.373 | 2.466 | Air Voids (%) 3.8<br>Flow (0.25 mm) 11.1<br>Stability (N) 10176<br>VMA (%) 14.0 |
| | FA | Sherman Asphalt Sand | 6.02 | 1.671 | 2.603 | | | |
| P2′ | CA | 3M Trap Rock | 0.14 | 0.357 | 2.981 | 2.538 | 2.630 | Air Voids (%) 3.5<br>Flow (0.25 mm) 9.6<br>Stability (N) 9311<br>VMA (%) 14.9 |
| | FA | New Dundee Asphalt Sand | 4.33 | 1.217 | 2.664 | | | |

BSG is the bulk specific gravity of aggregates.
MRD is the maximum relative density and BRD is the bulk relative density of mix.

Marshall properties for AADT > 5000: air voids 3.5-4.5; flow ≥ 8; stability (N) ≥ 8900; and VMA according to gradation.

* No longer in production as of August 1996, and as of November 1996 3M will no longer be providing hot-mix aggregates.

## TABLE A5 PHASE 1 TEST RESULTS FOR BASE COURSE HL 4

| TREATMENT | MIX HL 4 | METHOD | MRS OR TSR | SATURATION (%) | AIR VOIDS (%) | COATING RATING UNCONDITIONED (DRY) | STRIPPING RATING CONDITIONED (WET)** | CRITERIA*** |
|---|---|---|---|---|---|---|---|---|
| Hydrated Lime (1%) | G | MTO | 88.8 | - | 7.9 | Heavy | 4 | ✓ |
| | | ASTM | 89.4 | 70.0 | 8.0 | Heavy | 4 | ✓ |
| | | AASHTO | 94.1 | 66.3 | 7.8 | Medium | 4 | ✓ |
| | M | MTO | 79.2 | - | 7.3 | Medium | 5 | ✓ |
| | | ASTM | 73.3 | 74.7 | 6.9 | Heavy stain | 6 | x |
| | | (ASTM)* | 84.3 | 67.3 | 7.0 | Light | 6 | ✓ |
| | | AASHTO | 79.7 | 70.3 | 7.0 | Medium stain | 5 | ✓ |
| | P1 | MTO | 93.0 | - | 7.2 | Medium | 3 | ✓ |
| | | ASTM | 82.1 | 72.5 | 7.5 | Medium | 4 | ✓ |
| | | AASHTO | 85.1 | 62.1 | 7.3 | Medium | 4 | ✓ |
| Pave Bond Lite (0.5%) | G | MTO | 81.3 | - | 7.3 | Medium | 5 | ✓ |
| | | ASTM | 75.0 | 69.2 | 6.9 | Heavy | 3 | ✓ |
| | | AASHTO | 69.8 | 73.4 | 7.1 | Heavy | 3 | x |
| | M | MTO | 70.6 | - | 6.7 | Medium | 4 | ✓ |
| | | ASTM | 63.9 | 70.0 | 6.1 | Light | 8 | x |
| | | AASHTO | 69.4 | 71.0 | 6.0 | Heavy stain | 5 | x |
| | P1 | MTO | 83.1 | - | 7.3 | Heavy | 4 | ✓ |
| | | ASTM | 84.1 | 68.4 | 7.0 | Medium | 3 | ✓ |
| | | AASHTO | 85.2 | 67.3 | 6.8 | Medium | 3 | ✓ |
| Pave Bond Lite (1%) | G | MTO | 79.0 | - | 7.1 | Medium | 5 | ✓ |
| | | ASTM | 76.4 | 68.4 | 6.9 | Medium | 4 | ✓ |
| | | AASHTO | 80.6 | 67.9 | 7.0 | Medium | 5 | ✓ |
| | M | MTO | 82.2 | - | 6.7 | Light | 4 | ✓ |
| | | ASTM | 86.9 | 62.7 | 6.2 | Light | 3 | ✓ |
| | | AASHTO | 71.0 | 62.3 | 6.5 | Light | 6 | x |
| | P1 | MTO | 85.0 | - | 6.8 | Heavy | 3 | ✓ |
| | | ASTM | 89.1 | 59.2 | 6.9 | Heavy | 3 | ✓ |
| | | AASHTO | 88.4 | 60.3 | 6.9 | Medium | 4 | ✓ |

## TABLE A5 (Continued) PHASE 1 TEST RESULTS FOR BASE COURSE HL 4

| TREATMENT | MIX HL 4 | METHOD | | MRS OR TSR | SATURATION (%) | AIR VOIDS (%) | COATING RATING UNCONDITIONED (DRY) | STRIPPING RATING CONDITIONED (WET) | CRITERIA*** |
|---|---|---|---|---|---|---|---|---|---|
| No Additive | G | MTO | 30 mm | 70.3 | - | 7.4 | Heavy | 5 | ✓ |
| | | | 60 mm | 72.1 | - | 7.3 | Heavy | 5 | ✓ |
| | | ASTM | | 56.8 | 70.1 | 7.2 | Medium | 8 | x |
| | | AASHTO | | 54.2 | 66.7 | 7.4 | Medium | 9 | x |
| | M | MTO | 30 mm | 41.2 | - | 6.6 | Light | 6 | x |
| | | | 60 mm | 42.8 | - | 6.4 | Light | 6 | x |
| | | ASTM | | 42.7 | 61.1 | 6.5 | Medium | 7 | x |
| | | AASHTO | | 67.5 | 70.8 | 6.5 | Medium | 6 | x |
| | P1 | MTO | 30 mm | 41.0 | - | 6.9 | Medium | 9 | x |
| | | | 60 mm | 42.5 | - | 7.0 | Medium | 9 | x |
| | | ASTM | | 42.9 | 60.0 | 7.5 | Medium stain | 7 | x |
| | | AASHTO | | 60.3 | 60.5 | 7.4 | Medium stain | 7 | x |

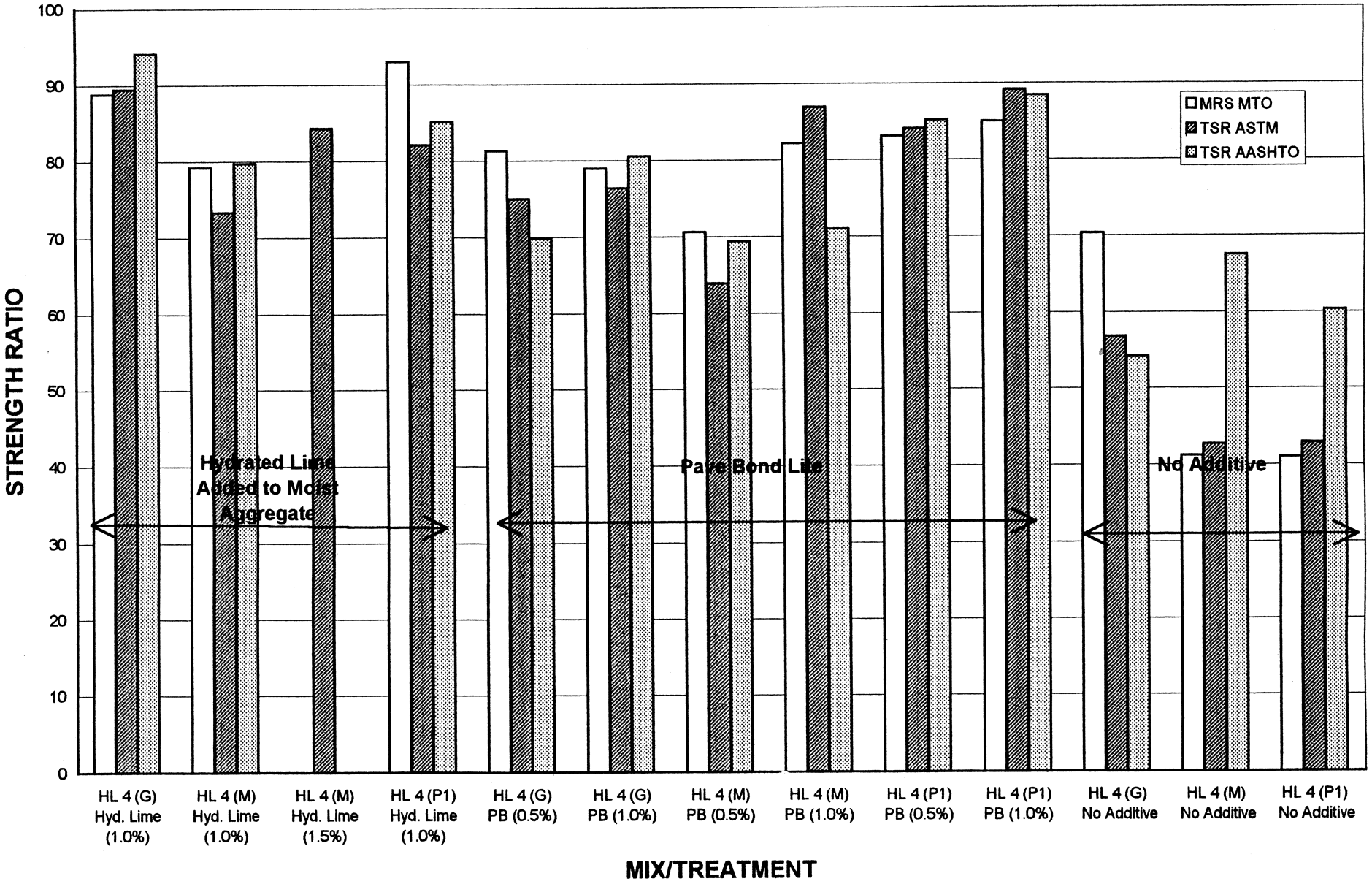
* ASTM at 1.5% hydrated lime.

** See Table 2 for stripping rating procedure, lower rating number is best.

*** Criteria MTO LS-283 at 30 mm Hg residual pressure for 1 hour — Minimum Marshall retained stability (MRS) of 70 percent.
ASTM D 4867 at 500 mm Hg vacuum for 5 minutes — Minimum tensile strength ratio (TSR) of 75 percent.
✓ Passing the criteria.
x Failing the criteria.

(SEE FIGURE A1 ALSO)

**FIGURE A1 PHASE 1 - STANDARD MIXES**
**STRENGTH RATIO FOR BASE COURSE MIXES**



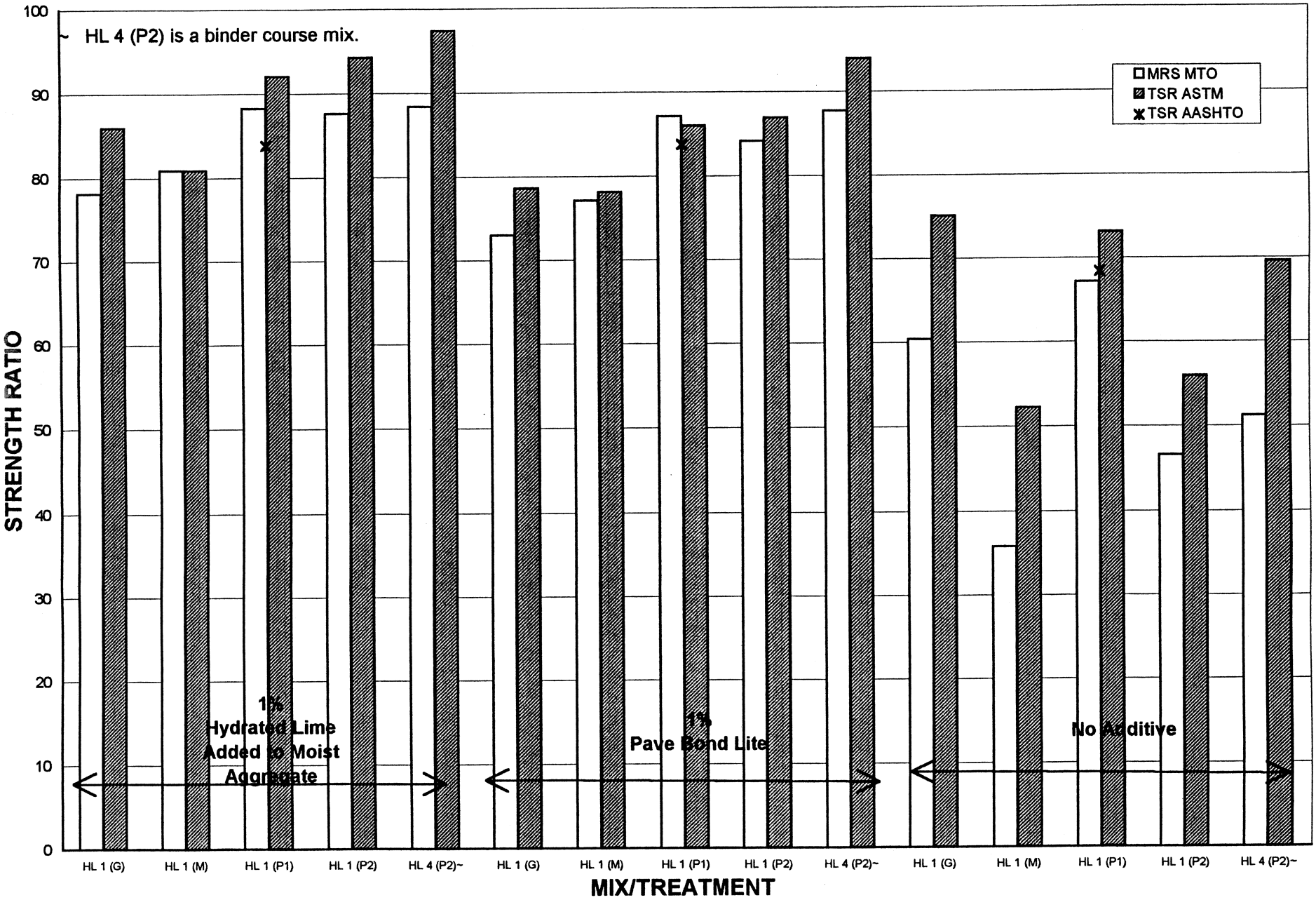
## TABLE A6 PHASE 2 TEST RESULTS FOR SURFACE AND BASE COURSE MIXES

| TREATMENT | MIX | METHOD | MRS OR TSR | SATURATION (%) | AIR VOIDS (%) | COATING RATING UNCONDITIONED (DRY) | STRIPPING RATING CONDITIONED (WET) | CRITERIA* |
|---|---|---|---|---|---|---|---|---|
| Hydrated Lime (1%) | HL 1 (G) | MTO | 78.1 | - | 6.5 | Heavy | 3 | ✓ |
| | | ASTM | 85.9 | 60.5 | 6.4 | Heavy | 4 | ✓ |
| | HL 1 (M) | MTO | 80.9 | - | 6.6 | Heavy | 7 | ✓ |
| | | ASTM | 80.9 | 70.1 | 6.6 | Heavy | 4 | ✓ |
| | HL 1 (P1) | MTO | 88.2 | - | 7.2 | Heavy | 3 | ✓ |
| | | ASTM | 92.0 | 72.5 | 7.1 | Heavy | 4 | ✓ |
| | | AASHTO | 83.8 | 68.0 | 7.0 | Heavy | 4 | ✓ |
| | HL 1 (P2) | MTO | 87.6 | - | 7.3 | Heavy | 5 | ✓ |
| | | ASTM | 94.2 | 61.9 | 7.1 | Heavy | 3 | ✓ |
| | HL 4 (P2) | MTO | 88.4 | - | 7.2 | Medium | 3 | ✓ |
| | | ASTM | 97.4 | 58.6 | 6.7 | Light | 6 | ✓ |
| Pave Bond Lite (1%) | HL 1 (G) | MTO | 73.0 | - | 5.5 | Heavy | 4 | ✓ |
| | | ASTM | 78.6 | 59.3 | 6.2 | Heavy | 4 | ✓ |
| | HL 1 (M) | MTO | 77.1 | - | 6.1 | Heavy | 3 | ✓ |
| | | ASTM | 78.1 | 62.4 | 5.9 | Heavy | 3 | ✓ |
| | HL 1 (P1) | MTO | 87.1 | - | 7.1 | Medium | 4 | ✓ |
| | | ASTM | 86.0 | 67.8 | 7.0 | Heavy | 3 | ✓ |
| | | AASHTO | 83.7 | 65.6 | 6.9 | Heavy | 3 | ✓ |
| | HL 1 (P2) | MTO | 84.1 | - | 7.3 | Heavy | 4 | ✓ |
| | | ASTM | 86.9 | 58.4 | 7.2 | Heavy | 3 | ✓ |
| | HL 4 (P2) | MTO | 87.7 | - | 7.1 | Medium | 3 | ✓ |
| | | ASTM | 93.9 | 61.3 | 6.8 | Light | 5 | ✓ |
| No Additive | HL 1 (G) | MTO | 60.4 | - | 6.4 | Heavy | 8 | x |
| | | ASTM | 75.1 | 61.6 | 6.6 | Heavy | 5 | ✓ |
| | HL 1 (M) | MTO | 35.8 | - | 6.4 | Heavy | 9 | x |
| | | ASTM | 52.2 | 58.5 | 5.6 | Heavy | 6 | x |
| | HL 1 (P1) | MTO | 67.2 | - | 6.9 | Heavy | 5 | x |
| | | ASTM | 73.1 | 63.8 | 6.8 | Heavy | 6 | X |
| | | AASHTO | 68.4 | 65.4 | 7.2 | Heavy | 8 | x |
| | HL 1 (P2) | MTO | 46.6 | - | 7.4 | Heavy | 8 | x |
| | | ASTM | 55.9 | 69.5 | 7.4 | Heavy | 7 | x |
| | HL 4 (P2) | MTO | 51.2 | - | 7.4 | Light | 7 | x |
| | | ASTM | 69.6 | 60.2 | 6.8 | Light | 7 | x |

* Criteria MTO LS-283 at 30 mm Hg residual pressure for 1 hour — Minimum Marshall retained stability (MRS) of 70 percent.
ASTM D 4867 at 500 mm Hg vacuum for 5 minutes — Minimum tensile strength ratio (TSR) of 75 percent.
✓ Passing the criteria.
x Failing the criteria.

(SEE FIGURE A2 ALSO)

## FIGURE A2 PHASE 2 - STANDARD MIXES
## STRENGTH RATIO FOR SURFACE COURSE MIXES



## TABLE A7 PHASE 2 TEST RESULTS FOR ADDITIONAL SURFACE COURSE MIXES

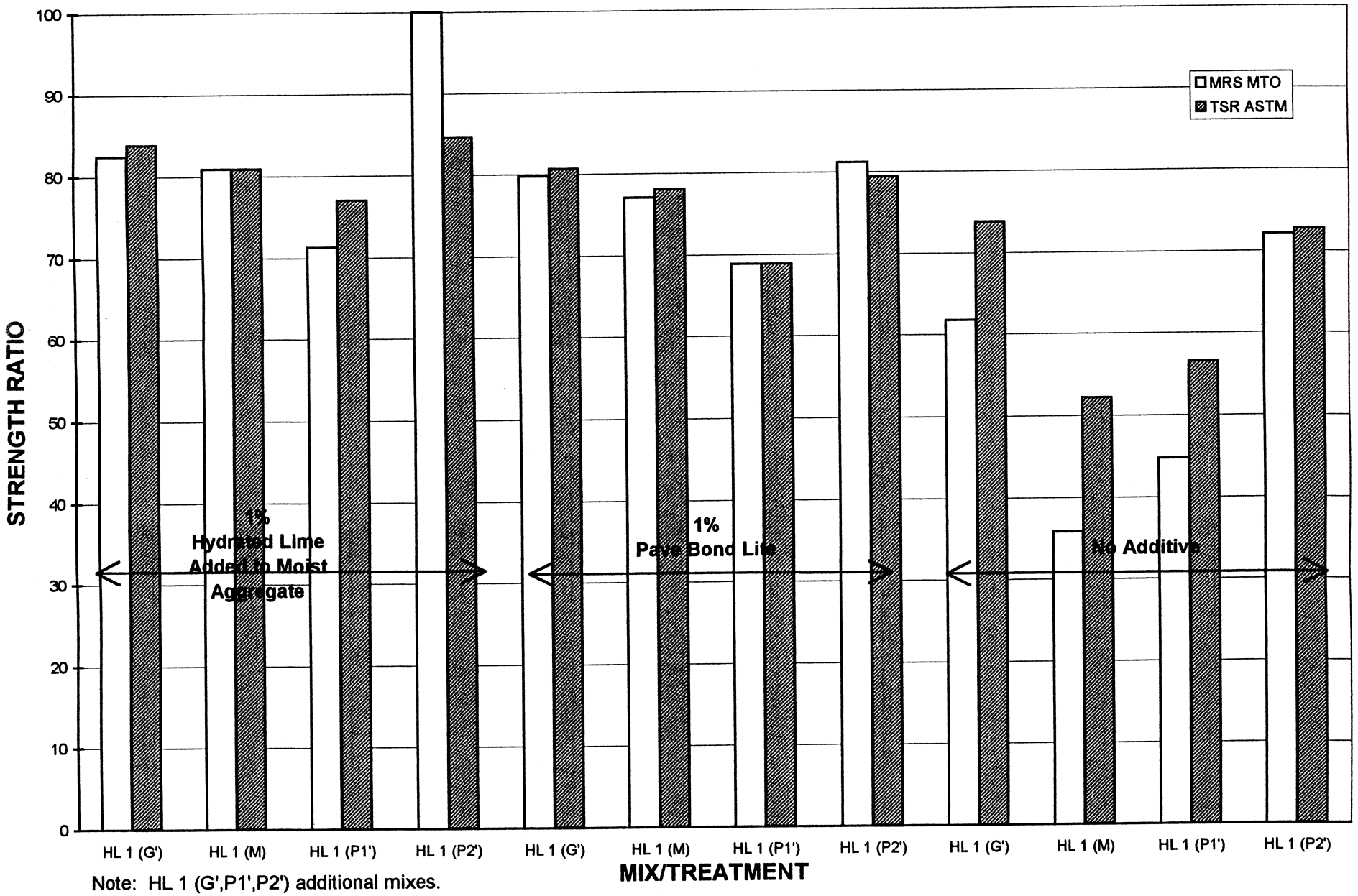
| TREATMENT | MIX | METHOD | MSR OR TSR | SATURATION (%) | AIR VOIDS (%) | COATING RATING UNCONDITIONED (DRY) | STRIPPING RATING CONDITIONED (WET) | CRITERIA* |
|---|---|---|---|---|---|---|---|---|
| Hydrated Lime (1%) | HL 1 (G′) | MTO | 82.5 | - | 7.4 | Medium | 6 | ✓ |
| | | ASTM | 83.9 | 65.1 | 7.2 | Medium | 3 | ✓ |
| | HL 1 (M) | MTO | 80.9 | - | 6.6 | Heavy | 7 | ✓ |
| | | ASTM | 80.9 | 70.1 | 6.6 | Heavy | 4 | ✓ |
| | HL 1 (P1′) | MTO | 71.3 | - | 6.7 | Medium | 5 | ✓ |
| | | ASTM | 77.0 | 70 | 6.1 | Medium | 5 | ✓ |
| | HL 1 (P2′) | MTO | 100 | - | 7.5 | Medium | 3 | ✓ |
| | | ASTM | 84.7 | 61.1 | 7.1 | Medium | 4 | ✓ |
| Pave Bond Lite (1%) | HL 1 (G′) | MTO | 79.8 | - | 6.8 | Medium | 6 | ✓ |
| | | ASTM | 80.7 | 62.7 | 6.7 | Heavy | 3 | ✓ |
| | HL 1 (M) | MTO | 77.1 | - | 6.1 | Heavy | 3 | ✓ |
| | | ASTM | 78.1 | 62.4 | 5.9 | Heavy | 3 | ✓ |
| | HL 1 (P1′) | MTO | 68.6 | - | 6.1 | Medium | 5 | x |
| | | ASTM | 68.6 | 64.6 | 5.6 | Heavy | 5 | x |
| | HL 1 (P2′) | MTO | 81.2 | - | 6.6 | Medium | 4 | ✓ |
| | | ASTM | 79.4 | 76.7 | 6.0 | Light | 4 | ✓ |
| No Additive | HL 1 (G′) | MTO | 61.8 | - | 6.4 | Medium | 8 | x |
| | | ASTM | 73.8 | 63.5 | 6.4 | Heavy | 6 | x |
| | HL 1 (M) | MTO | 35.8 | - | 6.4 | Heavy | 9 | x |
| | | ASTM | 52.2 | 58.5 | 5.6 | Heavy | 6 | x |
| | HL 1 (P1′) | MTO | 44.7 | - | 6.4 | Medium | 6 | x |
| | | ASTM | 56.5 | 69.2 | 5.7 | Medium | 8 | x |
| | HL 1 (P2′) | MTO | 72.1 | - | 6.5 | Heavy | 7 | ✓ |
| | | ASTM | 72.7 | 66.5 | 6.4 | Medium | 6 | x |

Note: HL 1 (G′, P1′, P2′) are the additional standard mixes.

* Criteria MTO LS-283 at 30 mm Hg residual pressure for 1 hour — Minimum Marshall retained stability (MRS) of 70 percent.
ASTM D 4867 at 500 mm Hg vacuum for 5 minutes — Minimum tensile strength ratio (TSR) of 75 percent.
✓ Passing the criteria.
x Failing the criteria.

(SEE FIGURE A3 ALSO)

## FIGURE A3 PHASE 2 - STRENGTH RATIO FOR ADDITIONAL SURFACE COURSE MIXES




Note: HL 1 (G',P1',P2') additional mixes.

## TABLE A8 PHASE 3 - STAGE 1 TEST RESULTS FOR BASE COURSE STANDARD MIXES

| TREATMENT | MIX HL 4 | METHOD | MSR OR TSR | SATURATION (%) | AIR VOIDS (%) | COATING RATING UNCONDITIONED (DRY) | STRIPPING RATING CONDITIONED (WET) | CRITERIA*** |
|---|---|---|---|---|---|---|---|---|
| Hydrated lime (1%) Added dry | G | ASTM | 76.2 | 66.8 | 7.1 | Heavy | 4 | ✓ |
| | M | ASTM | 67.5 | 64.1 | 6.2 | Medium stain | 7 | x |
| | P1 | ASTM | 82.2 | 60.7 | 6.7 | Medium | 4 | ✓ |
| No Additives | G | ASTM | 56.8 | 70.1 | 7.2 | Medium | 8 | x |
| | M | ASTM | 42.7 | 61.1 | 6.5 | Medium | 7 | x |
| | P1 | ASTM | 42.9 | 60.0 | 7.5 | Medium stain | 7 | x |
| Pave Bond Lite (1%) | G* | MTO | 82.2 | - | 6.8 | Heavy | 4 | ✓ |
| | | ASTM | 69.7 | 63.7 | 6.8 | Heavy | 5 | x |
| | M* | MTO | 80.2 | - | 6.5 | Light | 4 | ✓ |
| | | ASTM | 75.8 | 65.7 | 6.4 | Light | 5 | ✓ |
| | P1* | MTO | 84.7 | - | 6.9 | Medium | 3 | ✓ |
| | | ASTM | 79.2 | 68.3 | 6.8 | Medium | 3 | ✓ |
| No Additives | G* | MTO | 72.3 | - | 6.8 | Medium | 5 | ✓ |
| | | ASTM | 67.8 | 69.4 | 6.8 | Medium | 5 | x |
| | M* | MTO | 51.2 | - | 6.5 | Light | 6 | x |
| | | ASTM | 48.7 | 73.1 | 6.1 | Heavy stain | 7 | x |
| | P1* | MTO | 68.9 | - | 6.8 | Medium | 7 | x |
| | | ASTM | 71.2 | 64.5 | 7.0 | Medium | 7 | x |
| Pave Bond Lite (1%) | P1** | MTO | 79.7 | - | 6.5 | Medium | 4 | ✓ |
| No Additives | P1** | MTO | 72.6 | - | 6.6 | Medium | 4 | ✓ |

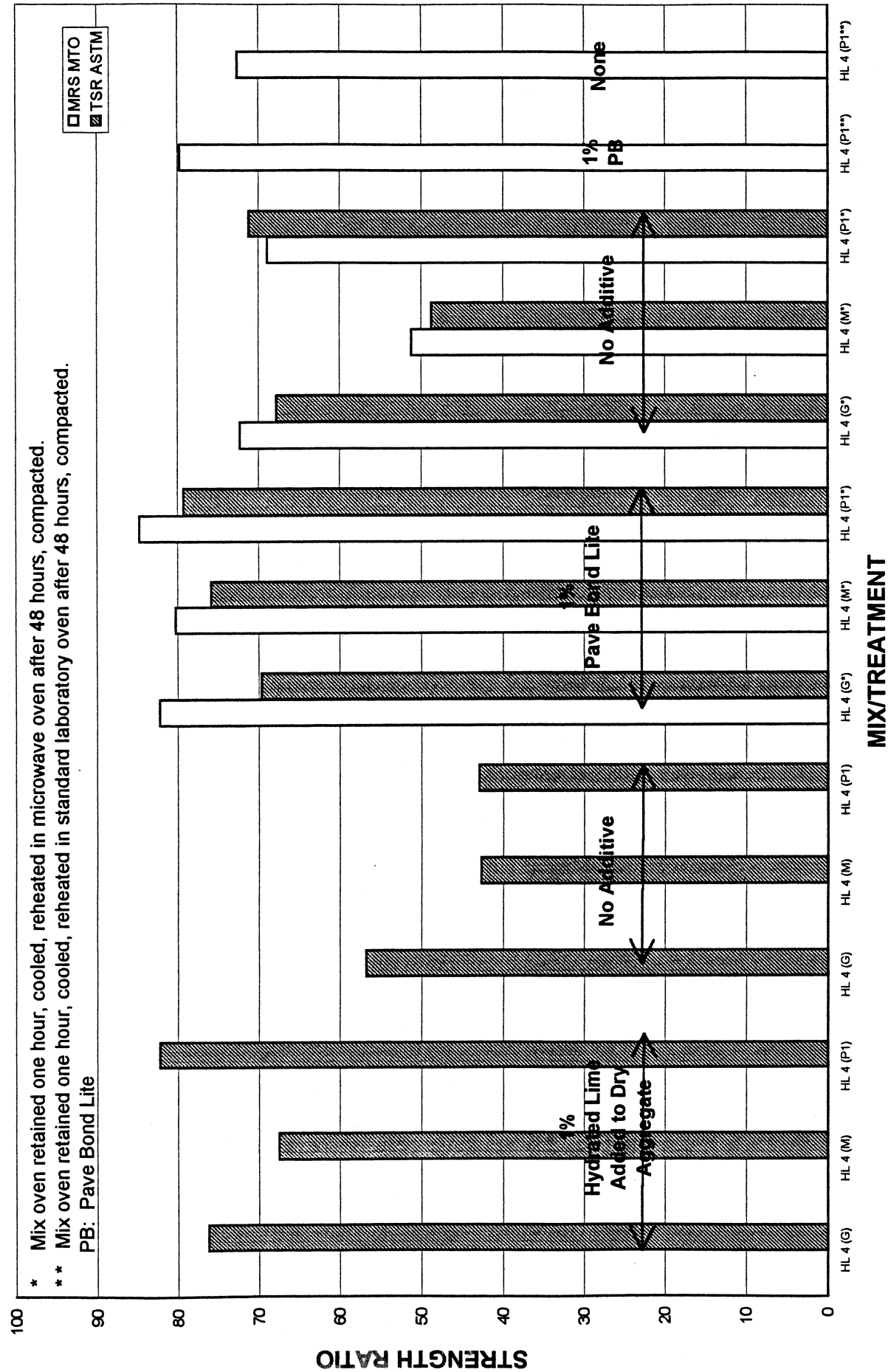
* MTO LS-283 and ASTM D 4867 - Mix oven retained one hour, cooled, reheated in microwave after 48 hours, compacted.

** MTO LS-283 - Mix oven retained one hour, cooled, reheated in standard oven after 48 hours, compacted.

*** Criteria MTO LS-283 at 30 mm Hg residual pressure for 1 hour — Minimum Marshall retained stability (MRS) of 70 percent.
ASTM D 4867 at 500 mm Hg vacuum for 5 minutes — Minimum tensile strength ratio (TSR) of 75 percent.
✓ Passing the criteria.
x Failing the criteria.

(SEE FIGURE A4 ALSO)

**FIGURE A4 PHASE 3 - STAGE 1 - STANDARD MIXES**
**STRENGTH RATIO FOR BASE COURSE MIXES**



## TABLE A9 PHASE 3 - STAGE 2 TEST RESULTS FOR BASE COURSE SPECIAL MIXES*

| TREATMENT | ASPHALT CEMENT | MSR OR TSR | SATURATION (%) | AIR VOIDS (%) | COATING RATING UNCONDITIONED (DRY) | STRIPPING RATING CONDITIONED (WET) | CRITERIA*** |
|---|---|---|---|---|---|---|---|
| Hydrated Lime (1%) | 85-100 Group A (Petro Canada) | 71.7 | 72.5 | 6.8 | Light | 6 | x |
| | 85-100 Venezuelan (Esso) | 81.1 | 60.5 | 6.8 | Light | 6 | ✓ |
| | 150-200 Group A (Petro Canada)** | 73.3 | 74.7 | 6.9 | Heavy stain | 6 | x |
| | 150-200 Venezuelan (Esso) | 76.7 | 61.3 | 6.5 | Light | 5 | ✓ |
| | PG 58-34 (Esso) | 86.6 | 57.7 | 5.9 | Light | 5 | ✓ |
| | PG 58-34 (McAsphalt) | 80.0 | 64.1 | 6.5 | Light | 5 | ✓ |
| Pave Bond Lite (1%) | 85-100 Group A (Petro Canada) | 73.1 | 63.1 | 6.0 | Heavy stain | 6 | x |
| | 85-100 Venezuelan (Esso) | 74.1 | 67.3 | 5.8 | Light | 5 | x |
| | 150-200 Group A (Petro Canada)** | 86.9 | 62.7 | 6.2 | Light | 3 | ✓ |
| | 150-200 Venezuelan (Esso) | 78.0 | 64.0 | 6.1 | Light | 5 | ✓ |
| | PG 58-34 (Esso) | 71.4 | 60.1 | 5.5 | Light stain | 5 | x |
| | PG 58-34 (McAsphalt) | 74.6 | 70.8 | 6.0 | Light | 5 | x |
| No Additive | 85-100 Group A (Petro Canada) | 56.0 | 67.8 | 6.2 | Light | 7 | x |
| | 85-100 Venezuelan (Esso) | 53.3 | 62.0 | 5.8 | Light | 7 | x |
| | 150-200 Group A (Petro Canada)** | 42.7 | 61.1 | 6.5 | Medium | 7 | x |
| | 150-200 Venezuelan (Esso) | 60.8 | 58.9 | 5.8 | Heavy stain | 7 | x |
| | PG 58-34 (Esso) | 67.3 | 61.3 | 5.2 | Light stain | 7 | x |
| | PG 58-34 (McAsphalt) | 54.7 | 73.9 | 6.3 | Light | 7 | x |

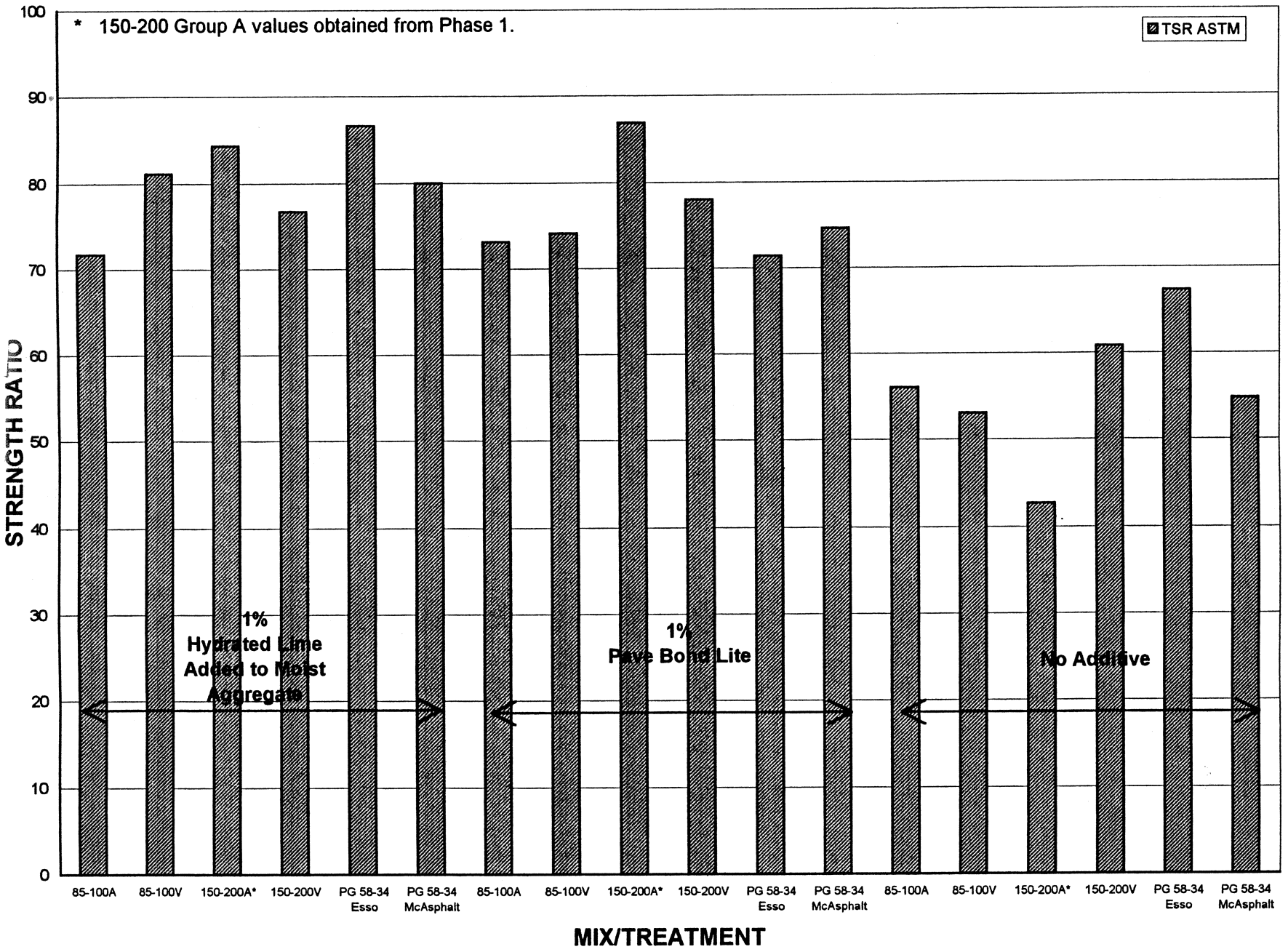
* HL 4 (M) was used since it gave the worst performance with respect to stripping resistance for ASTM D 4867.

** 150-200 A was the asphalt cement used in Phases 1, 2 and 3 - Stage 1. Test results shown are from Phase 1.

*** Criteria MTO LS-283 at 30 mm Hg residual pressure for 1 hour — Minimum Marshall retained stability (MRS) of 70 percent.
ASTM D 4867 at 500 mm Hg vacuum for 5 minutes — Minimum tensile strength ratio (TSR) of 75 percent.
✓ Passing the criteria.
x Failing the criteria.

(SEE FIGURE A5 ALSO)

## FIGURE A5 PHASE 3 - STAGE 2 SPECIAL MIXES
## STRENGTH RATIO FOR WORST PERFORMANCE MIX (HL 4 (M))



## TABLE A10 NEWFOUNDLAND AGGREGATES - TEST RESULTS

| MIX | HYDRATED LIME ADDED TO MOIST AGGREGATE (1%) | | NO ADDITIVE | |
|---|---|---|---|---|
| | MTO LS-283 at 30 mm Hg | ASTM D 4867 | MTO LS-283 at 30 mm Hg | ASTM D 4867 |
| MRS OR TSR | 69.0 | 74.2 | 45.9 | 61.1 |
| % Saturation | - | 56.1 | - | 79.4 |
| % Air Voids | - | 6.0* | - | 6.0* |
| Coating Rating | Heavy | Medium | Medium | Medium |
| Stripping Rating | 5 | 6 | 9 | 7 |
| Criteria** | x | x | x | x |

* Air voids assumed to be 6.0 percent.

** Criteria MTO LS-283 at 30 mm Hg residual pressure for 1 hour — Minimum Marshall retained stability (MRS) of 70 percent.

ASTM D 4867 at 500 mm Hg vacuum for 5 minutes — Minimum tensile strength ratio (TSR) of 75 percent.

✓ Passing the criteria.

x Failing the criteria.

## TABLE A11 CEMENT KILN DUST HL 4 BASE COURSE STANDARD MIX - TEST RESULTS

| TREATMENT MIX HL 4 (M) | METHOD | MRS OR TSR | SATURATION (%) | AIR VOIDS (%) | COATING RATING UNCONDITIONED (DRY) | STRIPPING RATING CONDITIONED (WET) | CRITERIA** |
|---|---|---|---|---|---|---|---|
| CKD (0 %) No Additive | MTO | 49.9 | - | 6.4 | Light Stain | 7 | x |
| | ASTM | 43.4 | 71.6 | 6.5 | Light Stain | 7 | x |
| CKD (1%) Added to Moist Aggregates | MTO | 64.9 | - | 6.5 | Medium Stain | 6 | x |
| | ASTM | 71.1 | 75.7 | 6.1 | Medium Stain | 6 | x |
| CKD (2%) Added to Moist Aggregates | MTO | 58.7 | - | 6.0 | Medium Stain | 6 | x |
| | ASTM | 62.8 | 69.6 | 6.0 | Medium Stain | 6 | x |
| TEST RESULTS FOR HL 4 BASE COURSE WITH DIFFERENT ANTISTRIPPING ADDITIVES | | | | | | | |
| Hydrated Lime (1%) Added to moist aggregates | MTO | 79.2 | - | 7.3 | Medium | 5 | ✓ |
| | ASTM | 73.3 | 74.7 | 6.9 | Heavy stain | 6 | x |
| | (ASTM)* | 84.3 | 67.3 | 7.0 | Light | 6 | ✓ |
| Pave Bond Lite (0.5%) | MTO | 70.6 | - | 6.7 | Medium | 4 | ✓ |
| | ASTM | 63.9 | 70.0 | 6.1 | Light | 8 | x |
| Pave Bond Lite (1%) | MTO | 82.2 | - | 6.7 | Light | 4 | ✓ |
| | ASTM | 86.9 | 62.7 | 6.2 | Light | 3 | ✓ |
| No Additive | MTO | 41.2 | - | 6.6 | Light | 6 | x |
| | ASTM | 42.7 | 61.1 | 6.5 | Medium | 7 | x |

* ASTM D 4867 at 1.5% hydrated lime.

** Criteria MTO LS-283 at 30 mm Hg residual pressure for 1 hour — Minimum Marshall retained stability (MRS) of 70 percent.
ASTM D 4867 at 500 mm Hg vacuum for 5 minutes — Minimum tensile strength ratio (TSR) of 75 percent.
✓ Passing the criteria.
x Failing the criteria.

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