HYDRATED **LIME**

A PROVEN ADDITIVE FOR DURABLE ASPHALT PAVEMENTS

critical literature review

The incorporation of hydrated lime into asphalt is a relatively old practice, since the first addition dates back to the late nineteenth century in the United States. In Europe, hydrated lime was cited by Duriez to improve bitumen/aggregate adhesion in the 1950s. Today, feedback from experience in the field and the numerous laboratory studies conducted on the subject all lead to the same conclusion: hydrated lime is not only an adhesion-promoter but it is a multifunctional additive profoundly modifying the properties of asphalt.

By reacting with both bitumen and aggregate, by chemical (microscopic level) or physical (macroscopic level) interactions, hydrated lime:

- improves bitumen/aggregate adhesion
- slows down the oxidation of bitumen (age hardening)
- stiffens the mastic at high temperature (improving the rutting resistance) without weakening it at low temperature (temperature-dependent stiffening effect).

Today, about 40 Mt of the bituminous mixtures produced in the United States contain hydrated lime. According to road agencies, the estimated gains in durability for surface layers vary from 20% to 50%.

For the same reasons, road administrations in the Netherlands require the use of hydrated lime in its porous asphalt. Other European countries such as Switzerland, the UK and Austria are also using the technique on a regular basis.

In France, the private highway agency SANEF requires the addition of 1.5% hydrated lime in the surface layers of its road network, having observed that asphalt mixtures containing hydrated lime were 20-25% more durable. The systematic use of hydrated lime dates back to 2003, but its inclusion is much older and goes back to the very first porous asphalt placed in France on its network in the early 1980s.

Thus,hydrated lime benefits from extensive practical experience together with numerous laboratory studies conducted worldwide. This document aims to report the experience accumulated through one hundred published studies on the use of hydrated lime in asphalt paving. The reader will thus be able to better understand the mechanisms of action, the benefits as well as the limitations of this additive which is still relatively unknown in the road transport industry.

This study was carried out as part of a working group on asphalt paving, by the European Lime Association (EULA).

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CRITICAL LITERATURE REVIEW

Report to the European Lime Association / Asphalt Task Force

December 2011

Foreword

It is scientifically proven that hydrated lime has beneficial effects on the asphalt mixtures used in road construction. This has been studied in depth in the USA where hydrated lime is present in 10% of the Hot Mix Asphalt (HMA) produced each year. Unfortunately, in Europe, the functionalities of hydrated lime are still rather poorly known and thus the use of hydrated lime is less usual.

In the recent years, Europe has been reconsidering the design and management of road infrastructures to better meet the needs generated by the increase of heavy traffic and by environmental concerns. Additionally, constrained budgets require to better optimize the use of all available resources (financial, materials, etc.).

To take advantage of this context, the **European Lime Association (EuLA)** has decided to develop the European awareness on the benefits of hydrated lime in asphalt mixtures, the challenge being to convince the road community to use hydrated lime in a more systematic way. To address this issue, and due to the complexity of this market, it is crucial for the lime industry to have a credible and consistent message.

In 2008, a first EuLA ad-hoc group produced a promotional leaflet called "Lime in asphalt paving" available on the EuLA website (www.eula.be/121.html#c1285).

In 2009, EuLA has decided to go further and to set up, within the Lime Application Committee, an **Asphalt Task Force (ATF)** with the following key objectives:

1. Establish a European long term strategy (5 to 10 years) for the promotion of the use of hydrated lime in asphalt mixtures,
2. Streamline and coordinate the national and regional approaches,
3. Pool lime industry resources to foster or initiate scientific research,
4. Develop promotional tools and actions.

The ATF started its work by gathering European data, country by country, on the state of development of the use of hydrated lime in asphalt mixtures, essentially HMA. Table 1 summarizes the current situation.

Then, one of the tasks also assigned to the ATF was to summarize the existing knowledge on the modification of Hot Mix Asphalts by hydrated lime. From this, a better understanding of hydrated lime functionalities in this application was sought for. Also, existing gaps in knowledge could be identified in order to launch new research works.

All members of the ATF participated in sharing the information they already had on the topic. This large amount of published work was then gathered and studied. As a result, D. Lesueur prepared a first version of this report, which was carefully reviewed by J. Petit, D. Puiatti and H.-J. Ritter.

Then, a second version was written based on the initial review and all members of the ATF contributed with their comments. This third and final version of the report takes into accounts all of these contributions.

Acknowledgments: the Author would like to thank all of the ATF members for their valuable help and comments in the preparation of this report.

All inquiries about this report or the ATF shall be sent to e-mail: secretariat@ima-europe.eu

The **composition of ATF** at the time of writing this report was:

- **chairman**: Daniel Puiatti (Lhoist Europe),
- **secretary**: Bert D'Hooghe (IMA-Europe/EuLA),
- **technical experts**: Didier Lesueur (Lhoist R&D), Jöelle Petit (Carmeuse Benelux), Hans-Josef Ritter (Bundesverband der Deutschen Kalkindustrie e.V.),
- **active members ATF**: Gorka Argaiz (Calcinor), Hans--Günther Brendl (Schaefer Kalk), Larry Byrne (Clogrennane Lime), Angelo Canziani (Unicalce), Joe Connolly (Clogrennane Lime), Christophe Denayer (Carmeuse), Steve Foster (Singleton Birch), Christoph Kunesch (Wopfinger Baumit), Emma Lopez (Ancade), Alan Lowe (Roadstone), Siegmund Luger (Schaefer Kalk), Stefan Neumann (Wopfinger Baumit), Rafal Pozyczka (Lhoist Poland), Martin Sarobe (Calcinor), Tom Zaremba (Lhoist North America).

Country	Level of experience	Start	[Lime treated HMA] vs [total HMA] (estimated in %)	% hydrate in HMA	Form	Objective	Applications
Austria	voluntary	2003	1	1.5 to 3.5	pure	stripping, rutting	AC, SMA, PA
Belgium	from compulsory to voluntary	80's	< 1	1.5	mixed filler	stripping	SMA, PA (asphalt rubber)
Czech Republic	tests	1996	< 1	1.5	pure	stripping, rutting	AC, PA (asphalt rubber)
Denmark	voluntary	mid 90's	< 1	1 to 1.5	pure	stripping	AC
Finland	voluntary	?	< 1	1 to 2	pure or mixed filler	stripping, aging, other	AC, SMA, CMA
France	voluntary	? (> 1945)	1	1 to 1.5	pure or mixed filler	stripping, aging, other	AC, CMA, PA, PA (asphalt rubber), BBTM
Germany	voluntary	2000	< 1	1 to 3	pure or mixed filler	stripping, aging	AC, SMA
Hungary	tests	2009	< 1	2	to be defined	stripping, rutting	AC
Ireland	voluntary	2001	< 1	2	pure	stripping, rutting	PA
Italy	voluntary	mid 90's	< 1	1 to 2	mixed filler	stripping	SMA, PA
The Netherlands	compulsory	mid 90 's	7	2	mixed filler	stripping, aging, durability	PA
Poland	voluntary	1998	< 1	1 to 3	mixed filler	stripping	AC
Portugal	voluntary	beginning 2000's	< 1	1 to 2	pure	stripping	PA (asphalt rubber)
Romania	tests	2007	< 1	2	mixed filler	stripping, rutting	AC, SMA
Slovakia	tests	2009	< 1	2	pure or mixed filler	stripping	
Spain	voluntary	2004	< 1	1 to 2	pure	stripping	SMA
Sweden	voluntary / compulsory	1998	< 1	1	pure	stripping, aging	AC
Switzerland	preferred	2006	1	1.5	pure	stripping, aging, durability	PA, AC, SMA,
UK	voluntary	early 2000's	1	1 to 2	pure	stripping	AC

Table 1. Current use of hydrated lime in asphalt mixtures in Europe. All data were gathered by the Asphalt Task Force. Note that the values for the percentage of HMA modified with hydrated lime in the total HMA production is a rough estimate used to quantify the level of "lime awareness" in each country. Orange color: more than 5% of the HMA production is modified with hydrated lime; grey color – about 1%. AC – asphalt concrete; SMA – stone mastic asphalt; PA – porous asphalt; CMA – cold mix asphalt; BBTM – very thin asphalt layer.

Content

Summary

Hydrated lime has been known as an additive for asphalt mixtures from their very beginning. It experienced a strong interest during the 1970s in the USA, partly as a consequence of a general decrease in bitumen quality due to the petroleum crisis of 1973, when moisture damage and frost became some of the most pressing pavement failure modes of the time. Hydrated lime was observed to be the most effective additive and as a consequence, it is now specified in many States and it is estimated that 10% of the asphalt mixtures produced in the USA now hold hydrated lime.

Given its extensive use in the past 40 years in the USA, hydrated lime has been seen to be more than a moisture damage additive. As is detailed in this report, hydrated lime is known to reduce chemical ageing of the bitumen. Furthermore, it stiffens the mastic more than normal mineral filler, an effect that is only observed above room temperature. This impacts the mechanical properties of the asphalt mixture, and if strength and modulus are seen to be modified by hydrated lime addition for a little more than half of the mix formulas, it improves the rutting resistance in about 75% of the mix formulas. In all cases, most of the studies focus on hydrated lime contents of 1-1.5%, and these effects are generally more pronounced for higher hydrated lime contents. Finally, the few published studies on fatigue resistance indicate that hydrated lime improves the fatigue resistance of asphalt mixtures in 77% of the cases.

In line with the observation that hydrated lime does not exhibit a higher stiffening effect than mineral filler at low temperature, no effect on the thermal cracking resistance is reported in the literature.

The reasons why hydrated lime is so effective in asphalt mixtures lie in the strong interactions between the major components, i.e. aggregate and bitumen, and the combination of 4 effects, two on the aggregate and two on the bitumen. Hydrated lime modifies the surface properties of aggregate, allowing for the development of a surface composition (calcium ions) and roughness (precipitates) more favourable to bitumen adhesion. Then, hydrated lime can treat the existing clayey particles adhering to the aggregate surface, inhibiting their detrimental effect on the mixture. Also, hydrated lime reacts chemically with the acids of the bitumen, which in turns slows down the age hardening kinetics and neutralizes the effect of the "bad" adhesion promoters originally present inside the bitumen, enhancing the moisture resistance of the mixture. Finally, the high porosity of hydrated lime explains its stiffening effect above room temperature. The temperature dependence and the kinetics of the stiffening effect might explain why hydrated lime is not always observed to stiffen asphalt mixtures and why it is more efficient in the high temperature region where rutting is the dominant distress.

The various ways to add hydrated lime, i.e., into the drum, as mixed filler, dry to the damp aggregate, as lime slurry, with or without marination are described. No definitive evidence demonstrates that one method is more effective than the other, and all methods are seen to allow for the beneficial effects of hydrated lime to develop. As far as fabrication control is concerned, hydrated lime can be easily quantified inside the mixture.

Given that all the above mixture properties impact the durability of asphalt mixtures, the use of hydrated lime has a strong influence on asphalt mixtures durability. The field experience from North American State agencies estimate that hydrated lime at the usual rate of 1-1.5% in the mixture (based on dry aggregate) increases the durability of asphalt mixtures by 2 to 10 years, that is by 20 to 50%.

The European experience is not yet as developed as in the USA, but the beneficial effects of hydrated lime on asphalt mixture durability have also been largely reported. As an example, the French Northern motorway company, Sanef, currently specifies hydrated lime in the wearing courses of its network, because they observed that hydrated lime modified asphalt mixture have a 20-25% longer durability. Similar observations led the Netherlands to specify hydrated lime in porous asphalt, a type of mix that now covers 70% of the highways in the country. As a result, hydrated lime is being increasingly used in asphalt mixtures in most European countries, in particular Austria, France, the Netherlands, the United Kingdom and Switzerland.

If the benefits of hydrated lime on asphalt mixtures are clearly demonstrated with a diversity of materials (aggregate, bitumen, mixture formulas) covering the 5 continents, the European experience remains somewhat lower than the one coming from the USA. As a consequence, the effect of hydrated lime on asphalt mixtures as measured by several European standard test procedures are not described in the literature. Among those of the highest interest, ITSR and fatigue must be mentioned.

Also, the description of hydrated lime in the European standards for aggregates is not totally appropriate. First, test methods such as the delta ring and ball test can not be performed on hydrated lime, although they are required for mineral fillers. Hydrated lime being considered as a filler in the standards on asphalt mixtures, it is critical to resolve this situation. Then, the mixed filler classes appearing in the aggregate standards do not cover all existing products currently used.

Finally, some theoretical aspects remain to be understood, and in particular the temperature-dependence of the stiffening effect of hydrated lime in bitumen and the modification of the aggregate surface after hydrated lime treatment.

Introduction

Hydrated lime has been used in asphalt mixtures from their very beginning. In the USA, at the end of the 19th century the National Vulcanite Company already used, in the cities of Washington DC and Buffalo, a proprietary asphalt mixture called Vulcanite containing hydrated lime (0.3wt.% of "air-slacked lime" [1]). At the beginning of the 20th century, other proprietary asphalt mixture formulas used in the USA such as Warrenite [2] and Amiesite held hydrated lime [2, 3, 4] and Richardson mentions the use of slaked lime with soft coal tar in England [5].

A few decades later, hydrated lime was still listed as a possible filler component in asphalt mixtures in the USA [6]. At about the same time, in France, Duriez and Arrambide described and recommended the use of hydrated lime as a way to improve bitumen-aggregate adhesion [7]. They mentioned the use of hydrated lime as filler for tarmacadam, the open-graded coal tar mixture principally used for airfield during the 1950's in England, France and Germany.

However, hydrated lime experienced a renewed interest during the 1970's in the USA. Partly as a consequence of a general decrease in bitumen quality due to the petroleum crisis of 1973, moisture damage and frost became some of the most pressing pavement failure modes of the time [8, 9]. The various additives to asphalt mixtures available to limit moisture damage were thoroughly tested both in the laboratory and in the field, and hydrated lime was observed to be the most effective additive [8]. As a consequence, hydrated lime is now specified in many States and it is estimated that 10% of the asphalt mixtures produced in the USA now hold hydrated lime [10].

Given its extensive use in the past 30 years in the USA, hydrated lime has been seen to be more than a moisture damage additive [11, 12, 13, 14]. As will be detailed in this report, hydrated lime is known to reduce chemical ageing of the bitumen. Furthermore, it generally stiffens the mechanical properties of the asphalt mixture which has an impact on the rutting resistance of the mixtures. In parallel, the resistance to cracking is also mentioned to be improved. As a result, and as will also be detailed later on, State agencies estimate that hydrated lime increases the durability of asphalt mixtures for highways by 2 to 10 years, that is by 20 to 50%.

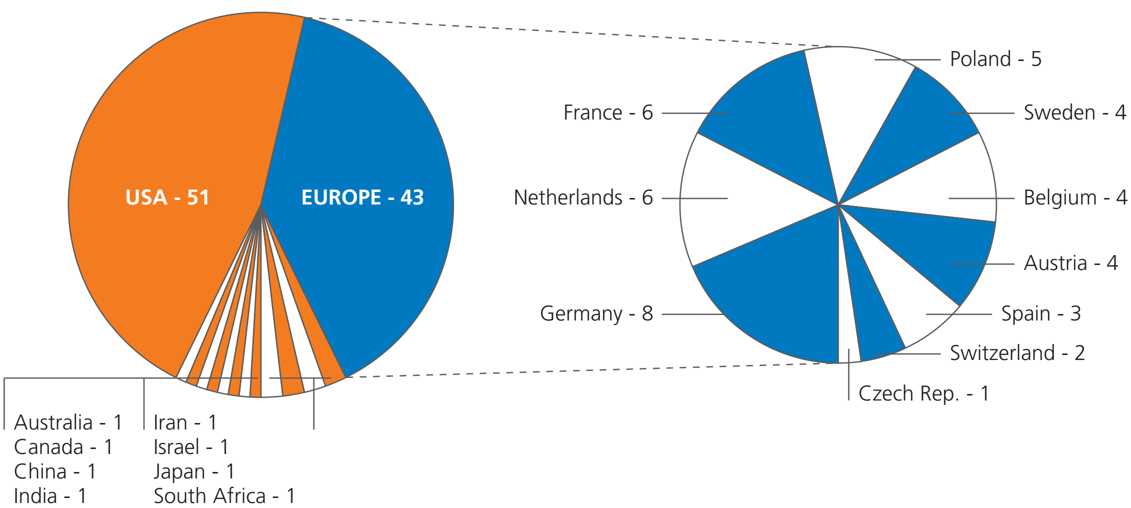


Figure 1. Origin of first author for the documents in the database (110 documents).

The European experience is not yet as developed as in the USA, but the beneficial effect of hydrated lime on asphalt mixture durability has also been largely reported. As an example, the Sanef motorway company, managing 1,740 km of highways in Northern France, currently specifies hydrated lime in the wearing courses of its network [15]. Sanef observed that hydrated lime modified asphalt mixtures have a 20-25% higher durability [15]. Similar observations led the Netherlands to specify hydrated lime in porous asphalt [16, 17], a type of mix that now covers 70% of the highways in the country [18]. As a result, hydrated lime is being increasingly used in asphalt mixtures in most European countries, in particular Austria, France, the Netherlands, the United Kingdom and Switzerland.

Given this context, the objective of this report was to review the existing evidence concerning the increase in durability of asphalt pavements by addition of hydrated lime. Many sources were studied in order to build the report, and a bibliographical database was constructed with 110 documents (see details in Annexes 1 and 2). The origin and publication date of the corresponding documents are given in Figure 1 and Figure 2 respectively.

This confirms that, although a great part of the literature comes from the USA, hydrated lime in asphalt mixture is clearly a subject with a strong interest in all of the major European countries. Publications from other countries like Argentina, Brasil, China, India, Iran, Japan, Korea, Saudi Arabia or Turkey confirm that hydrated lime can be successfully used with any material source. Also, most of the references are quite recent (Figure 2), showing that it is an active research field worldwide.

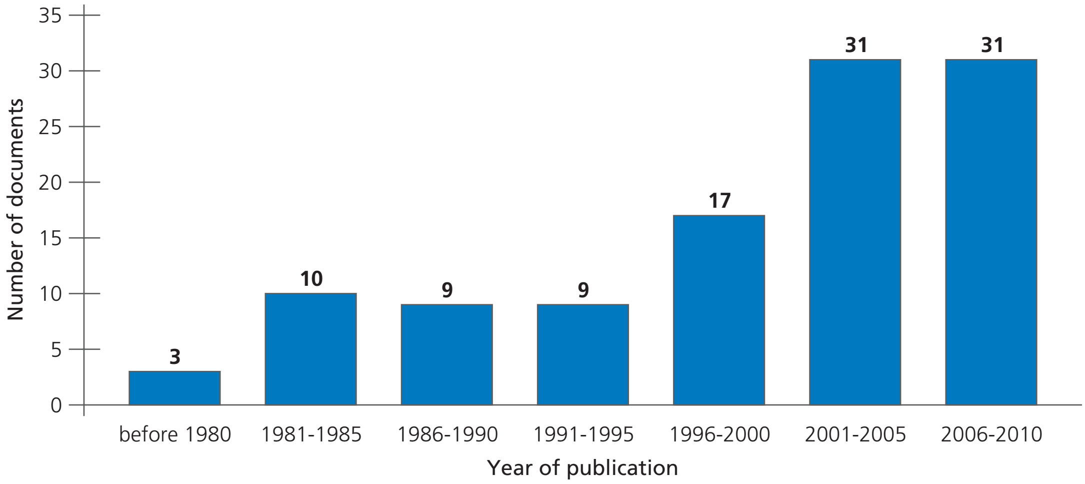


Figure 2. Year of publication of the documents in the database (110 documents).

The structure of the report

In a **first** chapter, hydrated lime is presented, highlighting the relevant properties allowing its use in asphalt mixtures.

Then, a **second** chapter details the effect of hydrated lime on asphalt mixtures based on laboratory testing. The mostly used testing procedures allowing to evaluate several aspects of asphalt mixtures durability are presented, including moisture damage, ageing and mechanical properties (modulus, rutting, fatigue and thermal cracking).

A **third** chapter reviews the current understanding on the mechanisms of hydrated lime modification of asphalt mixtures.

Finally, a **fourth** chapter presents the current practical experience with hydrated lime, not only confirming the laboratory tests on durability but also explaining how hydrated lime is currently used in the asphalt plants.

1. Hydrated lime
as an active filler for asphalt mixtures

1.1 Hydrated lime: properties

Hydrated lime is mainly composed of calcium dihydroxide $Ca(OH)_2$. It is obtained by hydrating quicklime (essentially calcium oxide CaO) using specific equipments called hydrators. Quicklime is manufactured by burning limestone of very high purity (made of calcium carbonate $CaCO_3$) at temperatures around 900°C in dedicated kilns [4].

The same cycle can be performed on dolomite made of $CaCO_3.MgCO_3$, in order to obtain dolime or dolomitic lime (CaO.MgO) and then hydrated dolime or hydrated dolomitic lime ($Ca(OH)_2.Mg(OH)_2$ or $Ca(OH)_2.MgO.Mg(OH)_2$ if it is only partially hydrated – [4]).

Hydrated lime and quicklime, including dolimes, for construction and civil engineering applications are specified within the European standard EN 459-1 [19]. The principal qualities of the various grades of hydrated products are summarized in Table 2. The grades for hydrated calcium lime are labelled:

CL XX S

where **CL** stands for calcium lime and the number **XX** identifies the purity in terms of mass content of CaO + MgO. The letter **S**, standing for "slaked", identifies hydrated products in powder form. This allows for differentiating with quicklimes (Q) and hydrated lime in the form of putties (S PL) or milk of lime (S ML).

Grade	CaO + MgO [wt.%]	Available lime [wt.%]
CL 90 S	≥ 90	≥ 80
CL 80 S	≥ 80	≥ 65
CL 70 S	≥ 70	≥ 55

Table 2. The various grades of hydrated lime according to EN 459-1:2010.

As far as asphalt mixtures modification is concerned, standard calcic hydrated lime is the mostly used product. Still, hydrated dolime is also mentioned and was shown to behave in a similar manner [20, 21, 22]. **Quicklime**, on the opposite, **was shown to be detrimental when used as a substitute for hydrated lime** [20]. Still, some very specific applications use either quicklime or hydrated lime with porous aggregate (basalt, slag, ...) in order to prevent the so-called "soup--phenomenon" observed when the water from the aggregate emulsifies the bitumen during mixture transportation [23]. But in this case, the remaining water inside the porosity of the aggregate hydrates the quicklime and in the end, hydrated lime is present in the mixtures. Therefore, this report will focus on standard hydrated lime, although the results mostly apply to hydrated dolime as well.

Hydrated lime purity can be assessed by EN 459-2 [24]. The method consists basically in an acid-base titration. The same principle is used to quantify hydrated lime in asphalt mixtures as detailed in Chapter 4.

Hydrated lime generally comes in the form of a dry white powder (Figure 3) with a particle density close to 2.2 Mg/m^3 [4]. Because of a high level of particle porosity (of order 50%), its apparent density typically ranges from 0.35 to 0.8 Mg/m^3 as measured by EN 459-2.

As will be detailed in Chapter 4, hydrated lime can be used directly as such on an asphalt plant using a dedicated silo. However; some plants do not have the possibility to have a specific silo for hydrated lime and therefore prefer to use mixed filler consisting of a blend of between 10% to 75% of hydrated lime with another filler, generally a pure limestone filler.

Figure 3. Hydrated lime (source: Lhoist).

1.2 Hydrated lime as a filler

Because of its mineral origin and powder form, hydrated lime is generally compared to mineral fillers in the asphalt industry. In fact, the European standards for hot-mix asphalt (series EN 13108-1 through -7) state that hydrated lime shall be considered as filler and note 1 in paragraph 4.3.4 clearly says: "filler includes materials as cement and hydrated lime" [25].

In this sense, hydrated lime can be evaluated using the specifications on aggregates for asphalt mixtures as detailed in EN 13043 [26]. More precisely, the relevant part of this standard for hydrated lime is the one dealing with fillers. The case of mixed filler is also described in the standard.

The standard mainly considers the properties of the filler related to its stiffening effect on the bitumen. In particular, the voids of the dry compacted filler (Rigden air voids) and delta ring and ball are measured.

1.2.1 Voids of the dry compacted filler (Rigden air voids)

The voids of the dry compacted filler (EN 1097-4 [27]) consists in measuring the density of a compacted specimen of the studied filler and divide it by the particle density of the filler. The ratio therefore gives the volume fraction of voids in the packed filler. The test was proposed by P. J. Rigden of the British Road Research Laboratory back in 1947 [28] and is therefore also known as "Rigden air voids".

Mineral fillers generally have voids ranging from 28 to 45% [29, 30, 31, 32, 33, 34], 30-34% being the usual range for many fillers such as most limestone fillers, as pictured in Figure 4. Hydrated lime has a lot higher Rigden value, generally between 60 and 70%, 65% being a common value [29, 31].

When mixed fillers are concerned, Rigden air voids increase when the hydrated lime content increases, with typical values in the 45-50% range for 25wt.% hydrated lime in the mixed filler ([29, 31, 35] – Figure 4). Note that fly ash also contributes to increasing the Rigden air voids value [35].

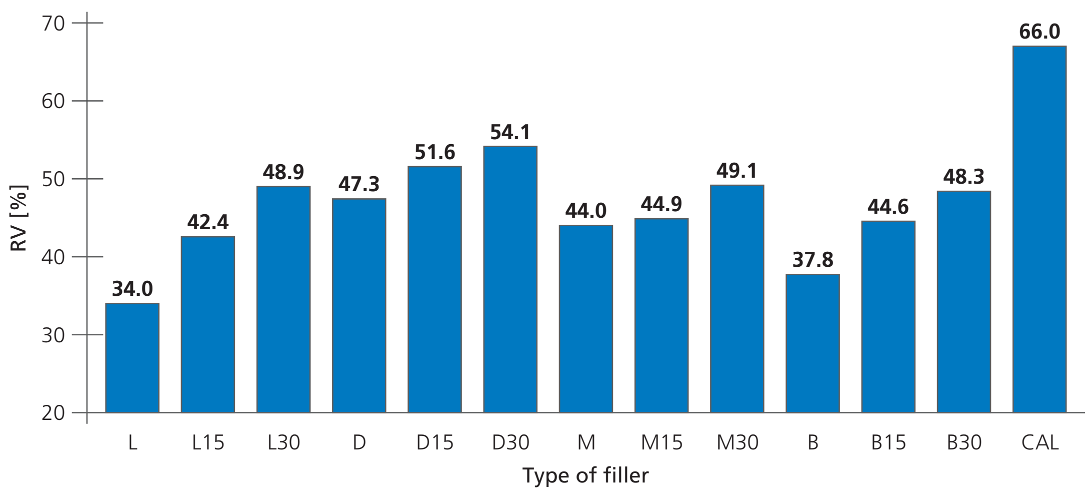


Figure 4. Rigden air voids of several fillers and mixed fillers. L – limestone; D - dolomite; M – melaphyr; B – basalt; CAL – hydrated lime; X15 – filler X with 15wt.% hydrated lime; X30 – filler X with 30wt.% hydrated lime (from [31]).

1.2.2 Delta ring and ball

The delta ring and ball test (EN 13179-1 [36]) consists in measuring the increase in softening temperature of a 70/100 bitumen after addition of 37.5vol.% of the studied filler.

Mineral fillers typically have delta ring and balls between 8 and 25°C, 15°C being a common value ([29, 31] – Figure 5).

As detailed in several studies [31, 37], the test can not be performed on pure hydrated lime. As a matter of fact, the stiffening power of hydrated lime is so pronounced that the 37.5vol.% blend is not fluid enough to prepare the test specimen.

Still, lower amount of hydrated lime than the one specified in the European standard allow quantifying the stiffening effect [37, 38, 39], as pictured in Figure 6. For example, German studies generally use a Stability Index consisting in finding the filler/bitumen ratio that raises the Ring and Ball value of a 200 penetration bitumen by 20°C [38, 39]. Values for hydrated lime are typically in the 0.7-1.0 range, meaning that hydrated lime contents of 40-50wt.% raise the Ring and Ball value by 20°C. Mineral fillers usually have values in the 1.5-2.5 range [29, 37, 38, 39].

As a consequence, when hydrated lime is used in the form of a mixed filler, 15 and 30wt.% hydrated lime were seen to increase the delta ring and ball by, respectively, 2 to 10°C and 8 to 20°C (Figure 5).

Note that the volume fraction used in the test is not representative of the typical hydrated lime content in an asphalt mixture. As detailed in a later section, typical hydrated lime content in an asphalt mixture is 1-1.5wt.% based on dry aggregate. For a typical binder content of 5wt.% (based on dry aggregate), this amounts to 20-30wt.% or 10-15vol.% hydrated lime in the bitumen.

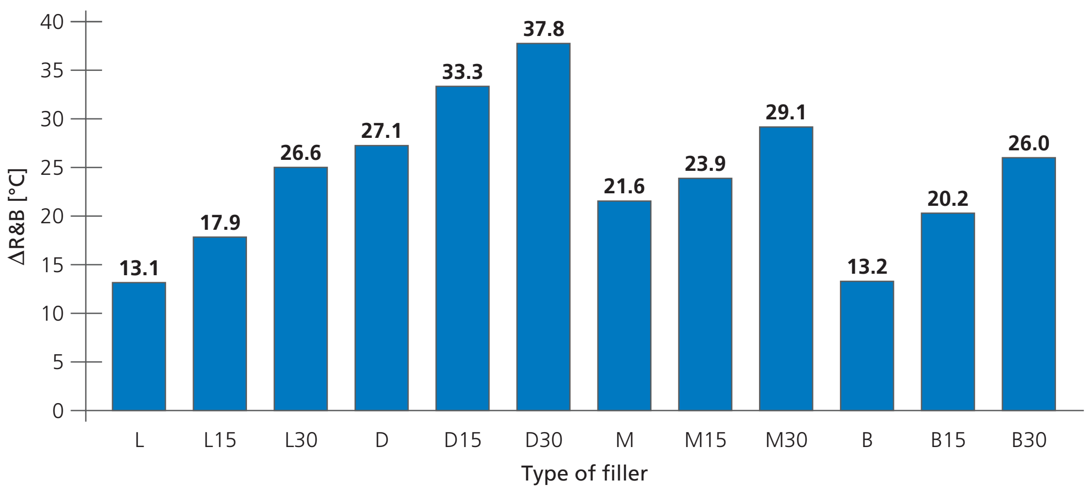


Figure 5. Delta ring and ball of several fillers and mixed fillers. L – limestone; D - dolomite; M – melaphyr; B – basalt; X15 – filler X with 15wt.% hydrated lime; X30 – filler X with 30wt.% hydrated lime (from [31]).

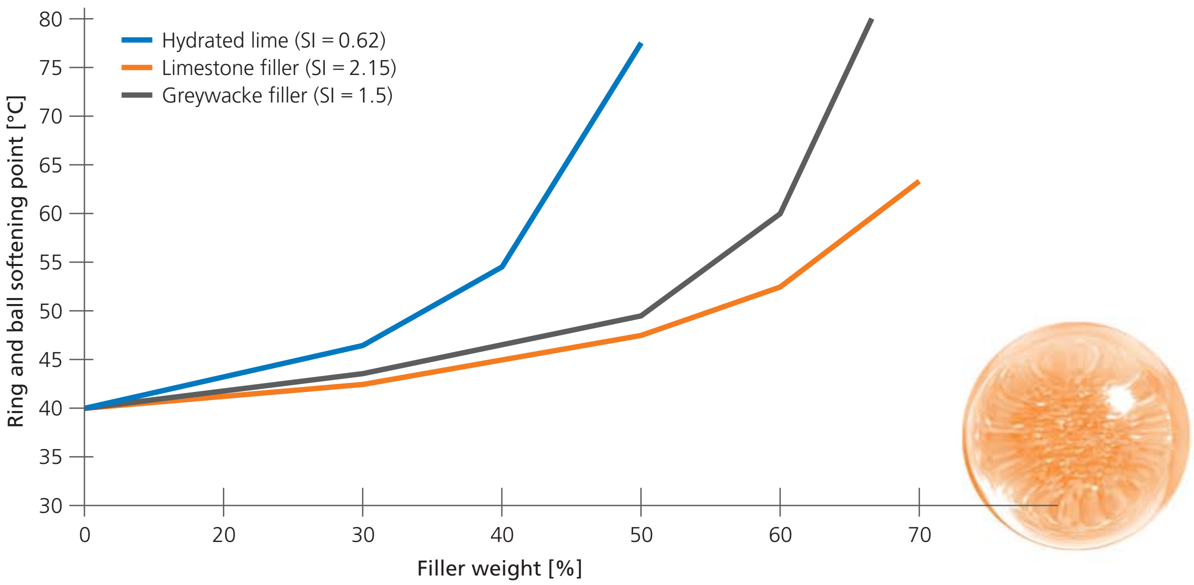


Figure 6. Ring and ball softening temperature of a 200 penetration grade bitumen as a function of filler content (wt. %) for hydrated lime, limestone filler and greywacke filler (from [37]).

1.2.3 Other properties

Other properties used to specify mineral fillers in the asphalt industry are also listed in Table 3. Of special interest is the bitumen number (EN 13179-2 [40]), which consists in measuring the amount of water in ml that needs to be added to 100 g of filler in order to reach a reference consistency defined by a penetration value of 5 to 7 mm. The test is being used especially in the Netherlands (where it is also known as de Van der Baan number) and gives an information on the stiffening power of the filler, which is somewhat similar to the Rigden air voids value.

Property	Method	Unit	Hydrated lime	Mineral filler	Reference
Particle density	EN 1097-7	Mg/m^3	2.2	2.6 - 2.9	[29, 31]
Voids in dry compacted filler	EN 1097-4	%	60 - 70	28 - 45	[29, 31, 34]
Delta ring and ball	EN 13179-1	°C	not measurable	8 - 25	[29, 31]
Bitumen number	EN 13179-2	–	70 - 120	40 - 50	[31, 35]
Mass in kerosene	EN 1097-3	Mg/m^3	0.3	0.5 - 0.9	[26]
Blaine specific surface	EN 196-6	cm^2/g	> 10,000	7,000	
Specific surface area	BET with nitrogen adsorption	cm^2/g	150,000 - 200,000	14,000 - 95,000	[4, 34]
Methylene blue value	EN 933-9	g/kg	< 1	0 - 20	[34]

Table 3. Typical properties of hydrated lime compared to mineral fillers.

Mass in kerosene is also sometimes used to characterize fillers (EN 1097-3 [41]). It measures the so-called apparent density of 10 g of filler in 25 ml of kerosene, obtained by measuring the height of filler that sediment in kerosene after 6 hours. It was shown by P. J. Rigden [28], although measured in benzene, that this parameter is less relevant than the Rigden air voids in order to predict the stiffening effect of mineral fillers in bituminous binders.

Methylene blue value (EN 933-9 – [42]) is not relevant for hydrated lime, because the test is intended to measure the amount of clayey materials in an aggregate. Even if a clayey limestone is used to manufacture the lime, the clays are chemically modified in the kiln and are not found in the final material. Still, the asphalt industry uses the test a lot to characterize fillers and there is no difficulty to perform it on hydrated lime. The value is normally inferior to 1 g per kg for hydrated lime.

Although the Blaine method (EN 196-6 – [43]) is intended for cements, it is sometimes used to characterize hydrated lime. This is generally not appropriate, because the high porosity of hydrated lime makes it impossible to run the test according to the required level of porosity, which in turns strongly affects the repeatability of the method. Still, values can be obtained and they are usually higher than 10,000 cm^2/g (= 1 m^2/g) for standard hydrates. Specific surface area can be best measured by the Brunauer-Emmett-Teller method (BET) with nitrogen adsorption, and it is then of order 15-20 m^2/g [4]. Most fillers have values in the 1-5 m^2/g range, but higher values close to 10 m^2/g can still be found [34]. However, no standard exist to detail the way the BET method should be applied to either mineral fillers or hydrated lime.

Table 3 summarizes the typical values for some properties of hydrated lime as compared to mineral fillers obtained from the crushing and classification of mineral aggregates. Table 3 is only intended to give reasonable estimates for the listed properties, which will of course vary depending on the origin of the materials. Note that fillers from other sources such as fly ash, ... can have very different properties than mineral fillers and must therefore not be mistaken for mineral fillers.

2. Effect of hydrated lime on asphalt mixtures properties

As described in the introduction, the renewed interest for hydrated lime that occurred in the USA in the 1970s focused on its beneficial effect on moisture damage and frost resistance. However, it turned out that hydrated lime improved other properties of asphalt mixtures as well. In the end, hydrated lime is now seen as a multifunctional additive that improves the durability of asphalt mixes. Unfortunately, measuring the durability of asphalt mixtures in the laboratory is not possible, because of the many distresses and failure modes that an asphalt mixture can experience.

Still, test methods are available in order to evaluate the resistance of pavement materials to the action of detrimental agents such as water, freeze-thaw cycles, temperature and UV-exposure (ageing) and/or traffic.

Hence, this chapter reviews the evidence gathered in the literature on the effect of hydrated lime on asphalt mixtures as regards:

- the resistance to moisture damage and frost,
- the resistance to chemical ageing,
- the mechanical properties, in particular modulus, strength, rutting resistance, fatigue and thermal cracking.

Although these laboratory tests can allow for a comparison between materials, especially with reference materials of known field behaviour, they hardly provide direct information on the durability in terms of time to failure for the material under field conditions. Except for fatigue cracking and rutting that can be used in pavement design methods in order to predict a time to failure, properties such as moisture damage and ageing are difficult to translate into field durability. Therefore, this chapter will only focus on laboratory testing and Chapter 4 will cover field behaviour.

2.1 Resistance to moisture damage and frost

Moisture induced-damage and the effect of freeze-thaw cycles are common phenomena with asphalt mixtures. It generally materializes by the progressive loss of aggregate as illustrated in Figure 7. The bitumen-aggregate bond gets weakened in the presence of water to the point that it becomes not strong enough to hold the aggregate. This is generally called aggregate stripping or ravelling when it is limited to the surface [44]. Flushing is also one type of water damage that similarly yields to the loss of aggregate, but from the bottom layer of the material as a consequence of the traffic-induced water pressure in the binder course [9]. If untreated, these damages can deteriorate into potholes. Frost and freeze-thaw cycles tend to enhance these detrimental effects, and a tough winter can directly generate potholes.

Figure 7. Aggregate stripping as a consequence of moisture induced--damage (from [45]).

According to a US survey back in the early 1990s [8], water--induced damages typically occur for untreated mixes between 3 to 4 years after construction on average, sometimes the very first year.

As already said, hydrated lime has been known for years to improve the resistance to moisture damage of asphalt mixtures. M. Duriez with the French Central Laboratory of Roads and Bridges (LCPC) and his coauthor J. Arrambide talked extensively about the subject when the hot mix asphalt technology was emerging in Europe [7, 46]. Also, this property explains the renewed interest 40 years ago in the USA [8]. According to the North American State agencies, it is still the reason why they specify hydrated lime in their asphalt mixtures [10], as will also be detailed below.

Many test methods are available to evaluate the moisture and frost resistance of asphalt mixtures. Table 4 lists the most frequently used in the literature. Their predictive power is still debated and there is no clear consensus on which method is best suited in order to eliminate moisture damage in the field [47]. In particular, water diffusion inside the mixture [47] is not currently directly measured when it might explain the 100% water-saturation observed with damaged field mixtures [9]. However, lab methods used in the current specifications barely reach 80% saturation. Still, the Lottman test (AASHTO T-283 – Table 4) was found to be one of the most effective among the tests in use in the USA in 1991 (Figure 8).

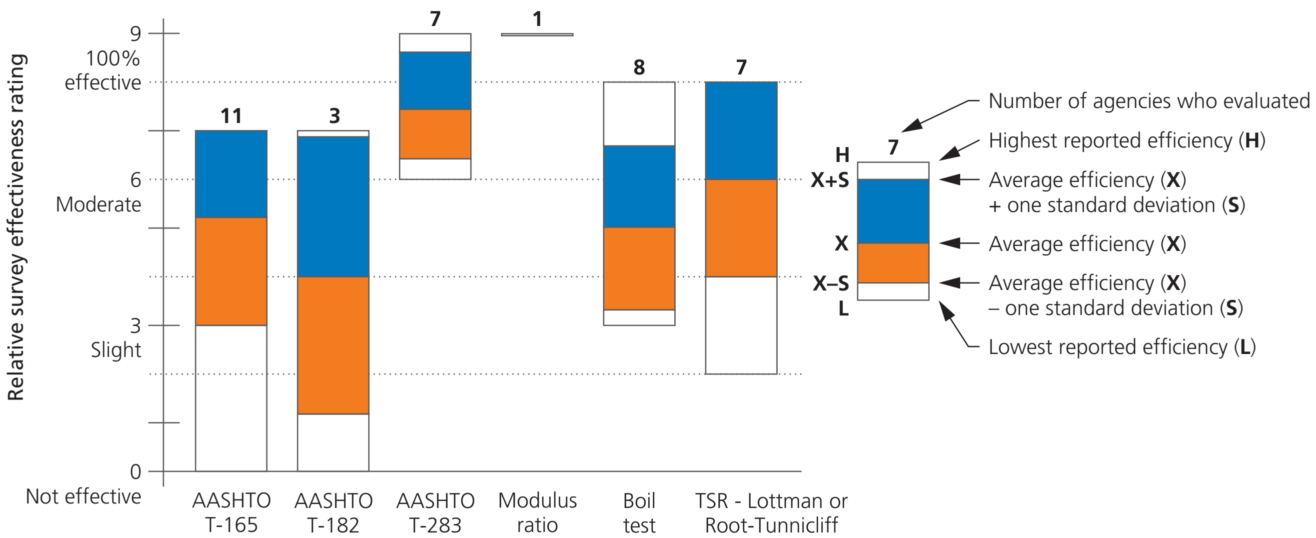


Figure 8. Comparison of the effectiveness of several test methods in order to predict moisture damage as evaluated by North American State agencies experience (from [8]).

In all cases, the published data confirm that hydrated lime at 0.5-2wt.% on dry aggregate successfully improves the moisture and frost resistance of asphalt mixtures regardless of the testing method. At least 1wt.% is needed in order to fully benefit from this effect [48]. Examples of the potential gain with hydrated lime are listed in Tables 5, 7, 8 and 9.

Figure 9 illustrates the comparison of several additives to hydrated lime (in two added methods) using a wide range of testing methods on aggregates of different sources. The data come from a study by P. Hao and Y. Hachiya with the National Institute for Land and Infrastructure Management of the Japanese Ministry of Land, Infrastructure and Transport [49]. It makes it clear that some tests are more severe than others in order to highlight the beneficial effect of hydrated lime. In particular, all additives (except Portland cement) look identical when retained Marshall stability is used as a criteria (Figure 9). However, the Lottman test is more discriminating and clearly demonstrates that hydrated lime performs better than other additives when the testing method becomes more severe (Figure 9). In the same line of thinking, the Hamburg Wheel Tracking Device (HWTD) also shows that hydrated lime is more efficient that other additives in order to increase moisture resistance of asphalt mixtures (Figure 9 – see also section 2.3.4 for a description of the test results).

Clearly, the relative improvement is test-method and materials dependent (Table 5). A good overview of the comparison between liquid antistrip and hydrated lime was prepared by Professor P. E. Sebaaly of the University of Nevada in Reno [13]. Several other studies allow for a comparison [49, 50]. They all show that hydrated lime is in overall equal or better than commercial liquid antistrips. Still, for some specific study with the given raw materials at hand and the type of testing chosen to evaluate them, a liquid antistrip can be observed once to behave better (Tables 7 and 9 – Figure 9). As a result, multiple freeze-thaw procedures (such as repeated Lottman – Figure 10 or Texas pedestal – Table 8) and HWTD (Table 5) are the most differentiating test methods in order to highlight the beneficial effect of hydrated lime [13, 51].

In the field, the experience with hydrated lime is quite conclusive. Several studies were published illustrating that the good laboratory results obtained with hydrated lime were also observed in the field. For example, G. W. Maupin Jr. with Virginia Transportation Research Council reported about 12 Virginia DOT test sections comparing hydrated lime to other liquid antistrip additives [52]. After 3-4 years, the 3 sections with hydrated lime showed much less stripping than the one with chemical additives [52].

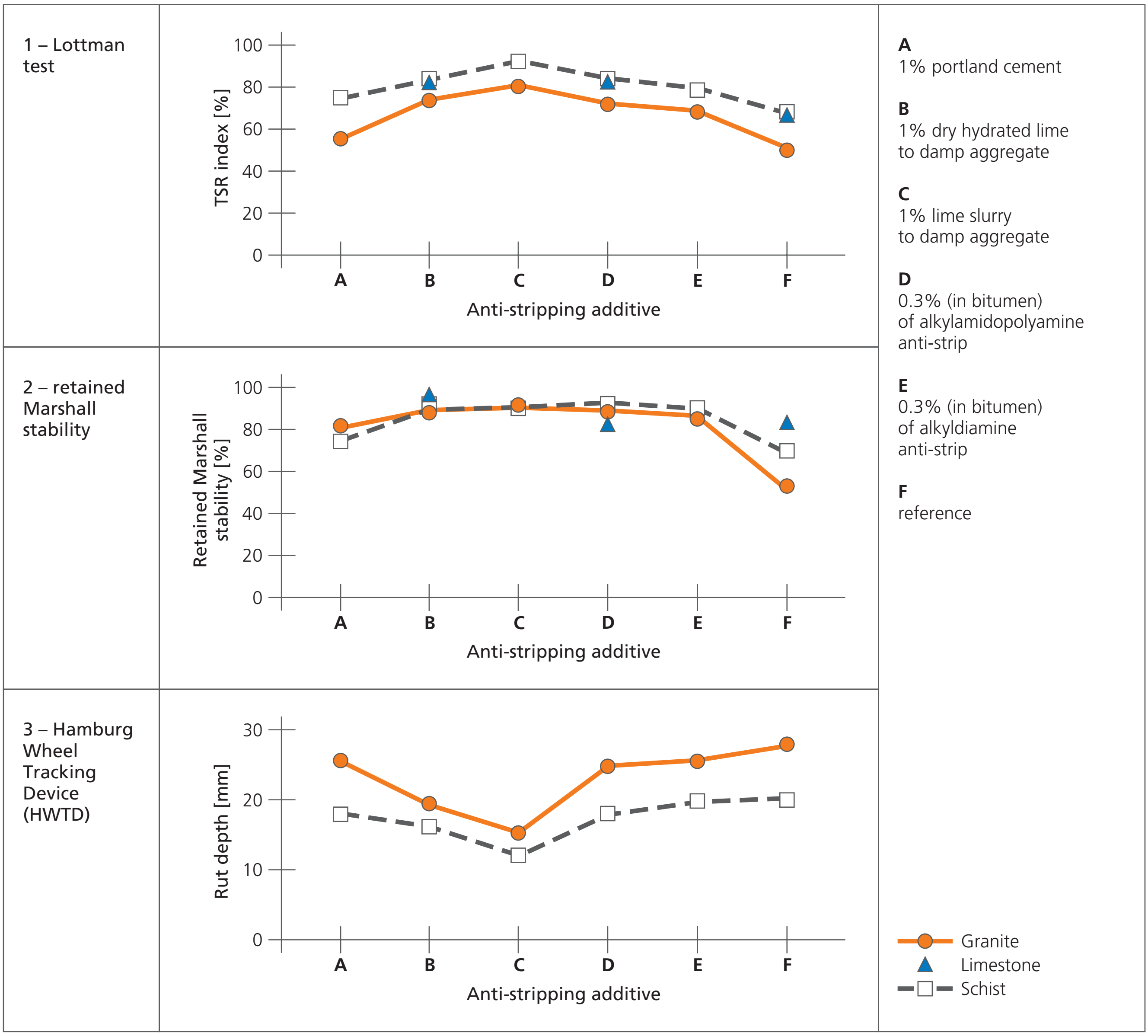


Figure 9. Moisture resistance of 0/20 asphalt mixtures made with different aggregate sources and 4.8% 70/100 penetration grade and several anti-strip additives. The testing was done by: 1 – the Lottman test; 2 – retained Marshall stability; 3 – HWTD at 60°C (from [49]).

Test method	Standard	Type of specimen	Testing method	Conditioning	Test result
Hamburg Wheel Tracking Device (HWTD)	EN 12697-22 – method B under water	260 x 300 mm rectangular slabs with final thickness	wheel tracking device under water	testing under water at 50°C	rut depth in mm
Indirect tensile strength ratio (ITSR)	EN 12697-12 – method A	100 mm diameter (or 150 or 160 for large aggregate size) cylindrical specimen of the asphalt mixture to be tested	indirect tensile strength (ITS) at 25°C and 50 mm/min.	• specimens in vacuum (7 kPa) for 30 min. • 70 hrs in water at 40°C • 2 hrs at 25°C	ITS ratio in % (after conditioning / no conditioning)
Duriez	EN 12697-12 – method B	100 mm diameter (or 80 or 120 or 150 or 160) cylindrical specimen of the asphalt mixture to be tested	compressive strength at 18°C and 55 mm/min.	• specimens in vacuum (47 kPa) for 120 min. • 7 days in water at 18°C	ITS ratio in % (after conditioning / no conditioning)
Cantabro	EN 12697-17	101.6 mm diameter x 63.5 mm cylindrical specimen of the asphalt mixture to be tested (generally a porous asphalt)	mass loss after 300 revolutions in the Los Angeles test (without steel balls)	generally the same as ASTM D1075	mass loss ratio (after conditioning / no conditioning)
Saturation sgeing tensile stiffness (SATS)	UK Specification for Highway Works – Clause 953	100 mm diameter x 60 mm cylindrical specimen of the asphalt mixture to be tested, cored from a slab with 8% voids	indirect tensile stiffness modulus measured at 20°C using the Nottingham Asphalt Tester	• specimens in vacuum (55 kPa) for 30 min. • 65 hrs at 85°C and 2.1 MPa in water saturated vessel • 24 hrs at 30°C and 2.1 MPa	indirect tensile stiffness ratio in % (after conditioning / no conditioning)
Lottman	AASHTO T283 Tex 531-C	101.6 mm diameter x 63.5 mm cylindrical specimen of the asphalt mixture to be tested compacted to 6.5-7.5% voids	indirect tensile strength (ITS) at 25°C and 50.8 mm/min.	• pore saturation 70-80% • 16 hrs at -17.8°C • 24 hrs in water at 60°C • 2 hrs in water at 25°C	ITS ratio (after conditioning / no conditioning)
Repeated Lottman	–	101.6 mm diameter x 63.5 mm cylindrical specimen of the asphalt mixture to be tested compacted to 6.5-7.5% voids	indirect tensile strength (ITS) at 25°C and 50.8 mm/min.	Lottman conditioning but with consecutive freeze-thaw cycles (generally from 1 to 20)	ITS ratio vs number of freeze-thaw cycle
Texas freeze-thaw pedestal		41.3 mm diameter x 19 mm cylindrical briquet of 0.4/0.8 sand coated with bitumen at optimum +2% compacted by static pressure of 27.58 kN for 20 min.	visual (crack)	• briquet immerged in distilled water • 15 hrs at -12°C • 45 min. in water at 24°C • 9 hrs at 49°C then repeat	number of freeze-thaw cycles to failure

Table 4. Most used testing methods in order to evaluate the improvement of the moisture resistance of asphalt mixtures (continued on next page).

Test method	Standard	Type of specimen	Testing method	Conditioning	Test result
Retained tensile strength (tensile splitting ratio / indirect tensile strength / Root-Tunnicliff test)	ASTM D4867	101.6 mm diameter x 63.5 mm cylindrical specimen of the asphalt mixture to be tested compacted by any mean (static / Marshall, ...) to 6-8% air voids	indirect tensile strength (ITS) at 25°C and 50.8 mm/min.	• pore saturation 55-80% • 24 hrs in water at 60°C • 1 hrs at 25°C	ITS ratio (after conditioning / no conditioning)
Immersion / compression	ASTM D1075 AASHTO T165	101.6 mm diameter x 101.6 mm cylindrical specimen of the asphalt mixture to be tested compacted by static compaction on both sides (3,000 psi during 2 min.)	compressive strength at 25°C and 5 mm/min.	• 4 days in water at 48.9°C • 1 day in water at 60°C	compressive strength ratio (after conditioning / no conditioning)
Retained Marshall		101.6 mm diameter x 76.2 mm cylindrical specimen of the asphalt mixture to be tested compacted by impact compaction (50 or 75 blows)	Marshall stability at 60°C – 50.8 mm/min.	24 hrs in water at 60°C	stability ratio (after conditioning / no conditioning)
Texas Boil Test	ASTM D3625 Tex 530-C	(300 g + bitumen content) of asphalt mixture to be tested or (100g + bitumen) of 4.8/9.8 aggregate	visual (aggregate surface covered in bitumen)	asphalt mixture in boiling water for 10 min.	% of retained bitumen after boiling

Table 4. (continued from previous page) Most used testing methods in order to evaluate the improvement of the moisture resistance of asphalt mixtures.

Materials	Hydrated lime content and addition method [% based on dry aggregate]	Criteria	No hydrated lime	With hydrated lime	Type of comparison material	Comparison material	Reference
Colorado mixes 4 different aggregates 5.1% AC-20 6.5% air voids	1%	rut depth at 45°C after 20,000 passes (between parenthesis the mixes that failed)	• mix 1: (17 mm) • mix 2: (> 20 mm) • mix 3: (> 20 mm) • mix 4: 8.7 mm	• mix 1: 1,4 mm • mix 2: 2.3 mm • mix 3: 2.5 mm • mix 4: 2.3 mm	0.5% of best liquid antistrip in binder	• mix 1: 2.2 mm M • mix 2: 8.1 mm • mix 3: (13.7 mm) • mix 4: 6.2 mm	[56, 11]
Louisiana mixes 0/19 siliceous limestone 3.6-4% binder 3.6% air voids	1.5% in slurry form (LS) or inside the binder (LM) – filler substitution	rut depth at 50°C after 20,000 passes	• PG64-22: 10.1 mm • PG70-22: 3.7 mm • PG76-22: 3.5 mm	• PG64-22: 9.5 mm (LS) 8.9 mm (LM) • PG70-22: 2.6 mm (LS) 2.9 mm (LM) • PG76-22: 1.9 mm (LS) 1.8 mm (LM)			[57]
Mix C Lithonia Granite 5% PG67-22	2%	rut depth at 50°C after 8,000 passes	12 mm	4 mm	0.5% liquid antistrip in the binder	4 mm	[58]
Texas DOT mixes 6 different aggregates 4.6-5.5% AC-20 7% air voids		creep slope (cycles at 40°C to get 1 mm rut depth in the creep region) / stripping slope (cycles at 40°C to get 1 mm rut depth in the creep region) NS = no stripping observed	• mix 1: 4,856/459 • mix 2: 2,979/640 • mix 3: 1,926/446 • mix 4: 9,815/NS • mix 5: 2,082/279 • mix 6: 907/163	• mix 1: 8,871/NS • mix 2: 9,919/NS • mix 3: 7,026/NS • mix 4: 10,465/NS • mix 5: 5,252/NS • mix 6: 3,427/NS	liquid antistrip	• mix 1: 5,469/777 • mix 2: 4,780/1,050 • mix 3: 3,626/1,402 • mix 4: 5,770/NS • mix 5: 1,511/491 • mix 6: 3,471/744	[59, 14]
0/16 Superpave mixes limestone + crushed gravel 5.4-5.8% PG64-22 3.6-4.5% air voids	1% dry lime to damp aggregate (B2) or lime slurry (B3) – no filler substitution	stripping point at 50°C (number of cycles)		B2: 4,300 B3: 2,200	1% limestone screenings (no filler substitution)	1,800	[60]
0/11 S asphalt concrete 50/70 bitumen	1.5% as mixed filler (Ka_{25})	rut depth at 50°C after 20,000 cycles	10.9	5.2			[37]
0/16 S asphalt concrete 50/70 bitumen	1.5% as mixed filler (Ka_{25})	rut depth at 50°C after 20,000 cycles	4.6	3.1			[37]

Table 5. Some examples quantifying the improvement in the moisture resistance of asphalt mixtures by addition of hydrated lime as measured by the Hamburg Wheel Tracking test (EN 12697-22 – small size – method B underwater). See also section 2.3.4 for a description of the test results.

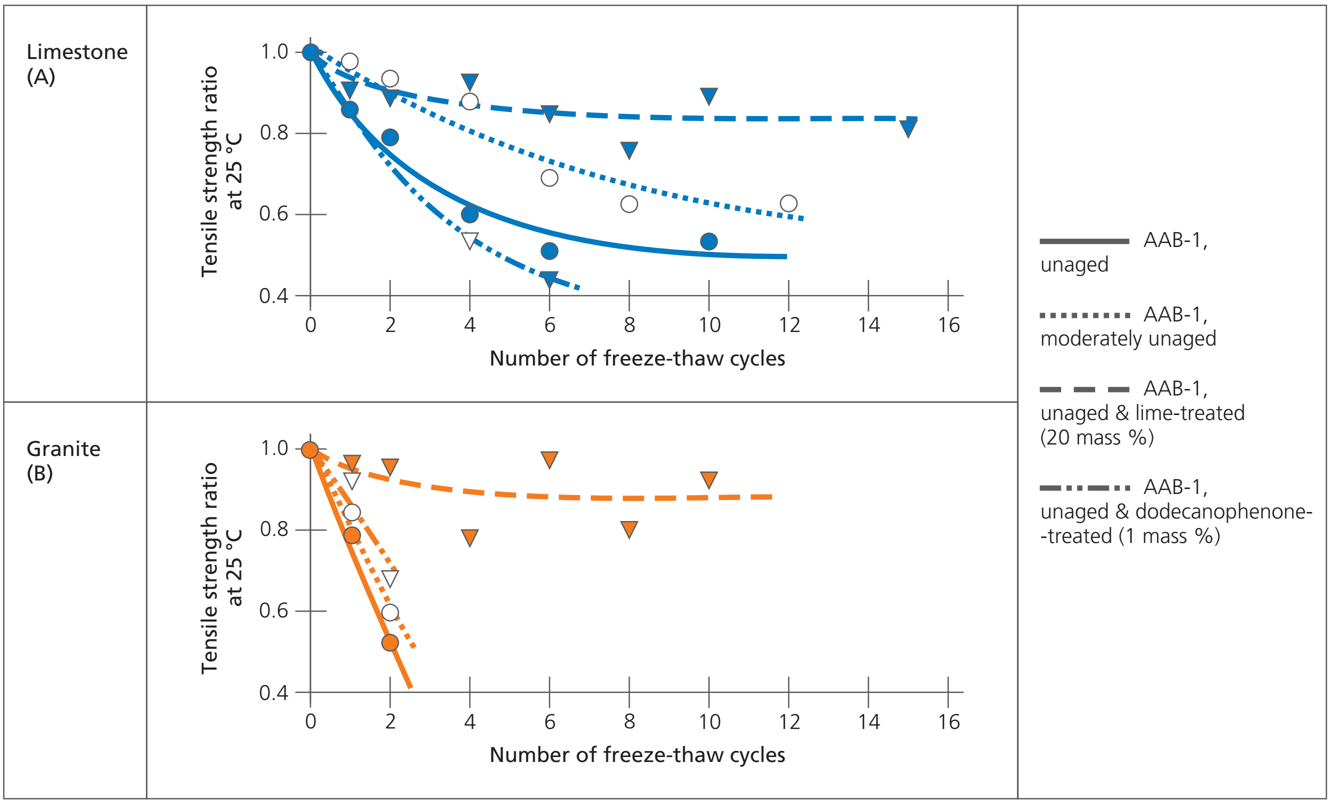


Figure 10. Multiple freeze-thaw test on asphalt mixtures made with limestone (A) or granite (B) aggregate and bitumen AAB-1. The unaged and aged binder were tested, together with the one modified with hydrated lime (20% based on binder with a binder content of 5.5wt.%) and a sample modified with 1% (based on binder) dodecanophenone (from [65]).

The 15 Federal HighWayAdministration experimental sections in Wyoming, Montana, New Mexico and Georgia with hydrated lime were performing from good to excellent condition after more than 5 years [53]. The Nevada DOT experience reported the good behaviour of hydrated-lime treated sections versus untreated one for a period of 5-10 years. The 4 hydrated lime treated sections experienced no reduction in Present Serviceability Index (PSI) except in one case with moderate reduction, when the untreated materials showed moderate (2) or severe (2) reductions in PSI [54].

In Europe, the Polish section with hydrated lime did not have any damage after 4 years of traffic [55].

But the most convincing field evidence comes from the 1991 survey of the existing additives used for treating moisture damage [8]. The State agencies from Northern America reported that hydrated lime was the most effective additive used so far (Figure 11). Moreover, no agency reported that hydrated lime was only slightly effective, whereas all other additives were considered so by some agencies.

In the 2003 survey, the North American State agencies reported that the first reason why they use hydrated lime is because of moisture damage (Table 6 – [10]).

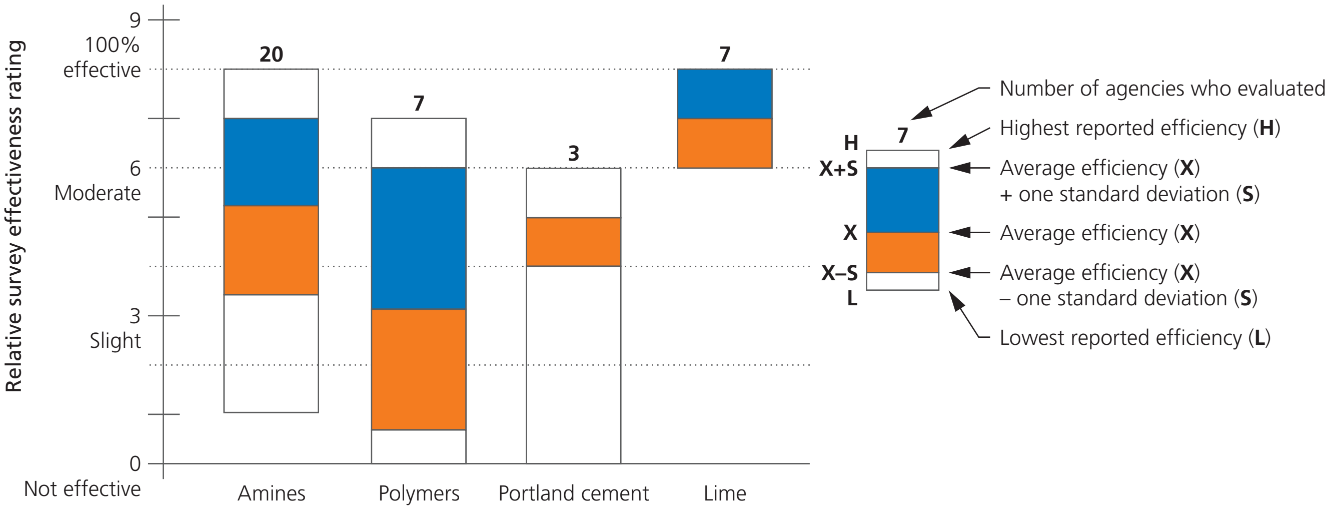


Figure 11. Comparison of the effectiveness of several additives in order to treat moisture damage as evaluated by North American State agencies experience (from [8]).

Road agency / State of USA	Resist stripping	Improve aging resistance	Stiffen binder	Improve fracture toughnees	Alter properties of fines
Arizona	1	3	2	3	2
California	1	2	3	3	3
Colorado	1	3	3	3	1 (when appropriate)
Federal HighWay Administration (FHWA)	1	2	3	2	3
Georgia	1	3	3	3	3
Mississippi	1	1	2	—	3
Nevada	1	3	3	2	1
Oregon	1	2	3	3	3
South Carolina	1	2	2	2	2
Texas	1	3	2	3	2
Utah	1	2	2	2	2

Table 6. Reasons to use hydrated lime as evaluated by North American State agencies experience. Level of importance: 1 – very important; 2 – moderately important; 3 – less important (from [10]).

Materials	Hydrated lime content and addition method [% based on dry aggregate]	Criteria	No hydrated lime	With hydrated lime	Type of comparison material	Comparison material	Refe-rence
Mix C Lithonia Granite 5% PG67-22	2%	unconditioned strength (MPa) / conditioned strength (MPa) / retained strength at 25°C	1 / 0.4 / 40%	1.2 / 1.1 / 92%	0.5% liquid antistrip in the binder	1.1 / 1.1 / 100%	[58]
0/16 Superpave mixes limestone + crushed gravel 5.4-5.8% PG64-22 3.6-4.5% air voids	1% dry lime to damp aggregate (B2) or lime slurry (B3) – no filler substitution	retained strength at 25°C	69%	B2: 77% B3: 74%	1% limestone screenings (no filler substitution)	77%	[60]
Nevada mix River gravel AR-4000 binder	1-2% dry lime to damp aggregate	retained strength at 25°C	36%	1%: 84% 2%: 70%	0.5, 1 and 2% of best liquid antistrip in binder	0.5%: 41% 1%: 66% 2%: 79%	[61, 14]
California mix limestone AR-4000 binder	1-2% dry lime to damp aggregate	retained strength at 25°C	37%	1%: 93% 2%: 81%	0.5, 1 and 2% of best liquid antistrip in binder	0.5%: 47% 1%: 58% 2%: 76%	[61, 14]
0/25 Type 2C Nevada DOT mixes Lockwood felsite / basalt polymer-modified AC-20	1.5% dry lime to damp aggregate with (DLW) or without (DLN) 48 hours marination or lime slurry with (LSW) or without (LSN) marination	retained strength at 25°C	39.8%	DLN: 108.7% DLW: 97.2% LSN: 100.0% LSW: 108.0%			[62]
0/25 Type 2C Nevada DOT mixes Lockwood felsite / basalt polymer-modified PG64-34	1.5% dry lime to damp aggregate with (DLW) or without (DLN) 48 hours marination or lime slurry with (LSW) or without (LSN) marination	retained strength at 25°C	68.4%	DLN: 89.3% DLW: 96.5% LSN: 84.3% LSW: 92.8%			[62]
0/25 Type 2C Nevada DOT mixes Lone Mountain quartzite / limestone gravel AC-30	1.5% dry lime to damp aggregate with (DLW) or without (DLN) 48 hours marination or lime slurry with (LSW) or without (LSN) marination	retained strength at 25°C	35.3%	DLN: 104.8% DLW: 109.7% LSN: 103.1% LSW: 105.2%			[62]

Table 7. Some examples quantifying the improvement in the moisture resistance of asphalt mixtures by addition of hydrated lime as measured by the Lottman test.

Materials	Hydrated lime content and addition method [% based on dry aggregate]	Criteria	No hydrated lime	With hydrated lime	Type of comparison material	Comparison material	Reference
Polish 0/16 mix w/ Glensanda granite 2/16 and 0/2 Graniczna sand Two binders: B50 bitumen from Plock and O45 Olexobit 45 from BP Poland (1)	1.5%	retained strength after 18 freeze-thaw cycles (not exactly repeated Lottman test)	B50: 68% O45: 76%	B50: 81% O45: 89%	0.4% liquid antistrip (fatty amine) in the binder	B50: 74% O45: 81%	[63]
0/16 Superpave mixes limestone + crushed gravel 5.4-5.8% PG64-22 3.6-4.5% air voids (1)	1% dry lime to damp aggregate (B2) or lime slurry (B3) – no filler substitution	retained strength after 6 cycles	11%	B2: 49% B3: 40%	1% limestone screenings (no filler substitution)	11%	[60]
Idaho 0/16 dense graded mixture crushed gravel 5.3% PG58-28 (1)	1% dry lime on damp aggregate with 48 hours marination	resilient modulus at 25°C (ksi) after 0-21 freeze-thaw cycles		0: 264 3: 268 6: 272 9: 266 12: 243 15: 184 21: 172	0.5% of liquid antistrip in binder	0: 233 3: 255 6: 228 9: 161 12: 176 15: 106 21: 86	[64]
Wyoming 0/19 mixture limestone 5.5% AAB-1 bitumen 7% air voids (1)	1% lime in the binder	indirect tensile strength (kPa) after 0-15 freeze-thaw cycles	0: 591 1: 505 2: 464 4: 352 6: 298 10: 310 12: failed	0: 524 1: 473 2: 471 4: 480 6: 446 10: 466 15: 423			[65]
Wyoming 0/19 mixture granite 5.5% AAB-1 bitumen 7% air voids (1)	1% lime in the binder	indirect tensile strength (kPa) after 0-10 freeze-thaw cycles	0: 573 1: 459 2: 296 4: failed	0: 484 1: 468 2: 464 4: 385 6: 477 8: 396 10: 448			[65]
Texas Asphalt Concrete mix with 62% Pea gravel, 15% washed sand and 23% field sand 5% AC-20 binder (2)	1.5% lime (dry lime in wet aggregate and lime slurry LS with or without marination, sometimes treating only one granular fraction)	number of freeze-thaw cycles to failure	6	• > 137 when whole aggregate treated • 113 for LS treatment of gravel only • 25 for LS treatment of field sand only • 23 for LS treatment of washed sand only			[2, 66]
Fine river gravel E or A binder (2)	lime slurry	number of freeze-thaw cycles to failure	E: 4 A: 4	E: 22 A: > 25	21 commercial liquid anti-strips (amines, amidoamines, imidazoles, pyridine and organosilane)	E: 3-10 A: 2-10	[2, 67]

Table 8. Some examples quantifying the improvement in the resistance to repeated freeze-thaw cycles of asphalt mixtures by addition of hydrated lime. Test method: (1) – repeated Lottman; (2) – Texas freeze-thaw pedestal.

Materials	Hydrated lime content and addition method [% based on dry aggregate]	Criteria	No hydrated lime	With hydrated lime	Type of comparison material	Comparison material	Refe-rence
Porous asphalt B40/50 or PMB with 3% EVA (3)	1%	retained compressive strength	B40/50: 62% PMB: 88%	B40/50: 78% PMB: 78%			[68]
0/16 porfire dense mix 6.4% filler 1.9-2.5% air voids (4)	1.6% as active filler (Ka_{25})	retained mass loss after 300 turns	arabian crude: 1.3	arabian crude: 1.0			[69]
0/11 gravel dense mix 5.7% filler 1.9-2.5% air voids (4)	1.4% as active filler (Ka_{25})	retained mass loss after 300 turns	venezuel crude: 1.6	venezuel crude: 1.5			[69]
Porous asphalt B40/50 or PMB with 3% EVA (4)	1%	retained mass loss	B40/50: 1.02 PMB: 0.99	B40/50: 0.93 PMB: 0.94			[68]
0/16 porfire dense mix 6.4% filler 1.9-2.5% air voids (5)	1.6% as active filler (Ka_{25})	retained stability	arabian crude: 89% venezuel crude: 97%	arabian crude: 91% venezuel crude: 102%			[69]
0/11 gravel dense mix 5.7% filler 1.9-2.5% air voids (5)	1.4% as active filler (Ka_{25})	retained stability	arabian crude: 97% venezuel crude: 111%	arabian crude: 97% venezuel crude: 120%			[69]
Undefined mixes Lithonia granite 5% PG67-22 (6)	2%	% covered surface	5%	90%	0.5% liquid antistrip in the binder	95%	[58]
Polish 0/16 mix w/ Glensanda granite 2/16 and 0/2 Graniczna sand D50 bitumen (6)	1.5%	% covered surface	90%	100%	0.4% liquid antistrip (fatty amine) in the binder	100%	[63]
River gravel (gem sand) (6)	calcic lime (c) / dolomitic lime (d)	% covered surface	10%	c: 68% d: 72%			[2]
Limestone (6)	calcic lime (c) / dolomitic lime (d)	% covered surface	60%	c: 72% d: 80%			[2]

Table 9. Some examples quantifying the improvement in the moisture resistance of asphalt mixtures by addition of hydrated lime as measured from some of the other widely used tests. Test method: (3) – Duriez; (4) – Cantabro; (5) – retained Marshall; (6) – Texas Boil test.

2.2 Resistance to chemical ageing

Hydrated lime was early observed to decrease bitumen chemical aging. The first observations of the anti-ageing effect of hydrated lime on bituminous materials date back from the late 1960's in Utah, when C. V. Chachas and coworkers with the Utah State Department Highways observed that control specimens of bitumen recovered from hydrated lime treated asphalt mixtures were surprinsingly softer than the reference materials [70, 71]. From then on, many laboratory studies (Table 10) confirmed the impact of hydrated lime on bitumen chemical ageing and several studies also confirmed its occurrence in the field (Table 11).

Note that the field demonstration of the anti-ageing effect remains tricky because of the difficulty to recover the aged binder. Ageing being more intense on the top of the upper layer, the first centimeters (if not millimeters) must be extracted in order to quantify the ageing intensity. However, in some cases, the full mixture layer, sometimes with thicknesses of several centimeters is analysed, diluting the effects of ageing with little aged bitumen from the bottom.

From the published evidence detailed in Table 10, the effect of hydrated lime on bitumen ageing can be described as follows:

- Hydrated lime-modified bitumens show a decreased ageing susceptibility [11, 12, 72, 73, 74, 75, 76]. This is materialized by a slower increase in viscosity (or any other mechanical property) versus ageing time, as pictured in Figure 12.
- In parallel, the rate of carbonyl formation slows down in hydrated lime-modified bitumens [72, 74, 75]. However, this effect was only found at ageing temperatures of 88°C and above, but was not found when low temperature ageing was studied (60°C – [76]).
- Sulfides, sulfoxides and ketones formation seem not to be significantly modified by hydrated lime [22, 76].
- In all cases, asphaltenes content increases at a slower pace with hydrated lime-modified than with non-modified bitumens [22, 69, 72, 74, 75].
- Hydrated lime-treated bitumens, i.e., bitumens that have been in contact with hydrated lime that was later removed, still show this reduced ageing effect [22, 72].
- These effects are only seen with hydrated lime and not with limestone filler [22, 77].

Some elements of interpretation of these observations, in terms of bitumen and hydrated lime interactions, are further discussed in Chapter 3.

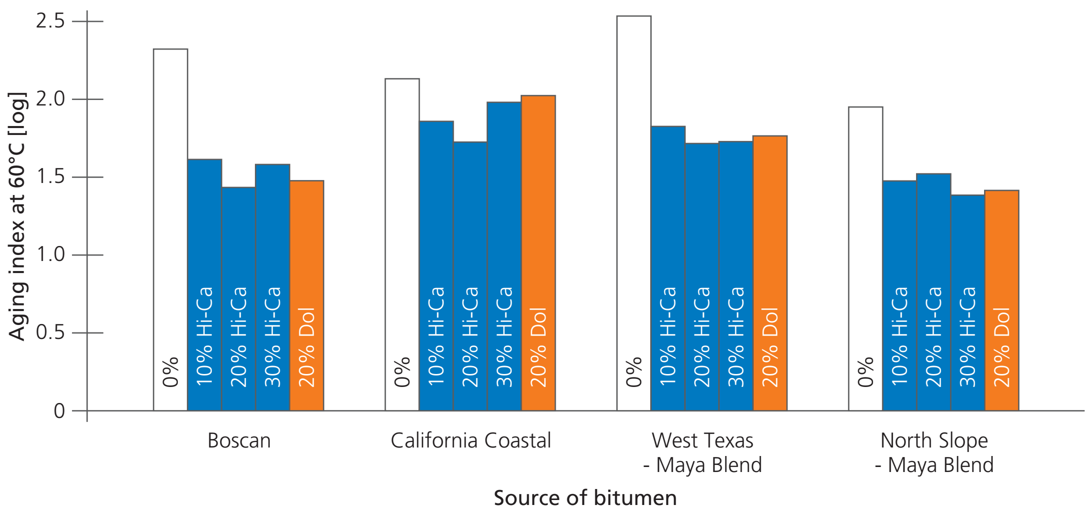


Figure 12. Aging index at 60°C (viscosity after ageing divided by the viscosity before) for various sources of bitumen modified with different weight proportions of hydrated lime (Hi-Ca) and hydrated dolomitic lime (Dol). Ageing was performed in the Thin Film Accelerated Aging Test (TFAAT) corresponding to 3 days at 113°C under air exchange (from [22]).

Researcher, year	Aging procedure	Tested bitumens	Hydrated lime content [wt.% based on bitumen]	Main conclusions	Refe-rence
Plancher, 1976	• rolling thin film oven test (RTFOT - EN12607-1 - 75 min. at 163°C) • Rolling MicroFilm Circulating Oven RMF-C (48 hrs at 98.9°C)	4 AC10 from different locations	50 (from 1/1/600 HL/bitumen/ benzene solutions then HL and solvent removed)	• hydrated lime treatment seen to reduce age hardening (lower stiffening, lower asphaltene content, lower carbonyl-type oxidation products) • bitumen dependent effect but all bitumen benefit from hydrated-lime treatment	[72]
Edler, 1985	• weatherometer: 65°C with cyclic 102 min. UV and 18 min. UV + water spray (3 bars), 32.5 hrs, 73.5 hrs, 7 days, 14 days • RTFOT 163°C, 75 min. • RTFOT + POB (pressure oxygen bomb 65°C and 2.06 MPa of oxygen pressure, 96 hrs) • RTFOT + TFOT 163°C, 5 hrs • viscosity, FTIR, GPC	60/70 and 80/100	6 or 12wt.% hydrated lime	• much lower ageing with hydrated lime as noted by viscosity, almost regardless of hydrated lime content • lower ratio of C=O abs. (1710 cm^{-1}) / C=C abs. (1600 cm^{-1}) for lime modified bitumens after ageing • effect much clearer on weatherometer, almost unseen on RTFOT • little effect on molar weight	[78]
Petersen, 1987	thin film accelerated aging aest (TFAAT) of hydrated lime-treated materials at 113°C for 3 days	• AC10 California Coastal • AC10 Boscan • AC10 North Slope / Maya • AC10 West Texas / Maya	• hydrated lime 10, 20, 30 • dolomitic lime 20	• ageing procedure similar to 11-13 yrs in the field • 10% hydrated lime enough to neutralize most of the acids of the binders • hydrated lime treatment seen to reduce age hardening (lower stiffening, asphaltene content, and carbonyl oxidation products) • rate of carbonyl formation slows down for hydrated lime-treated bitumens- • rate of sulfides, sulfoxides and ketones formation not modified by hydrated lime • bitumen dependent effect but all bitumen benefit from hydrated-lime treatment • limestone filler does not have any effect on bitumen ageing	[22, 12]
Johansson, 1995	1 + 2 weeks in pressure aging vessel (PAV) at 60°C and 2.1MPa of air pressure	8 SHRP core bitumens	20	• hydrated lime reduces age-hardening based on ageing index (viscosity ratio) except for bitumen AAG • hydrated lime does not affect carbonyl or sulfoxydes formation, except for one bitumen (AAK)	[76, 71]
Oliver, 1995	ARRB durability test (RTFOT + thin film 20 microns ageing at 100°C)	85/100	6-26	hydrated lime improves the durability as measured by ARRB test	[79]
Johansson, 1996	144 hrs thin film oven test (TFOT – EN 12607-2) + PAV 60°C + 80°C	• AAA-1 • AAD-1	5	• hydrated lime suppresses the catalytic activity of vanadium compounds • no specific hydrated lime/vanadium compounds interactions observed • $Mg(OH)_2$ not effective as an anti-ageing compound for bitumen • bitumen dependent effect	[80, 71]

Table 10. A review of the laboratory studies showing the effect of hydrated lime on the ageing of bitumen (continued on next page).

Researcher, year	Aging procedure	Tested bitumens	Hydrated lime content [wt.% based on bitumen]	Main conclusions	Reference
Wisneski, 1996	pressure oxygen vessel (POV) at 88, 93 and 99°C	• AAA-1 • AAF-1 • blended or not with 4 rejuvenators	1-20	• anti-ageing effect observed both with quicklime and hydrated lime, slightly better with HL • lime reduces asphaltene formation upon ageing • lime reduces carbonyl rate formation • lime reduces the hardening susceptibility (slope of log viscosity vs carbonyl area) • bitumen dependent effect	[75]
Lesueur and Little, 1999	TFOT + PAV 100°C 20 hrs	• AAD • AAM	12.5	• hydrated lime reduces age-hardening based on ageing index (viscosity ratio) for bitumen AAD • higher viscosity increase for AAM with HL after ageing, although no increase was found in carbonyl area: part of the viscosity increase due to the kinetics of bitumen / HL interaction	[81]
Hopman, 1999	RTFOT (2.5 and 7 hrs)	• Venezuela 70/100 • Middle East 70/100	12.5	• hydrated lime reduces age-hardening (penetration, R&B, asphaltene formation) • bitumen dependent effect	[69]
Verhasselt, 2001	RTFOT (normal and 7 hrs)	• Venezuela 35/50 • Middle East 35/50	12.5	• hydrated lime reduces age-hardening (penetration, R&B, asphaltene formation) • bitumen dependent effect	[73]
Huang, 2002	PAV 60°C 100-2000 hrs	• AAD-1 • ABD-1	20	• hydrated lime reduces age-hardening (viscosity ratio, asphaltene formation) • bitumen dependent effect • limestone filler does not have any effect on bitumen ageing	[65]
Verhasselt and Puiatti, 2004	RCAT 235 min. at 163°C or 17, 65 and 140 hrs at 90°C	• Venezuela 35/50, 50/70 and 70/100 • Middle East 35/50	12.5	• hydrated lime reduces age-hardening (penetration, R&B, asphaltene formation) • decrease in 1700 cm^{-1} absorbance (carboxylic groups) with hydrated lime • bitumen dependent effect	[74]
Miro, 2005	long-term oven aging (LTOA) of mixture with 4.5% bitumen and 27% voids at 80°C	80/100	17-44	hydrated lime reduces age-hardening (penetration, R&B, viscosity)	[82]

Table 10. (continued from previous page) A review of the laboratory studies showing the effect of hydrated lime on the ageing of bitumen.

Researcher, year, country	Mixture type	Age [years]	Hydrated lime content [wt.% based on dry aggregate]	Main conclusions	Refe-rence
Chachas, 1971, USA (Utah)	many different mixtures from 24 existing projects, 1 to 6 years old half of them w/ lime and 6 new projects all w/ lime	0-6	1% (except in 2 occasions)	• the first notice of hydrated lime effect on bitumen aging (lower viscosity) • observation based on bitumen recovery which had lower viscosity for lime-modified mixtures than non-modified ones • the magnitude of the effect was found to be dependent of bitumen source	[70]
Decoene, 1983, Belgium	2-4 cm porous asphalts and 5 cm asphalt concrete, w/ unmodified and polymer-modified binders, some with hydrated lime	up to 10		same good condition for the HL sections as that with PmB on N5 between Neuville and Mariembourg	[83, 11]
Bruce, 1987, USA (Montana, Big timber test sections)	one aggregate type, 120/150 bitumen in most sections except: • 85/100 in one section • 200/300 + Chemcrete in one section • 200/300 + carbon black in one section	3	1.5% in the drum	penetration of recovered bitumen from mixes with HL 11% higher on average than reference	[84]
Oliver, 1995, Australia	chip seal w/ 85/100 penetration grade bitumen	7.7-10.6	1.5-15.3% in the binder	• no significant effect of HL • maybe due to HL carbonation	[79]
Jones, 1997, USA (Utah)		8		binder viscosity 50% lower for hydrated lime treated mixes, showing a lower ageing	[11]
Huang, 2002, USA (Montana, Big timber test sections)	same as above (Bruce, 1987)	5	1.5% in the drum	nearly same viscosity for all materials (treated and untreated)	[65]
Schneider, 2002, Schellenberg, 2004, Germany	• SMA 0/8 S • AB 0/11	2	1.4% as mixed filler	R&B of recovered bitumen between 1.5 and 7°C lower for hydrated lime modified mixes	[29, 85]
Sewing, 2006, Switzerland	• HMT 22 • SMA 11 • AB 11 N	2-4	2%	R&B of recovered bitumen between 1 and 1.7°C lower for hydrated lime modified mixes, except for one mix	[86, 87]
Bianchetto, 2008, Argentina	mixture 0/19	0	1%	lower aging index for the hydrated lime modified mixes manufactured at 135 or 160°C	[88]

Table 11. A review of the field studies showing the effect of hydrated lime on the ageing of bitumen.

2.3 Mechanical properties

Hydrated lime has been observed to improve the mechanical properties of asphalt mixtures from the very beginning of its use. In fact, the work already presented in the chapter on moisture damage is generally based on mechanical tests before and after some conditioning and some authors rapidly observed that hydrated-lime-modified mixtures tend to have higher strength and modulus than unmodified mixes.

This result is not surprising, knowing the high stiffening effect of hydrated-lime as measured by the European standard tests (see Chapter 1). Still, this section starts with a review of mastics rheology, that is blends of only bitumen and filler, showing the peculiar behaviour of hydrated lime which was already partially captured by the delta ring and ball test. Then, the section reviews the published evidence on several mechanical properties of hydrated-lime-modified asphalt mixtures, and in particular modulus, strength, rutting resistance, fatigue and thermal cracking.

Reasons why hydrated lime has such a stiffening effect are described in another section (see Chapter 3).

2.3.1 Mastics

In order to better understand the properties of asphalt mixtures, many researchers have used intermediate materials such as mastics, i.e. blends of only bitumen and filler, as model systems. The idea behind this research is that the material gluing together the aggregates inside the mixture is not the bitumen but the bitumen blended with the finest elements of the mineral skeleton, i.e. the filler.

When studying mastics, it becomes apparent that a mastic made with hydrated lime behaves in a distinct way than a mastic made with normal mineral filler. In fact, the delta Ring and Ball test described earlier (Chapter 1) is already a test on mastic showing that hydrated lime has a higher stiffening effect than normal mineral fillers.

Several studies confirmed that properties such as viscosity (or equivalently the complex modulus) are similarly increased when hydrated lime is used instead of regular mineral filler [89, 90, 91]. Note that this effect needs time to develop as further explained in Chapter 3 (see Figure 27). Still, most bitumens do show a higher stiffening effect with hydrated lime than normal mineral fillers. As a rule of thumb, and taking an average asphalt mixture with 5% mineral filler and 5% bitumen, the substitution of 1% and 2% mineral filler by 1% and 2% hydrated lime respectively would be equivalent to using a bitumen with a R&B softening temperature higher by ~2.5 and ~8°C respectively. Note that the difference in R&B temperature range between two adjacent paving grades is about 5°C in the current European specifications [92].

Therefore, the 2% hydrated lime substitution is on average similar to shifting the bitumen to the next harder grade (i.e., a 35/50 with hydrated lime would be similar to a 20/30 without hydrated lime).

This can be quantified by means of the intrinsic viscosity $[\eta]$ defined as:

$$[\eta] = \lim_{\phi \to 0} \left(\frac{\eta(\phi) - \eta_0}{\eta_0} \right)$$

where:

$\eta(\phi)$ the viscosity of the mastic with a volume fraction of filler ϕ

η_0 the viscosity of the base bitumen

The intrinsic viscosity $[\eta]$ allows for a good estimate of the viscosifying effect for any value of the filler volume fraction. This can be done using the following equation proposed by W. Heukelom and P. W. O. Wijga of the Koninklijke Shell Laboratorium in Amsterdam (The Netherlands) [93], as validated by other authors [81, 94]:

$$\eta = \eta_0 \left(1 - \frac{[\eta]\phi}{2} \right)^{-2}$$

Using this parameter that quantifies the stiffening effect of a filler, it is shown that hydrated lime ($[\eta]$ ~ 3-10) is about twice as stiffening as other mineral fillers ($[\eta]$ ~ 2.5-5) (Table 12 – [95]).

Filler type	[η]
Limestone	3.8
Limestone	2.6 - 3.9 (25 °C) 3.0 - 3.7 (70 °C)
Limestone	2.5 (65 °C) 2.4 (135 °C)
Dolomitic limestone	4.9 (25 °C) 4.4 (70 °C)
Hydrated lime	3.2 - 10
Lime	7
Sandstone	2.8 (25 °C) 4.0 (70 °C)
Siliccous filler	2.4 (65 °C) 2.4 (135 °C)
Granite	2.7 - 4.2 (25 °C) 3.5 - 4.1 (70 °C)
Fly ash	10.2 (25 °C) 14.1 (70 °C)
Slate dust	4.2
Ball clay	3.2
Kaolin	6.7
Carbon black	2.6 (65 °C) 3.9 (135 °C)
Asbestos	16.5
Polyester fibers	26 - 34
Mineral fibers	26

Table 12. Intrinsic viscosity [η] of various fillers (from [95]).

However, temperature is a key issue here, and the above results only hold because the testing was performed at high temperatures. On the contrary, the low temperature studies show that hydrated lime is similar to other mineral fillers in terms of stiffening effect at low temperature [33, 96]. The switch from the low temperature region of normal stiffening to the high temperature region of high stiffening occurs close to room temperature, as clearly observed for three different bitumens by J. P. Wortelboer and coworkers, in a joint-study between ESHA (Groningen, The Netherlands) and the French Central Laboratory of Roads and Bridges (LCPC – Figure 13 [97]). Other data support the fact that the stiffening effect of hydrated lime is temperature-dependent, with a behaviour similar to mineral filler below room temperature but more effective above [12, 81, 98, 99, 100].

Elements of interpretation of these effects are discussed in Chapter 3.

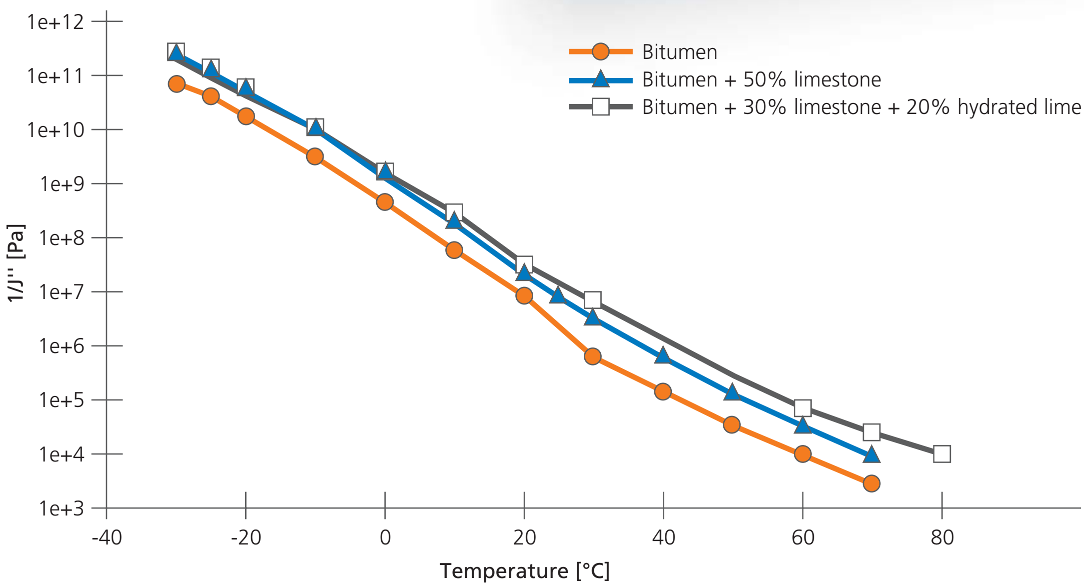


Figure 13. Temperature dependence of the stiffening effect of hydrated lime as compared to a limestone filler: inverse of the imaginary compliance (1/J'') at 10 rad/s versus temperature for a reference straight-run 70/100 bitumen and the same bitumen with 50wt.% of limestone filler or mixed limestone filler containing 40% hydrated lime (from [97]).

2.3.2 Modulus

Modulus is a fundamental mechanical property of materials [101]. It is the ratio between the stress applied to the material and the resulting deformation (or the opposite if the material is tested under a deformation-controlled mode). Modulus is called Young or tension modulus when it is measured in tension (compression is seen here as a negative tension). It is a Coulomb or shear modulus when measured in shear. Other measuring modes can also be found (flexion, ...).

The mechanical properties of an asphalt mixture are known to be temperature and loading time dependent, as a consequence of their viscoelastic behaviour [102]. So, the modulus is temperature and time (or frequency) dependent, and it is generally expressed in terms of a complex number, the complex modulus.

On the mix formulation standpoint, modulus is known to peak at an optimum bitumen content, to increase with the modulus of the binder and to decrease with the air void content [102].

Modulus is of critical importance in the design of pavement layers, because it governs the stress distribution inside each pavement layer. For given load and thickness, higher modulus means lower stresses in the layer.

Although the modulus is an intrinsic property, meaning that it should be essentially independent of the test set-up, small differences are generally observed when modulus is measured in compression, flexion, tension or indirect tension. Testing geometry, i.e. specimen shape and dimensions, and the signal type, i.e. controlled in deformation or force, amplitude, sinusoidal, ..., also affect somewhat the data. Therefore, it is recommended to always disclose the measuring conditions when talking about asphalt mixture modulus. A European standard EN 12697-26 exists in order to limit the differences [103].

A limited number of studies give information about how hydrated lime affects the modulus of asphalt mixtures. The most thorough study is probably the one by Professor M. W. Witczak and J. Bari at Arizona State University [104, 105]. They measured the dynamic modulus in tension-compression between -10°C and 54.4°C and frequencies ranging from 0.1 to 25 Hz for 17 mixture-lime percentage combinations across six different hot-mix formulas that were gyratory compacted to 7% air voids and sawn to 101.6 mm diameter and 152.4 mm high cylindrical specimens. The mixes were made with 4.2-5.2% of four different binders and contained 0, 1, 1.5, 2, 2.5 or 3% hydrated lime as a filler substitute. A typical result from this study is shown in the form of a master curve in Figure 14.

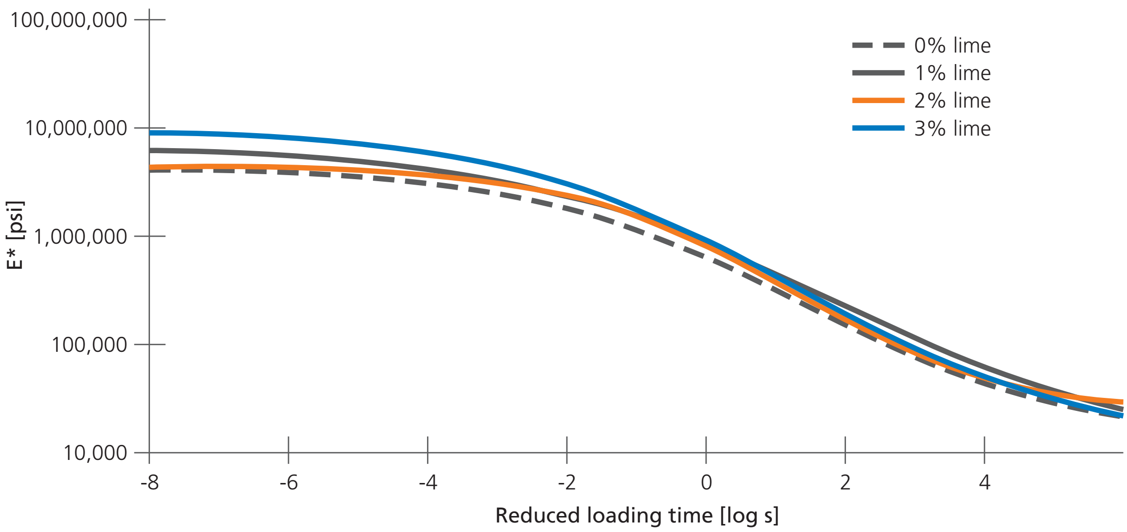


Figure 14. Master curve (norm of the complex modulus versus reduced loading time) at 21.1°C for the 0/18 mixes made of Two-Guns aggregate (4.3% filler) and 4.6% PG64-22 (from [104]).

As a result, hydrated lime was seen to increase the modulus of asphalt mixtures by 8% up to 65% across the range of mixtures and hydrated lime contents at all temperatures and frequencies, with an overall average of 25% increase. However, it must be reminded that the observed increases were of 25, 23, 8, 66 and 24% for respectively 1, 1.5, 2, 2.5 and 3% hydrated lime. Such a strange variation with hydrated lime content comes from the fact that no mix contained the full set of hydrated lime contents. The data with 1, 1.5, 2, 2.5 and 3% hydrated lime were obtained with 4, 1, 2, 1 and 3 mixes formulas respectively. Therefore, the variations come from the use of different bitumen origins and filler contents (between 2.6 and 6.1%), hence differences in stiffening at the mastic level. Note also that no temperature effect similar to the one mentioned with mastics was reported (see section 2.3.1).

Concerning the effect of hydrated lime concentration on the modulus, the published data do not give very conclusive results. As already mentioned, the Witczak study observed the highest stiffening with 2.5% hydrated lime, although all concentrations were not tested on all materials. In another study by F. Thiago S. Aragao and co-workers with the University of Nebraska, an optimum in hydrated lime content of 1.5% was observed when the concentration was changed from 0.5, 1, 1.5, 2 and 3% [106]. Unfortunately, no reference material without hydrated lime was included in the study. In yet another study, M. Ghouse Baig and H. I. Al-Abdul Wahhab at King Fahd University (Saudi Arabia) observed that 4% was the optimum hydrated lime content when increasing it from 1, 2, 3, 4 and 5.5% [107].

As a conclusion, hydrated lime does not always increase the modulus of asphalt mixtures. Of the just described 71 mix formulas, only 42 had a higher modulus (59%). When it is observed, this effect is typically of order of 25% for 1.5% hydrated lime. The optimum hydrated lime content in order to enhance this effect seem to be highly mixture dependent and published data give values ranging from 1.5 to 4%.

Researcher, year	Test conditions	Number of mixtures w/ hydrated lime	Range of hydrated lime content	Method of addition	Number of mixtures w/ hydrated lime having a significantly higher modulus than the reference	Reference
Waite, 1986	25°C	5		B, D, LS	2	[11]
Stroup-Gardiner and Epps, 1987	-28.9 / -1.1 / 25 / 40°C	10	1.5%	B, D, LS	4	[20]
Pickering, 1992	25°C	4	1 - 2%		4	[61,30]
Epps, 1992	25°C	8	1 - 2%		8	[11]
Nevada DOT, 1998	25°C	4			4	[11]
Ghouse Baig and Al-Abdul Wahhab, 1998	25°C	5	1 / 2 / 3 / 4 / 5.5%		4	[107]
Mohammad, 2000	5 / 25 / 40°C	4	1.5%	LS	2	[108]
Sebaaly, 2003	25°C	3	–		1	[54,13]
McCann and Sebaaly, 2003	25°C	12	1.5%	D, DM, LS, LSM	1	[62]
Berthelot, 2005	20°C	1	1%		1	[109]
Jaskula and Judycki, 2005	20°C	2	1.5%		1	[63]
Huang, 2008	-10 / 4.4 / 21.1 / 37.8 / 54.4°C	1	1%		1	[110]
Mohammad, 2008	-10 / 4.4 / 21.1 / 37.8 / 54.4°C	6	1.5%	B, LS	4	[57]
Khattak, 2008	25°C	2	0.9%	B	1	[99]
Vural Kok and Yilmaz, 2008		4	2%		4	[111]

Table 13. A survey of published modulus data. For each publication, the total number of mixes with hydrated lime is given together with the range of hydrated lime content and the number of data showing a significant increase in modulus for hydrated-lime modified mixes. The method of addition is: B – for inside the binder; D – for dry lime to damp aggregate; LS – for lime slurry; M – in case of marination.

So, the published data suggest that little more than half of the mixtures exhibit an increase in modulus when treated with hydrated lime, without any clear explanation on why they do or don't. Part of the explanation probably lies:

- In the temperature dependence of the stiffening effect (Figure 13), which shows that, at the usual concentration of 1-1.5%, hydrated lime should be little more stiffening than common mineral filler around room temperature where modulus is generally measured. Although only two studies [20, 110] suggest that this temperature-dependent effect is also observed on asphalt mixtures, the trend shows that higher hydrated lime content generally means higher modulus.
- In the slow build-up of hydrated lime-bitumen interactions observed with some bitumen, whereas others rapidly react with hydrated lime [81], as discussed in Chapter 3.

Finally, another study by M. Stroup-Gardiner and J. A. Epps with the University of Nevada compared various methods of adding hydrated lime from field specimens as compared to laboratory fabricated materials [53]. They observed that the modulus could be influenced by the method of adding hydrated lime, especially when a drum plant was used, but the influence appeared to be project specific. Field specimens also seemed to have consistently higher modulus than laboratory prepared samples.

2.3.3 Strength

Strength is an engineering mechanical property of materials [101]. It is the maximum stress applied to break the material. Strength is usually measured either in compression or in indirect tension for asphalt mixtures, and generally at controlled temperatures close to room temperature.

In general, modulus and strength are somewhat related when measured in the same temperature and loading conditions, although one is an intrinsic property (modulus) and the other strongly depends on specimen shape and dimensions and is therefore not intrinsic [101]. However, it is a lot easier to measure strength than modulus, hence its predominance in materials engineering. As a rule of thumb, the ratio between modulus and strength is usually quite constant for a given class of materials and loading method (compression, flexion, ...).

Because of this almost constant ratio between strength and modulus, mix variables affect the strength in the same way as the modulus. Therefore, strength is known to peak at an optimum bitumen content, to increase with the modulus of the binder and to decrease with the air void content [102].

A large number of studies give strength values, because most of the data on moisture resistance use strength values before and after conditioning in order to assess the resistance to water damage (see section 2.1). Therefore, the data on the dry strength allows for an evaluation of the effect of hydrated lime treatment on strength. Table 14 summarizes the published data.

As a conclusion, hydrated lime does not always increase the strength of asphalt mixtures. Of the 113 mix formulas described in Table 14, only 63 had a higher strength (56%). So, the published data suggest that only about half of the mixtures exhibit an increase in strength when treated with hydrated lime, without any clear explanation on why they do or don't. The proportion is similar to that observed with the modulus and the reasons why are probably the same: low hydrated lime content, measuring temperature in the low-stiffening zone (Figure 13) and kinetics of the stiffening effect, as discussed in Chapter 3.

Researcher, year	Number of mixtures w/ hydrated lime	Range of hydrated lime content	Method of addition	Number of mixtures w/ hydrated lime having a significantly higher strength than the reference	Refe-rence
Kennedy, 1983 (laboratory mixed mixtures)	16	1.5%	B, D, LS, LSM	1	[66]
Kennedy, 1983 (plant mixed mixtures)	12	1.5%	D, LSM	4	[66]
Stroup-Gardiner and Epps, 1987	10	1.5%	B, D, LS	5	[20]
Jimenez, 1990	1	1.5%		0	[112]
Hicks, 1991	5		B, D, LS, LSM	1	[8,11]
Pickering, 1992	4	1 - 2%		4	[61,13]
Mohammad, 2000	8	1.5%	LS	5	[108]
Sebaaly, 2003	6		D,LS	6	[113,13]
McCann and Sebaaly, 2003	12	1.5%	D, DM, LS, LSM	4	[62]
Huang, 2005	2	1%	B	0	[65]
Jaskula and Judycki, 2005	2	1.5%	–	0	[63]
Ameri and Aboutalebi, 2008	10	3%	–	10	[114]
Kim, 2008	2	1%	D,LS	2	[60]
Mohammad, 2008	12	1.5%	B, LS	10	[57]
Maldonado and Fee, 2008	1	2%	–	1	[58]
Gorkem and Sengoz, 2009	6	1 / 1.5 / 2%	–	6	[115]
Vural Kok and Yilmaz, 2008	4	2%	–	4	[111]

Table 14. A survey of published strength data. For each publication, the total number of mixes with hydrated lime is given together with the range of hydrated lime content and the number of data showing a significant increase in strength for hydrated-lime modified mixes. The method of addition is: B – for inside the binder; D – for dry lime to damp aggregate; LS – for lime slurry; M – in case of marination.

2.3.4 Rutting resistance

Rutting has been observed on asphalt mixtures since the very beginning of the technology, but became increasingly important after World War 2 when traffic loading started to increase rapidly [116]. It occurs when the traffic load over the asphalt mix exceeds its plastic limit, hence generating permanent plastic deformation (Figure 15). As a result, rutting is favoured by low-speed loads and high temperatures [117]. However, rutting remains a complex phenomenon, because the asphalt mixes deform in a viscoelastoplastic way under these conditions.

On the mix formulation standpoint, rutting is known to be favoured by several factors such as high bitumen content, high sand content, round aggregate shape (like uncrushed gravel) or high binder deformability [116]. Therefore, factors favouring the stiffening of the mixtures should also increase the rutting resistance. Still, rutting occurring at high temperatures when the binder softens, the mechanical properties at stakes are those in the high temperature range, that is typically in the 40-60°C range for Europe.

Figure 15. Rutting in an asphalt mixture (from [45]).

According to the US survey from the early 1990s already cited [8], rutting typically occurs for untreated mixes 5 years after construction on average, but sometimes also the very first year.

Several test methods are available to evaluate the rutting resistance of asphalt mixtures. Most are traffic simulators, others are mechanical tests quantifying the permanent deformation accumulated by the material under repeated loads at high temperature (generally in the 40-60°C range). A European standard gathering several test set-ups exist in order to test asphalt mixtures for rutting resistance [118]. The Asphalt Pavement Analyzer (APA) also falls in the category of traffic simulators. Some mechanical tests can also be used, such as creep measurements (sometimes repeated) or dynamic compression.

Data using the Hamburg Wheel Tracking Device (HWTD) were already listed in the moisture resistance section (Table 5). They are not fully conclusive as far as rutting resistance is concerned, because the test really measures the rutting resistance in the first part of the test, the second part after the stripping inflection point, assessing more the stripping potential (see Figure 16 – [13] gives for a good description of the HWTD).

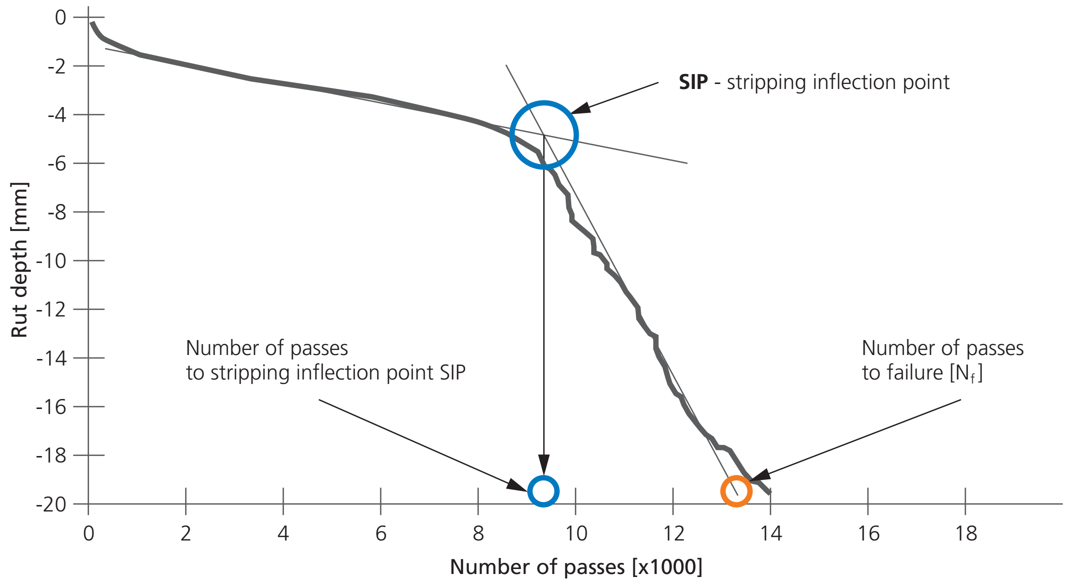


Figure 16. Interpretation of the experimental results from the HWTD (from [13]).

Therefore, it is difficult to identify whether the gain that is usually obtained by the modification with hydrated-lime, comes as a consequence of a better rutting resistance, a better moisture--resistance or both. That is why the test was described in a former section on moisture resistance, where it was shown that it was very useful in order to highlight the benefits of hydrated lime modification (see section 2.1).

When the data from the HWTD are not taken into account, the published data on rutting of hydrated lime modified mixtures become far less numerous (Table 15). Figure 17 illustrates the effect of hydrated lime on the rutting resistance of one asphalt mixture formula.

As a conclusion, hydrated lime increases the rutting resistance of asphalt mixtures in most of the cases. Of the 20 mix formulas described in Table 15, 15 had a higher rutting resistance (75%). So, the published data clearly suggest that hydrated lime generally improves the rutting resistance when treated with hydrated lime. Comparing to modulus and strength data, this might confirm that the stiffening effect of hydrated lime is generally more pronounced at high temperature (where rutting is measured) than at lower temperature. Also, hydrated lime content higher than 1.5% are generally seen to be more effective in order to observe a significant effect.

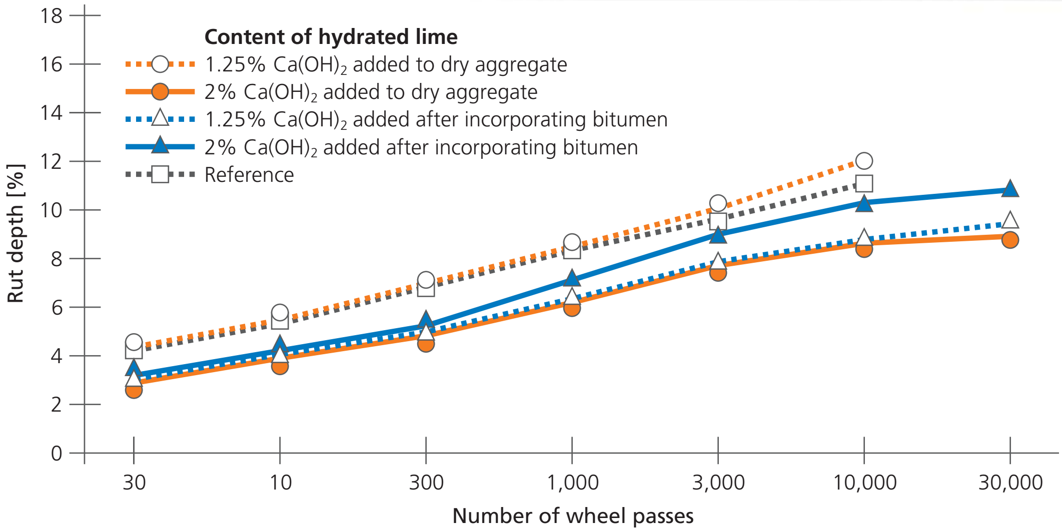


Figure 17. Effect of hydrated lime on the rutting resistance of a french BBSG 0/14 asphalt mixtures: rut depth vs number of load cycles in the french rut tester at 60°C. 1.25 or 2% hydrated lime were added either to the dry aggregate or to the mixture after incorporating the bitumen (from [73]).

Researcher, year	Method	Number of mixtures w/ hydrated lime	Range of hydrated lime content	Method of addition	Number of mixtures w/ hydrated lime having a significantly higher resistance than the reference	Reference
Little, 1994		3			3	[12]
Hiérnaux, 1995	french, 60°C	1	1%		1	[23]
Kim, 1995		1			1	[11]
Collins, 1997	APA	8			5	[119, 11]
Ghouse Baig and Al-Abdul Wahhab, 1998	45 and 60°C	2	2 - 5.5%		1	[107]
LCPC, 1999	french, 60°C	4	1 - 2%	D, B	3	[73]
Pilat, 2000	creep, 40°C	1	20% of the filler	MF	1	[100]
Little and Petersen, 2005	APA, 45°C	2	1%	D	2	[13]
Sewing, 2006	dynamic compression, 55°C	2	2%	D	2	[86]

Table 15. A survey of published rutting resistance data. Note that data with the Hamburg Wheel Tracking Device were already described in Table 5. For each publication, the total number of mixes with hydrated lime is given together with the range of hydrated lime content and the number of data showing a significant increase in rutting resistance for hydrated-lime modified mixes. The method of addition is: B – for inside the binder; D – for dry lime to damp aggregate; LS – for lime slurry; M – in case of marination; MF – for mixed filler.

2.3.5 Fatigue cracking

Fatigue cracking of asphalt pavements is a more recently studied phenomenon. Also it had been recognized as a possible failure mode for asphalt mixtures by M. Duriez at the French Central Laboratory of Roads and Bridges (LCPC) in the 1950s [7], it has really been demonstrated to be the case in the celebrated AASHO trials in the USA from 1957 to 1961 [120].

Fatigue cracking occurs when the repeated traffic loads progressively damage the asphalt mixtures, generating cracks propagating from the bottom of the layer to the top (Figure 18). As a consequence, fatigue cracking is favoured by low thicknesses of the layer or bad adhesion between the successive layers, that both promote high flexural stresses at the bottom of the asphalt layers [121].

Figure 18. Fatigue cracking (= alligator cracking) in an asphalt mixture (from [45]).

On the mix formulation standpoint, fatigue resistance is known to be enhanced by a high bitumen content or the use of high--performance binders [102]. Depending on the way fatigue is measured, a soft binder can increase the fatigue life (strain--controlled) or decrease it (stress-controlled).

Fatigue cracking is the main failure mode that is used in the design of pavement layers. More precisely, the bituminous layers are designed to be thick enough to insure that fatigue cracking won't appear until the end of design life, which can go from 10 to 40 years in Europe [122].

Fatigue life is generally studied in the lab by submitting a specimen to repeated loads of constant intensity. The load can be either stress or strain-controlled. In stress-controlled experiments, failure is easily detected as the breaking point of the specimen. In strain-controlled experiments, failure is conventionally defined as the point where the specimen modulus is decreased by 50%. The number of cycles to failure is measured as a function of loading intensity. Typical fatigue curves are shown in Figure 19. A European standard EN 12697-24 exists in order to test asphalt mixtures for fatigue resistance [123].

Not so many studies were published on the effect of hydrated lime on the fatigue resistance of asphalt mixtures. Examples of the effect of hydrated lime are listed in Table 16.

Except for the study by Professor L. N. Mohammad and coworkers at Louisiana State University [108], they all confirm that hydrated lime is beneficial for fatigue resistance. This makes 17 out of 22 mixtures with improved fatigue resistance (77%). However, none of the studies made measurement using the European standards. Moreover, all of the studies limited their range to strain / stress levels that gave life expectancies well below 1 million cycles. It is therefore not appropriate to extrapolate pavement life time from these data, where the cumulative loads range from 1 to 100 millions.

As a conclusion, little data were published on the effect of hydrated lime on fatigue resistance of asphalt mixtures. In 77% of the cases, they support the fact that hydrated lime increases the fatigue life, but the data are limited to low number of cycles with procedures not covered by the European standards and are therefore not fully conclusive.

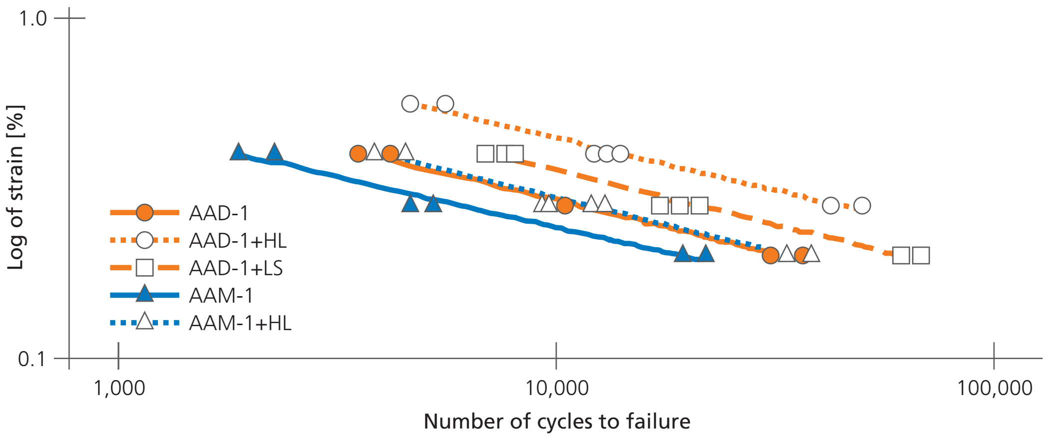


Figure 19. Effect of hydrated lime on the fatigue life of sand asphalt mixtures tested in torsion. Number of cycles to failure vs strain for several sand asphalts containing 10% of hydrated lime (HL) or limestone filler (LS) in the bitumen for two bitumen sources: AAD-1 and AAM-1 (from [90]).

Researcher, year	Test conditions	Number of mixtures w/ hydrated lime	Range of hydrated lime content	Method of addition	Number of mixtures w/ hydrated lime having a significantly higher resistance than the reference	Refe-rence
Rhagava Chari and Jacob, 1984	30°C, 1Hz	5	3 / 5 / 7 / 9 / 11%		5	[124]
Kim, 1995		1			1	[119,11]
M. Ghouse Baig and H. I. Al-Abdul Wahhab, 1998	45°C	5	1 / 2 / 3 / 4 / 5.5%		5	[124]
Mohammad, 2000	25°C	8	1.5%	LS	3	[108]
Little and Petersen, 2005		3	1%	D	3	[13]

Table 16. A survey of published fatigue resistance data. For each publication, the total number of mixes with hydrated lime is given together with the range of hydrated lime content and the number of data showing a significant increase in fatigue resistance for hydrated-lime modified mixes. The method of addition is: B – for inside the binder; D – for dry lime to damp aggregate; LS – for lime slurry; M – in case of marination; MF – for mixed filler.

2.3.6 Thermal cracking

Thermal cracking is especially seen in cold areas. In these regions, the low temperatures imposed on the bitumen, make it essentially perform in its glassy state where it becomes brittle. As a consequence, the thermal shrinkage occurring upon cooling develops stresses that can overcome the materials resistance, hence generating a large crack (Figure 20).

However, thermal cracking is not limited to cold regions. Large day-night amplitudes can also generate cracking patterns with the crack going down from the top of the layer to the bottom. Is has been observed in Southern France [125] and is known to be quite present elsewhere [126].

On the mix formulation standpoint, and just like fatigue cracking, thermal cracking resistance is known to be enhanced by a high bitumen content or the use of high-performance binders [127]. A soft binder increases the cracking resistance, hence their use in Nordic regions.

Thermal cracking is generally studied in the lab by submitting a specimen to a restrained cooling cycle (thermal stress restrained specimen test - TSRST). The dimensions of the specimens are maintained constant so that thermal stresses build up upon cooling. The temperature at which the specimen breaks is then recorded. Typical experimental curves are shown in Figure 20.

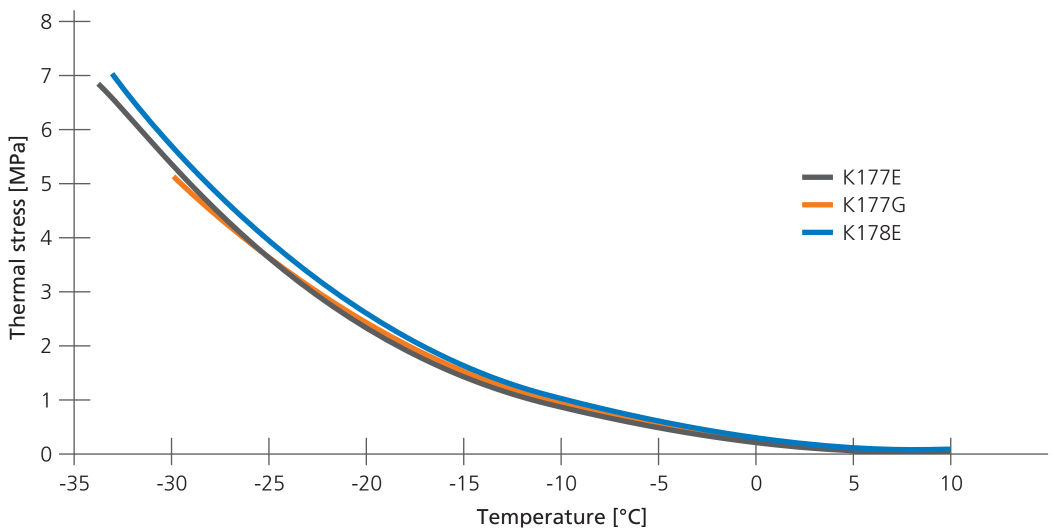


Figure 20. TSRST (thermal stress vs temperature) for 0/22 asphalt concrete with 4.5% polymer-modified bitumen and 2.5% hydrated lime. The curves correspond to repetitions for the same material (from [128]).

Asphalt mixture	Starting temperature [°C]	Temperature gradient [K/h]	Maximum thermal stress [N/mm²]	Breaking temperature [°C]
SMA 0/8 with 7.3% 50/70 bitumen, with 1.6% hydrated lime (in the form of Ka_{25} mixed filler)	20	-10	4.279 4.339	-24.3 -24.6
SMA 0/8 with 7.3% 50/70 bitumen	20	-10	4.296 4.238	-24.1 -24.5
AC 0/11 with 6.2% 70/100 bitumen, with 1.4% hydrated lime (in the form of Ka_{25} mixed filler)	20	-10	4.761 4.573	-26.6 -26.2
AC 0/11 with 6.2% 70/100 bitumen	20	-10	4.558 4.523	-26.3 -26.0

Table 17. TSRST (thermal stress vs temperature) data for two different asphalt mixtures with and without hydrated lime (from [29]).

The data in Table 17 show that the cracking temperature is essentially unmodified when a hydrated lime modified mixture is compared to the same mixture without hydrated lime. The results by M. McCann (U.S. Forest Service) and Professor P. E. Sebaaly (University of Nevada) confirm that neither the failure temperature nor the thermal stresses were significantly different between the hydrated lime modified and the unmodified materials [62].

Note that Professor L. N. Mohammad and co-workers at Louisiana State University published some fracture energy data on hydrated lime modified mixes, with the result that it decreased upon hydrated lime addition [57]. These results are not opposite to the TSRST results already mentioned, because they were in fact measured at 25°C, and are therefore not measuring the same property.

Note that these results are consistent with mastic toughness results. It was observed that hydrated lime toughens bituminous mastics, but essentially to the same extent as mineral filler at the same volume concentration (Figure 21 – [81]). Therefore, hydrated lime is not expected to affect the low temperature fracture properties differently than other mineral fillers, as confirmed by the limited number of studies published on the absence of improvement of hydrated lime on the low temperature cracking of asphalt mixtures.

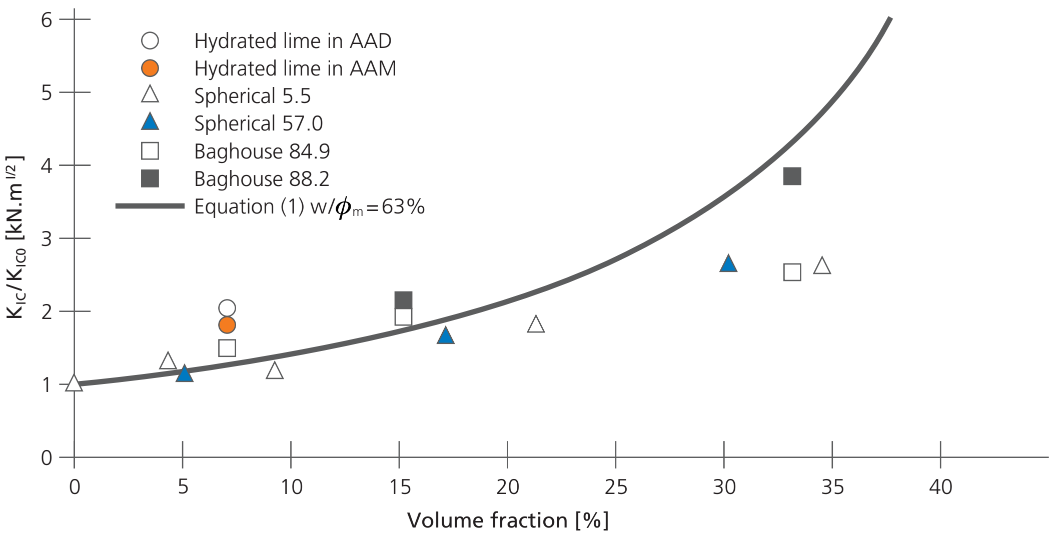


Figure 21. Mastic toughness (reduced to that of the base bitumen) versus filler volume fraction for several mastics made with two bitumens and hydrated lime. The data are compared to published data for mineral fillers (baghouse fines - particle size given in microns) or glass beads (spherical particles - particle size given in microns). Equation (1) correspond to the same equation as given for viscosity in 2.3.1 with $[\eta] = 2/\phi_m = 3.17$ (from [81]).

2.4 Hydrated lime combined to other additives

2.4.1 Hydrated lime and polymers

Several studies show that hydrated lime and polymer can act in a synergetic way. Polymers are used in order to modify the mechanical properties of the mixtures [95, 129]. It is then possible to benefit from the possible effect of hydrated lime on the mechanical properties in order to obtain mixtures with good mechanical properties but with lower polymer content, polymer being an expensive ingredient as compared to hydrated lime.

Depending on the properties used for the mix design, equivalent polymer-hydrated lime combinations can be found.

For example, B. Brûlé and co-workers with Entreprise Jean Lefebvre (now Eurovia) showed that a porous asphalt with 7% of an Ethylene Vinyl Acetate copolymer (EVA)-modified bitumen was equivalent to one with 1% hydrated lime and only 3% EVA when the Cantabro test was used as the main criteria [68]. Note that this mixture was applied on the A4 motorway in Reims (France) in 1992 and lasted until 2009, an excellent durability for a porous asphalt.

P. Cramer with Basalt AG and co-workers showed that a SMA 0/8 mixture with a polymer-modified bitumen (PmB 45 A) was equivalent to one with 1.4% hydrated lime and 30/45 binder when the HWTD test was used as the main criteria (Figure 22 – [37]).

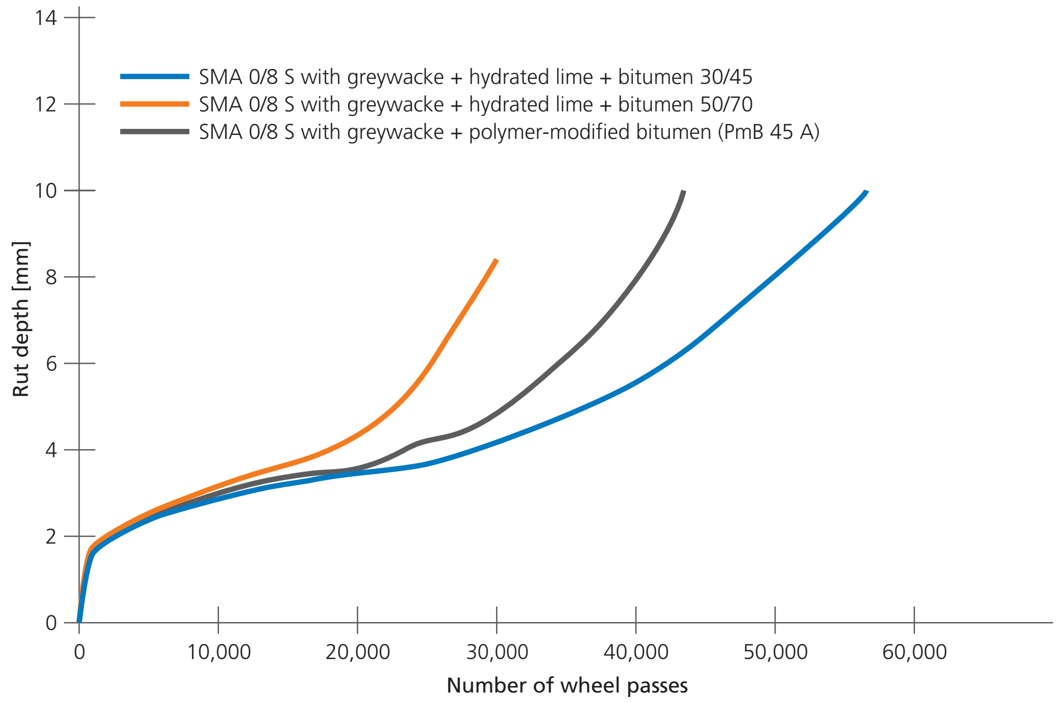


Figure 22. Rutting curves obtained on the HWTD for several SMA 0/8 mixtures made with the same aggregate (greywacke) but different binders: polymer-modified bitumen (PmB 45 A), 30/45 or 50/70 bitumen with 1.4% hydrated lime (in the form of mixed filler). An adequate choice of binder and hydrated lime content can give equivalent properties as those obtained with polymer-modified binders (from [37]).

C. Gorkem and B. Sengoz with Dokuz Eylul University in Izmir (Turkey) showed that 0/19 asphalt concrete mixtures made with two aggregates were equivalent in terms of tensile strength and retained tensile strength with 2-3% of a Styrene-Butadiene block-copolymer (SBS)-modified binder, 3-4% EVA-modified binder or 2% hydrated lime [115].

B. Vural Kok and M. Yilmaz with Firat University in Elazig (Turkey) showed that a 0/19 asphalt concrete mixture with 4% SBS-modified binder was equivalent to one with 2% SBS and 2% hydrated lime when modulus, indirect tensile strength or Lottman test were used as the design criterion [111].

M. Iwanski and M. Pobocha with Kielce University of Technology in Poland tried several hydrated lime (10-50wt.% in the filler) – SBS (2-8wt.% in the bitumen) combinations in the formulation of a Porous Asphalt [130]. Based on moisture damage (immersion / compression and Lottman test) and mechanical properties (creep and Marshall), an optimum was found with the combination of 30% hydrated lime in the filler and 4% SBS.

The Austrian experience, based this time on Marshall design and validated by rutting studies (30 000 cycles at 60°C), shows that 3.5% hydrated lime with neat 70/100 bitumen can be a substitute to asphalt mixtures made with PmB 30-50 or 60-90 polymer-modified bitumens [131]. The original validation was performed on dense asphalt surface and base mixtures (AB 11 LK S and BT 32 LK S respectively). Now, many road sections were paved with similar design with 2.5-3.5% hydrated lime and the results after 6 years are quite good [132].

Finally, it is important to recall that hydrated lime has also been used with great success in crumb rubber modified asphalt mixtures, especially for the very first applications of porous asphalt in Europe, as detailed in section 4.3.

2.4.2 Hydrated lime and polyphosphoric acids

In Northern America, some bituminous binders are now commonly modified with PolyPhosphoric Acids (PPA). PPA modification yields to stiffer binders [95, 133] and the technology is developing everywhere in the World. PPA being an acid, there has been some discussions about the compatibility between hydrated lime (a base) and PPA. However, the published data do not show any antagonist effects.

For example, a study by T. Arnold and coworkers with the Federal HighWay Administration showed that PPA modification combined with 1% hydrated lime did not show any risk of moisture damage in the HWTD [134].

These results are consistent with the observation that PPA and hydrated lime were seen to work in good conjunction in the National Center for Asphalt Technology test track in Auburn (Alabama) [135] or in some recent Brazilian studies from the University of Sao Paulo [136].

3. Mechanisms of hydrated lime modification of asphalt mixtures

The mechanisms by which hydrated lime modifies asphalt mixtures remain somewhat hypothetical. Still, the literature is rich of results showing that hydrated lime has in fact several effects, some having consequences in terms of adhesion, others in terms of ageing and yet some others in terms of mechanical properties.

Therefore, it seems reasonable to conclude that hydrated lime is acting at different levels:

- Hydrated lime is modifying the aggregate surface. Most of the US methods to add hydrated lime consist in putting it directly onto the wet aggregate, sometimes with marination (Table 20). This demonstrates that the surface modification of the aggregate is one key aspect of hydrated lime modification.
- Hydrated lime is also reacting with the bitumen. There are chemical reactions between this basic compound and some of the acidic moieties naturally present in the bitumen. This aspect is referred to as the chemical effect on bitumen.
- Then, hydrated lime develops some physical interactions with the bitumen, arising from its porous structure. As mentioned in Chapter 1, this differentiates hydrated lime from other mineral fillers and will be referred to as the physical effect on bitumen.

For all of these reasons, the interactions between hydrated lime and the other components of the asphalt mixture are quite intense, explaining the improvement in properties as different as moisture damage resistance, ageing resistance and mechanical properties.

3.1 Effect on the aggregate

3.1.1 Surface modification

It is well known in asphalt science that siliceous aggregates have worst adhesive properties toward bitumen than limestone aggregates [8, 137]. Reasons for that are that both anionic and cationic surfactants naturally present in the bitumen strongly bond with calcium ions when only cationic surfactants strongly bond with silica atoms [138]. As a consequence, anionic surfactants are easily displaced by water on siliceous aggregates.

Therefore, one of the effects of hydrated lime is to allow for the precipitation of calcium ions onto the aggregate surface, making it more favourable to bitumen. This effect was already recognized by I. Ishai and J. Craus with Techion-Israel Institute of Technology in 1977 (Figure 23 – [139, 140]). As a consequence, a surface treatment with almost no remaining hydrated lime particles already improves the bitumen-aggregate adhesion [141].

In addition, calcium carbonate can precipitate in the presence of water (at the manufacturing stage or in-situ upon rain exposure) and therefore create a higher surface roughness which is known to favour bitumen adhesion as well [142].

This effect can be quite strong to the point that part of the hydrated lime is not recovered after bitumen extraction as described later on in section 4.4. In the case of basalt filler, about 40% of the hydrated lime was not recovered probably due to the reactions with the aggregate when more than 90% of the hydrated lime was recovered with limestone filler (see Figure 30).

Still, the surface modification effect is not the only mechanism. In fact, this mechanism would be almost inexistent with limestone aggregates. However, hydrated lime is known to improve the adhesion of the limestone aggregates as well (Figure 9 – see also [57, 77]. So, other mechanisms must operate, and especially those acting on the bitumen as described below.

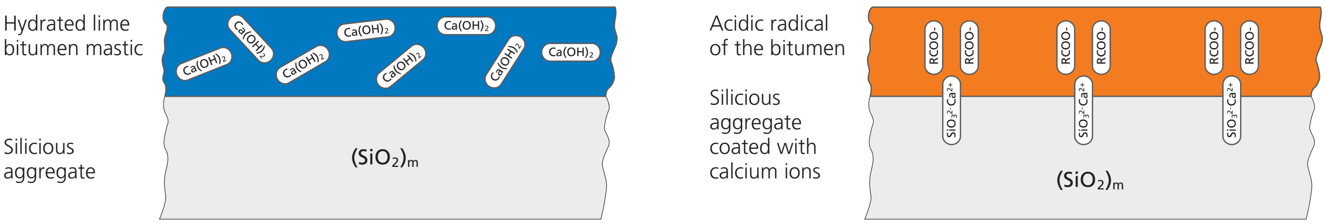
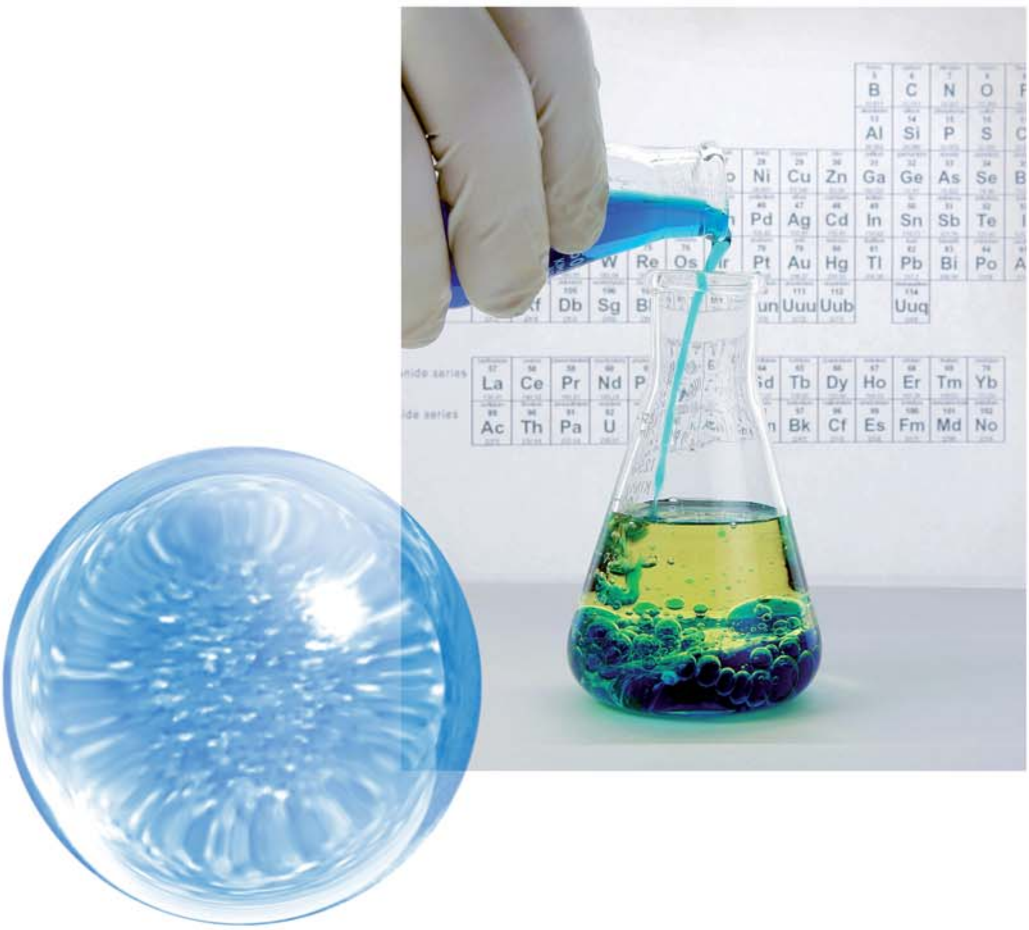


Figure 23. The effect of hydrated lime on the aggregate surface as proposed by I. Ishai and J. Craus (from [139]).

3.1.2 Clay focculation

In the case of clayey aggregates, hydrated lime is known to be highly effective in increasing the resistance to moisture damage. This is the reason why hydrated lime is used in such States as California, Colorado, Nevada or Utah which all have aggregates contaminated by large amounts of clays. More specifically, clays are generally present in the form of small inclusions inside the rock and are liberated upon crushing. In this case, the role of hydrated lime is similar as observed in soil treatment [143]: lime flocculates the clay particles, preventing them to build a water--displaceable barrier between the bitumen and the aggregate.

A German study by H.-J. Eulitz with the Institut für Materialsprüfung Dr. Schellenberg in Rottweil (Germany) and coworkers with controlled clay contamination confirmed that hydrated lime efficiently counteracts the effect of clay [38, 39].



3.2 Effect on the bitumen

3.2.1 Chemical effect on the bitumen

The chemical effect between hydrated lime and bitumen was observed by Plancher and coworkers at Western Research Institute (WY, USA) as early as 1976 [72]. They took four bitumens that varied widely in chemical composition. They prepared 1:1:600 weight solutions of bitumen, hydrated lime and benzene that were left to react for 24 hours. After centrifugation and solvent extraction, they recovered lime-treated bitumens that were carefully analyzed by infrared spectroscopy. About 4-6wt.% of each bitumen were strongly adsorbed onto the hydrated lime particles [72].

More recently, P. C. Hopman with the Netherlands Pavement Consulting showed that hydrated lime was more effective than limestone filler in respect to bitumen-filler interactions. On average, bitumen adsorption from several solvents (n-heptane, TetraHydroFuran – THF, toluene and methylchloride) on active limestone filler containing 25wt.% hydrated lime was 1.4 and 2.1 times higher than with regular limestone filler, for respectively Middle East and Venezuelan bitumens [69]. When comparing High Performance Gel Permeation Chromatography (HP-GPC) curves in toluene of the bitumens treated either with limestone filler or active filler (Figure 24), it appears that hydrated lime has adsorbed some of the heavy molecules of the bitumens. Note that the effect was less pronounced in THF than in toluene [69].

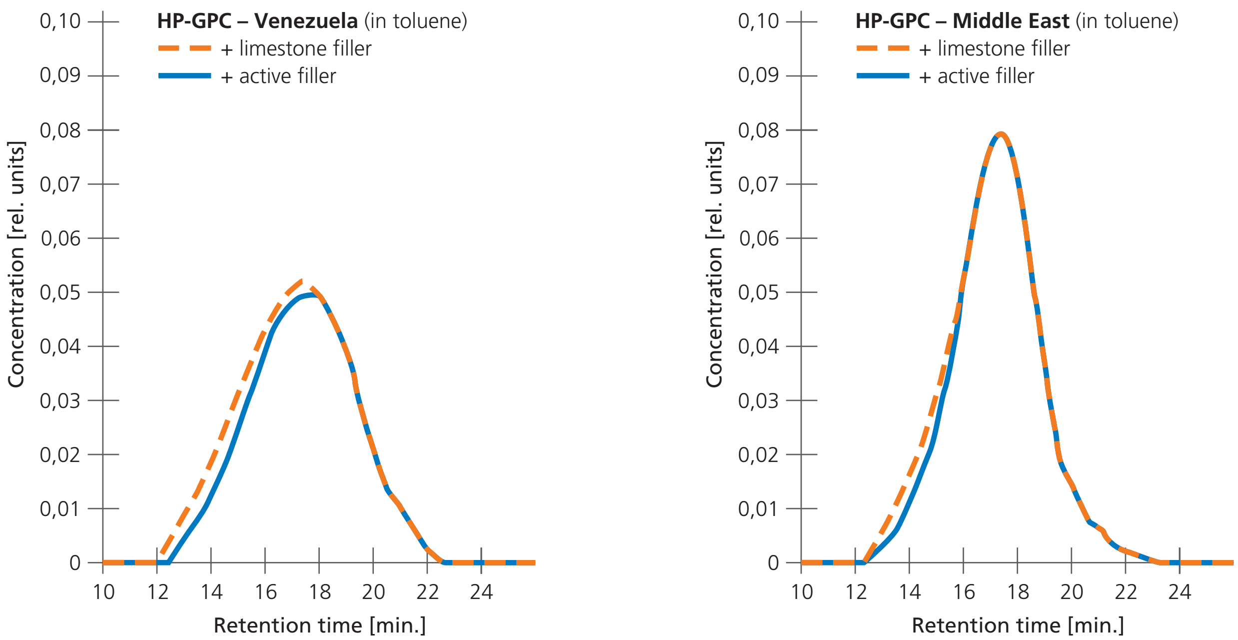


Figure 24. High performance gel permeation chromatography in toluene for two bitumens from Venezuela or Middle East, after contact with either a limestone filler or the same filler with 25wt.% hydrated lime (active filler) (from [69]).

Information concerning the bitumen species adsorbed onto the hydrated lime surface can also be found in the literature. As reproduced in Table 18, the lime-treated materials in the study by H. Plancher and coworkers at Western Research Institute (WRI) in Laramie (Wyoming, USA – [72]) showed lower concentrations in carboxylic acids, dicarboxylic anhydrides and 2-quinolones, which are typically concentrated in the heaviest components of bitumen called the asphaltenes (see [95] for a review of bitumen structure and chemistry). The ketones were however more numerous. Sulfoxides did not change significantly.

Asphalts	Concentration [moles/liter]				
	Ketones	Carboxylic acids	Dicarboxylic anhydrides	2-quinolone types	Sulfoxides
B-2959 without lime / with lime	0.015 0.039	trace (1)	0.0014 (1)	0.003 (1)	0.015 0.013
B-3036 without lime / with lime	0.021 0.039	trace (1)	0.001 (1)	0.001 (1)	0.022 0.019
B-3051 without lime / with lime	0.017 0.039	0.014 (1)	0.003 0.001	0.009 0.004	0.010 0.008
B-3602 without lime / with lime	0.045 0.1	0.06 (2) 0.014 (2)	(1) 0.007	0.011 0.006	0.015 0.015

Table 18. Concentration of functional groups in four AC-10 bitumens of different chemical composition before and after treatment by hydrated lime. (1) – below level of detection; (2) – present as carboxylate salts (from [72]).

Clearly, hydrated lime reacts with the acids, the anhydrides and the 2-quinolones of the bitumen. The same conclusion was reached in a more recent study by the same group [22]. 150 g of several bitumens were left to react under agitation for 6 hours at 150°C with various amounts of hydrated lime or hydrated dolomitic lime. The hydrated limes could then be solvent-extracted. Infrared spectroscopy was used to characterize analysis the materials with and without lime-treatment and before or after TFAAT ageing (see the results for the same material in Figure 12). As reproduced in Table 19, the presence of hydrated lime reduces the amount of ketones, anhydrides and most of all of carboxylic acids that form upon ageing.

Therefore, the acid-base reactions between hydrated lime and the acids naturally present in the bitumen are fully supported by the published data, as reviewed by Professor D. N. Little at Texas Transportation Institute (College Station, Texas) and J. C. Petersen, retired from WRI [12]. In addition, other data support the importance of acid-base reactions on the anti-ageing effect:

- L. Johansson with the Swedish Royal Institute of Technology (KTH) and coworkers observed that the anti-ageing effect was not present with $Mg(OH)_2$, a weaker base than $Ca(OH)_2$ [80].
- M. Wisneski and coworkers at Texas A&M University observed that quicklime had the same anti-ageing effect as hydrated lime [75].

Lime treatment		Aging test	Concentration [moles/liter]				
Type	%		Ketones	Anhydrides	Carboxylic acids	2-quinolone types	Sulfoxides
Without calcium	0	unaged	0	0	0.015	0.017	0.02
	0	aged	0.28	0.007	0.015	0.017	0.35
High calcium content	10	unaged	0.03	0	0.005	0.016	0.03
	10	aged	0.24	0.005	0.004	0.016	0.32
High calcium content	20	unaged	0.03	0	0.003	0.014	0.03
	20	aged	0.22	0.006	< 0.002	0.017	0.34
High calcium content	30	unaged	0.03	0	< 0.002	0.013	0.03
	30	aged	0.21	0.006	< 0.002	0.014	0.32
Dolomitic lime	20	unaged	0.03	0	0.006	0.013	0.03
	20	aged	0.22	0.006	0.005	0.014	0.34

Table 19. Concentration of functional groups in a Boscan bitumen before and after TFAAT ageing in the presence of various amounts of hydrated lime or hydrated dolomitic lime (from [22]).

Still, the acid-base reactions are probably not sufficient to explain the whole chemical interactions at stakes. J. C. Petersen and coworkers at WRI proposed that hydrated lime acts as an inhibitor for the oxidation catalysers naturally present in the bitumen [22, 72]. This was in part validated by L. Johansson (KTH) and coworkers, who showed that the catalytic effect of vanadium compounds on bitumen ageing was decreased by hydrated lime, although they could not highlight any specific vanadium – hydrated lime interactions in order to explain their findings [80]. In all cases, it must be reminded that the intensity of hydrated lime-bitumen interactions dependent on bitumen chemistry and therefore on bitumen crude source [22, 72, 74, 81].

In the end, the hydrated lime-bitumen chemical interactions have two effects:

- First, the polar molecules neutralized by the hydrated lime remain strongly adsorbed onto the hydrated lime particles [12, 22, 72]. This prevents them from further reacting as a consequence of bitumen chemical ageing. Since they are especially prone to ageing, their removal generates an overall slower ageing kinetics, as detailed in a former section.
- Second, these polar molecules that are neutralized by the hydrated lime particles are also prevented to diffuse to the bitumen-aggregate interface. As a consequence, only the remaining non-acidic surfactants of the bitumen can move to the bitumen-aggregate interface [137, 142]. These other surfactants are typically amine-based [144] and are not easily displaced by water, unlike anionic surfactants [137, 138]. This effect is confirmed by the observation that putting the hydrated lime directly inside the bitumen improves the moisture resistance of the corresponding asphalt mixtures [20, 53, 65].

As a conclusion, the chemical interactions between hydrated lime and the acidic moieties of bitumen contribute to both the improved ageing resistance and the improved adhesion of hydrated-lime modified mixes.

3.2.2 Physical effect on the bitumen

As described in a previous section, hydrated lime has higher dry porosity (Rigden air voids) than mineral fillers, with typical values ranging from 60 to 70% when mineral fillers have values closer to 30-34% (Figure 4). The difference comes from the higher porosity of the hydrated lime particles (Figure 25). For mineral filler, the porosity essentially comes from the voids between the particles. For hydrated lime, the porosity inside the particles sums up to the porosity between the particles, hence leading to a much higher value.

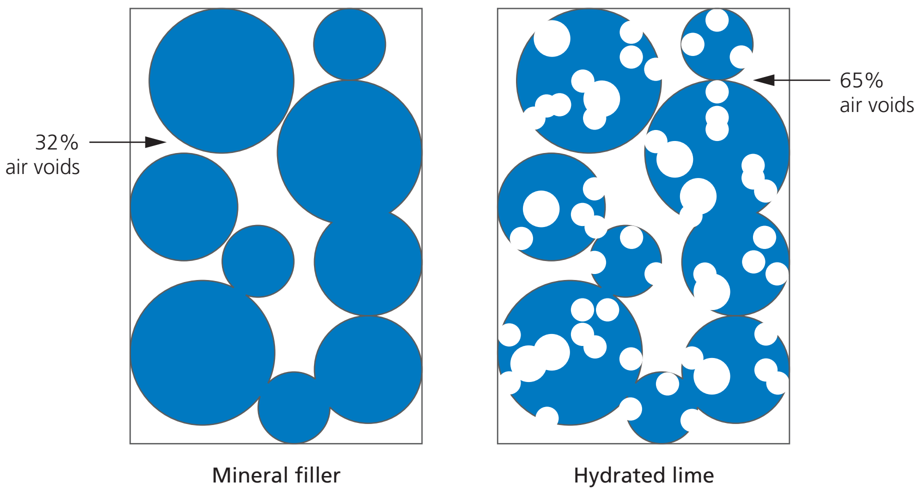


Figure 25. The dry porosity of hydrated lime (right) is higher than that of mineral filler (left) because the porosity inside the particles, which is negligible with mineral filler, sums up to the porosity between particles.

Rigden air voids correlates very well with the stiffening power as measured by the delta ring and ball, as illustrated in Figure 26 using data from a study performed by S. Vansteenkiste and A. Verstraeten at the Belgian Road Research Center [30], completed by data from the study by W. Grabowski et al. of Poznan University of Technology already described in Chapter 1 ([31] – see Figure 4 and Figure 5).

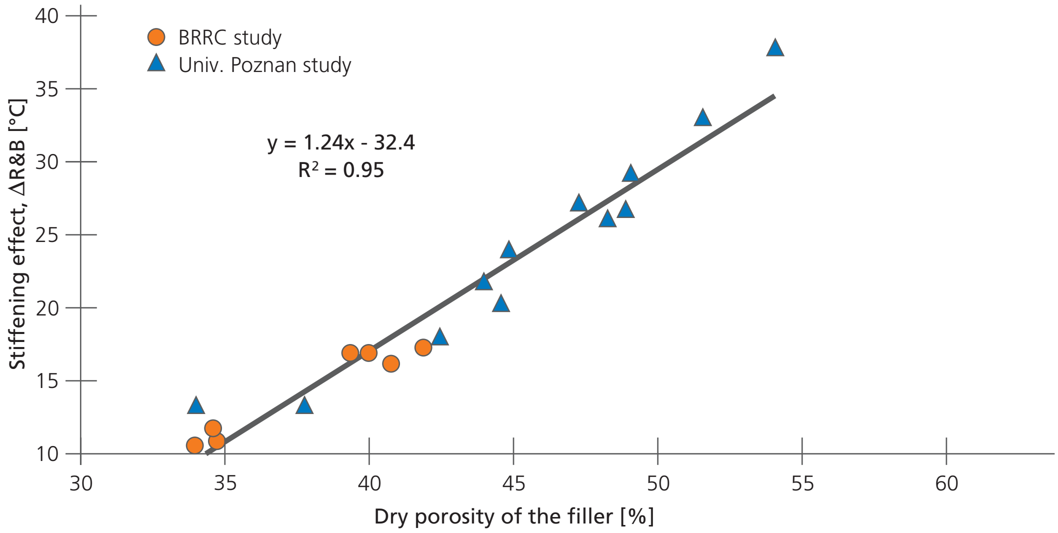


Figure 26. Correlation between the stiffening effect of several fillers with their dry porosity (Rigden air voids). The data are from two studies: one from Poznan University of Technology [30] (already described in Figure 4 and Figure 5) and the other from the Belgian Road Research Center [31]).

Therefore, the stiffening effect of hydrated lime at high temperature can be explained, at least partially, by the higher porosity as captured by the high Rigden air voids values. Note that the build-up of this effect is not immediate. It was observed that several hours at 138°C were needed for one bitumen (AAM) to develop a strong stiffening effect when modified with hydrated lime, whereas it was almost instantaneous at the same temperature for another bitumen (AAD) (Figure 27 – [81]). The kinetics of this process might explain why the stiffening of hydrated lime is not always observed when asphalt mixtures are tested (see Chapter 2).

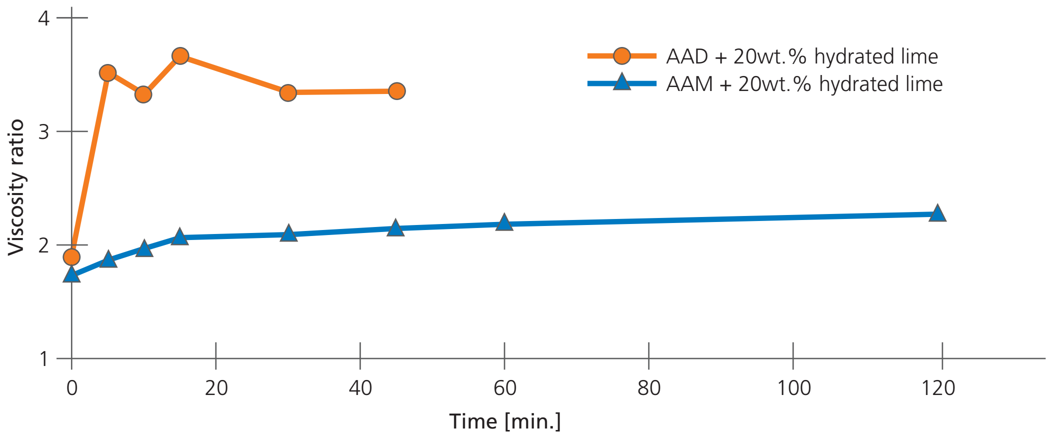


Figure 27. Kinetics of viscosity build-up at 138°C for two bitumens modified with 20% hydrated lime. The viscosity stabilizes quickly for AAD when it keeps increasing after 120 min. for AAM. The neat bitumen did not show any significant viscosity change in the mean time (from [81]).

Still, the contribution of other factors must also be considered. Several papers mention the adsorption of some bitumen components onto the hydrated lime particles [12, 81]. The consequence would be to increase the effective volume fraction of particles and hence the mechanical properties of the mastic. However, the importance of these effects would be highly particle size dependent and it remains difficult to calculate the expected effect without a precise knowledge of the thickness of the adsorbed layer.

Therefore, it can be concluded that the physical effect of hydrated lime essentially lies in its porosity which generates a higher stiffening effect than normal mineral fillers, as captured by the Rigden air void test. However, the contribution to the stiffening effect coming from a possible adsorbed layer of bitumen components onto the hydrated lime particles, remain to be quantified.

Finally, as described in section 2.3.1, the high stiffening effect observed with hydrated lime at high temperature disappears below room temperature (see Figure 13). No interpretation was proposed so far, and it could be a consequence of the mechanical contrast between the bitumen-swollen hydrated lime particles and the bituminous matrix. At high temperature, the internal porosity of the hydrated lime particles are filled with bitumen, and this filled particles are seen as hard spheres in the bitumen matrix, therefore increasing the volume fraction as explained above. The relevant volume fraction controlling the stiffening effect is therefore that of the bitumen-filled hydrated lime particles (BFHLP). Below room temperature, the BFHLP start to become deformable, and the mechanical contrast diminishes between matrix and inclusions. Therefore, the system tends to behave as a function of the true volume fraction of solid instead of that of BFHLP.

4. Hydrated lime in asphalt mixtures in practice

4.1 How to add hydrated lime to an asphalt mixture

There exist several ways to add hydrated lime in an asphalt plant. The hydrated lime content is generally between 1 and 2.5% of the dry aggregate, with a strong consensus around 1-1.5% (Table 20). Most mix formulation methods consider hydrated lime as a mineral filler. As a consequence, the filler content is reduced in the same amount as hydrated lime is added, so that total filler content is maintained constant.

Country / State	Hydrated lime content [%]	Ways to add hydrated lime					
		Pure hydrated lime	Mixed filler	Dry to dry aggregate	Dry to wet aggregate	Lime slurry to aggregate	Marination
Europe							
Austria	1.5 - 3.5	X					
France	1 - 1.5	X	X				
Netherlands	2		X				
Switzerland	1.5	X					
UK	1 - 2	X					
USA							
Arizona	1				X		
California	0 7 - 1.2					X	required
Colorado	1				X	X	optional
Florida		X				X	
Georgia	1	X		X			
Mississippi	1				X		
Montana	1.4	X					
Nevada	1 - 2.5				X		required
New Mexico					X		
Oregon	1				X		optional
South Carolina	1				X		
South Dakota					X		
Texas	1 - 1.5	X			X	X	
Utah	1 - 1.5					X	optional
Wyoming	1 - 1.5				X		

Table 20. Methods currently used to add hydrated lime to asphalt mixtures. Data for the USA are from [145]. Detailed data for Europe were already given in Table 1 Here, the focus is on these European countries for which the use of hydrated lime is close to 1% or more (estimates in terms of percentage of HMA modified with hydrated lime compared to the total HMA production).

The National Lime Association published a review of the methods currently used in the United States of America in order to put the hydrated lime into the mixes [145]. To these US methods, the mixed filler method in use in Europe must be added (Table 20). As a result, many studies exist that compare the several ways to add lime, with diverging conclusions as the best way to add lime [20, 57, 60, 146, 147, 148, 149]. Interestingly, all methods were found to be equally valid in order to benefit from the addition of hydrated lime [145, 150].

Therefore, the main factors affecting the selection of a given method are the choice of the plant manager and the local specifications.

4.1.1 Pure hydrated lime at the asphalt plant

Hydrated lime can be added to the asphalt plant by a specific silo with direct access to the mixer (Figure 28).

In the case of a batch plant, the most common method consists in having the hydrated lime weighted in the same device that weighs the mineral filler. The installation therefore consists in connecting the hydrated lime silo to the existing system by means of a screw conveyor.

In the case of a continuous plant, the most common method consists in having a weigh pot dispensing hydrated lime through a rotary vane feeder. The hydrated lime is then injected into the drum through a screw conveyor. The entry point is typically 1 m before the binder injection point [145]. This is a method in use in Europe (Austria, France, Germany, UK) and in USA (states: Florida, Georgia, Montana and Texas) (Table 20).

Note that initial implementation of this technology in continuous plants led to poor incorporation of hydrated lime into the mix because of losses as dust [2]. This could be solved by a proper modification of the hydrated lime feed, for example using donut-shaped baffles at the point of lime injection [2].

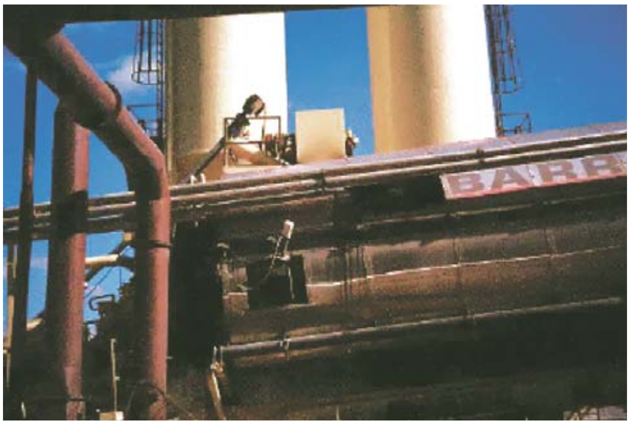


Figure 28. Asphalt plant in Georgia (USA) with two silos: one for mineral filler and the other for hydrated lime (from [145]).

In terms of capacity, it must be reminded that hydrated lime has a lower apparent density than mineral filler and that a minimum capacity must therefore be at least 70 m³ in order to unload a full truck. The silo has an aeration system with dehumidifier, with the air inlet system typically 1m above the cone of the silo. The silo is also equipped with a small filter baghouse on top [145].

4.1.2 Hydrated lime as a mixed filler

Hydrated lime can be added to the asphalt plant using the same silo as the one already existing for mineral filler. In this case, hydrated lime must be mixed with the filler prior to the plant, and most companies supply mixed filler. Mixed filler is a standard product in Europe and several categories are described in the specifications for aggregates in asphalt mixtures (EN 13043 – [26]). They are summarized in Table 21.

Most European countries have experience with the mixed filler. Since the target hydrated lime content is 1-1.5% in all countries, the hydrated lime content inside the mix filler must be adjusted. As a result, the Netherlands specify hydrated lime in the form of Ka_{25} with 25% hydrated lime for all their porous asphalts [16]. Germany has also a strong experience with Ka_{25}, but more categories can be found on the market [151]. In both countries, the quantity of filler used in most of the surface mixes is high (5-10%) thanks to the use of washed sand. On the contrary, France uses mixed fillers with a higher quantity of hydrated lime. The trend there is to supply mixed filler with up to 75% hydrated lime, given the low quantities of added filler (typically 2%) as a consequence of using unwashed sand.

Category	Calcium hydroxide content [wt.%]
Ka_{25}	≥25
Ka_{20}	≥20
Ka_{10}	≥10
$Ka_{declared}$	<10
Ka_{NR}	no Requirement

Table 21. Mixed filler categories as described in EN 13043 [26].

4.1.3 Other forms to add hydrated lime

Other methods exist in order to add hydrated lime to an asphalt mixture. All of these additional methods are not currently used in Europe but are well developed in the USA (Table 20). Most of these methods use a pugmill in order to mix the hydrated lime with the aggregate (Figure 29). Still, it can also be sprayed directly on the aggregate on the belt conveyor, but this is not a preferred solution because of the loss of material by dusting [2].

Figure 29. Pugmill used to mix hydrated lime with the wet aggregate in South Carolina (USA) (from [145]).

The most common method consists in adding the hydrated lime in dry form (hence the need for a dedicated silo) to the wet aggregate using a pugmill (Table 20). Still, some Georgia plants prefer to treat the dry aggregate (Table 20). Also, other States like California or Utah specify the use of a lime slurry instead of dry hydrated lime. This necessitates the presence of a lime slurry installation. The lime slurry method is also used in some plants in Colorado, Florida and Texas (Table 20).

Finally, some states also specify a marination period of typically 24-48 hours. The aggregate can then be treated and stockpiled for marination directly in the quarry and the treated marinated aggregate can then be processed at the asphalt plant [145].

The marination process is thought to allow for a better treatment of clayey aggregates. Also, the quality control is simplified because the hydrated lime content can be measured directly on the stockpiled material.

The marination period must not be extended for too long, because of a risk of hydrated lime recarbonation. Therefore, some States specify a maximum marination time. For example, Nevada says no more than 45 days [145]. Still, it was shown that recarbonation even after 6 months is only present in the top 8 cm of the stockpile [13].

4.2 Observed increase in durability in the United States of America

The experience gathered in the USA on pavement durability is well documented. As mentioned earlier on in the introduction, the National Lime Association survey of 2003 gave some precise numbers on the changes in asphalt mixtures durability thanks to the treatment by hydrated lime [10]. The survey was performed by sending a questionnaire to all the agencies that are experienced in the use of hydrated lime. The full results are given in Table 22.

From these data, it can be seen that the life expectancy for all types of roads is increased by 2 to 10 years when hydrated lime is added. Given that the life expectancy of untreated roads ranges from 5 to 20 years, the relative improvement goes from 20 up to 50% higher durability. Note that one state of USA (Georgia), reported no difference for treated mixes (low volume roads only).

Agency	Lime treated			Non-lime treated		
	10%	Average	90%	10%	Average	90%
Interstate roads						
Arizona	13	15	17	10	12	14
California	8	10	12	6	8	10
Colorado	8	10	12	6	8	10
Georgia	7	10	15		N/A	
Mississippi	7	10	15		N/A	
Nevada (1)	7	8	9	3	4	7
Oregon	10	15	20	8	12	15
South. Carolina	10	12	15		N/A	
Texas	8	12	15	7	10	12
Utah	15	20	25	7	10	15
State roads and U.S. highways						
Arizona	18	20	22	15	17	20
California	8	10	12	6	8	10
Colorado (1)	8	10	12		8	
FHWA	15	20	25		N/A	
Georgia	8	10	14		N/A	
Mississippi	12	15	17		N/A	
Nevada	10	12	14	6	8	10
Oregon	15	17	20	8	12	15
South. Carolina	8	10	12		N/A	
Texas	10	12	15	8	10	12
Utah	15	20	25	7	10	15
Low volume roads						
Arizona	20	25	30	15	20	25
California		N/A			N/A	
Colorado (1)	10	12	15	8	10	12
FHWA	15	20	25		N/A	
Georgia	8	10	15	8	10	15
Mississippi	12	15	17		N/A	
Nevada	18	20	22	12	15	18
Oregon	15	20	25	7	10	15
South. Carolina	10	15	20		N/A	
Texas	8	12	15	7	10	15
Utah	7	10	15	3	5	7

Table 22. Life expectancy of hydrated lime treated and untreated mixes in the USA. (1) – pavement preservation; N/A = not applicable (from [10]).

4.3 Observed increase in durability in Europe

The situation in Europe is unfortunately not fully documented as in the USA. Still, the local experiences show that the beneficial effect of hydrated lime allows for an increased durability of typically 20-25% in terms of pavement life expectancy.

The French motorway network SANEF commented that hydrated lime increases the durability of its wearing courses by 20-25% [15]. For example, one the very first application of porous asphalt in France was in 1984 on the A1 motorway from Paris to Lille. This highway is part of the SANEF network, one of the busiest highway in France, then with 35 000 vehicles per day with 27% heavy trucks. 10 km of porous asphalt between Ressons and Compiègnes (Lille-Paris direction) with a hydrated lime and crumb-rubber modified asphalt mixture [152, 153] were laid down and lasted over 16 years. A more recent application of porous asphalt with polymer-modifier and hydrated lime on the A4 motorway in Reims gave a similar duration of 17 years. Experience with untreated porous asphalt gives expectancies of order 12 years, clearly validating the increased durability.

The Danish experience also reports increases in durability of order of 20% for hydrated lime treated mixtures [23].

The Netherlands specify hydrated lime in their porous asphalts [16, 154]. Porous asphalts there are made exclusively out of unmodified 70/100 penetration grade bitumen and covers 70% of the highway network [18]. The current formulations give a life expectancy of 11 years [18]. Although no reference without hydrated lime allows for a direct evaluation of the observed increase in durability, the lack of hydrated lime is known to be one of the major reasons for premature failure [18].

In addition, it is also interesting to note that the Federation Internationale de l'Automobile (FIA) specifies hydrated lime in the wearing courses of the race tracks (Table 23).

As a consequence, the observed durability increase in Europe agrees with the data published in the USA. From the extensive field experience worldwide, it can be concluded that hydrated lime increases the durability of asphalt mixtures by at least 20%.

Country	Race course	Year built	Binder
Brazil	Rio de Janeiro	1999	PMB
Portugal	Estoril	2001	PMB
Italy	Fiorano	2002	PMB
Bahrain	Manama	2003/2004	PMB
China	Shanghai	2004	PMB
Spain	Barcelona	2004	PMB
Turkey	Istanbul	2005	B50/70+TE

Table 23. Race tracks built with hydrated lime modified mixtures. The last column states the type of binder used: PMB – polymer-modified bitumen; TE – Trinidad Epure (a natural hard asphalt).

4.4 Hydrated lime quantification

Hydrated lime can be quantified in an asphalt mixture. Two methods can be found in the literature, the first one coming from Germany and the second one from the USA.

The German method [155, 156] is very simple and derives from the lime characterization methods detailed in EN 459-2 [24]. In fact, the German method separates three different characterization methods:

- Hydrated lime purity.
- Hydrated lime content in a mixed filler.
- Hydrated lime content in the filler recovered from an asphalt mixture.

The method consists in a hydrochloric acid titration of a suspension of the product to be tested. The acid has to be weaker (0.5 M) when mixed or recovered fillers are concerned, in order to adapt for a lower basicity. The filler is recovered from an asphalt mixture using solvent extraction of the bitumen as described in EN 12697-1 (usually using trichloroethylene or tetrachloroethylene as a solvent – [157]). The suspension to be titrated is then obtained by blending 1 g of recovered filler to 150 ml of water, 10 ml isobutanol and 5 ml of a surfactant solution (1 g sodium dodedylsulfate and 1 g polyethyleneglycol – dodecylether in 100 ml water).

The surfactant solution is needed only when recovered filler is tested, in order to wash out the filler from remaining bitumen or solvent from bitumen extraction. The coloured indicator is phenolphtalein (0.5 g in 50 ml ethanol, completed to 100 ml by water). Titration rate is 12 ml/min initially, but decreases to 4 ml/min near the transition point. The method was shown to work with all types of fillers, including limestone filler [155]

A round-robbin test was performed with 12 laboratories. The repeatability (in terms of wt.% of hydrated lime in the filler) was 0.52wt.% and the reproducibility was 0.91wt.% for a mean value of 27.3wt.%.

Section	Nominal hydrated lime content [wt.%]	Measured hydrated lime content in recovered filler [wt.%]
1	0	0.9
2	0	0.7
3	25	29.2
4	25	26.0

Table 24. Results of the validation of the german dosification method (from [155]).

The method was validated on samples taken out of cores 1.5 years after construction (Table 24). The SMA 0/8 S mixes were made either with a normal filler or with mixed filler containing 25wt.% hydrated lime and the results are given in Table 24 [155].

Note also that a study using different methods showed that the titration method was equivalent to the sugar method, which is the reference one in EN 459-2. Interestingly, the comparison based on asphalt mixtures made with different aggregates showed that part of the hydrated lime was not fully recovered, because of the hydrated lime – aggregate reactions (Figure 30). As a result, these reactions were more important for basalt aggregate (about 60% recovery), than moraine (about 80%) and limestone filler (about 90%).

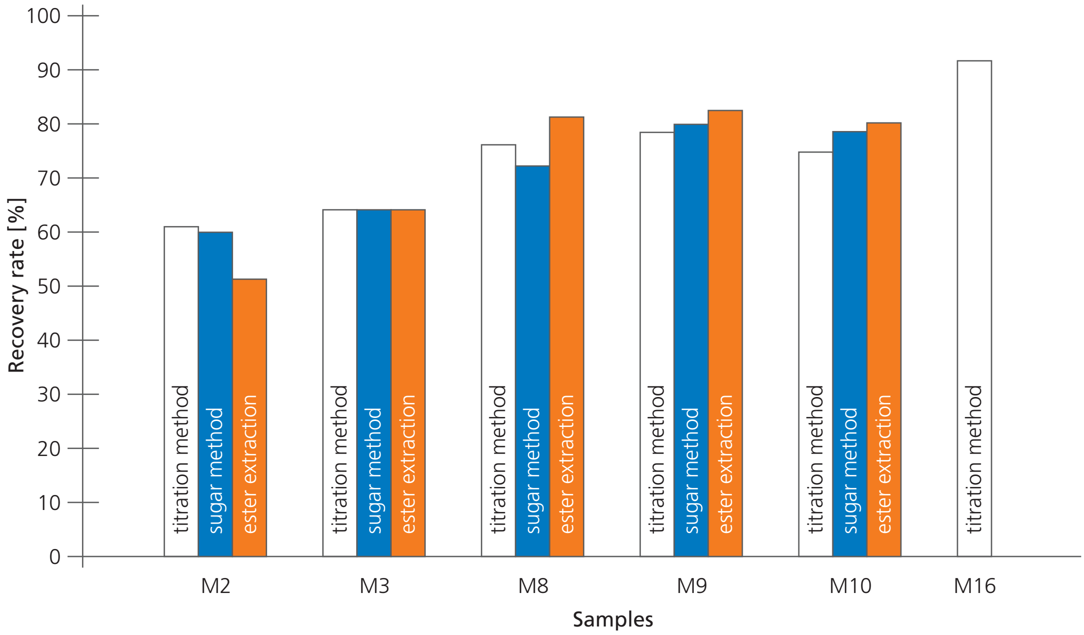


Figure 30. Recovery rate (measured hydrated lime divided by nominal hydrated lime content) obtained using three different chemical methods: "titration method" refers to the direct titration following the German method [156] described at length in the text; "sugar method" refers to the titration of a saccharose extract of the filler to be tested; "ester extraction" refers to an ethyl-acetoacetate extract (from [155]). The materials were asphalt mixtures with different fillers mixed with hydrated lime: M2 and M3 – with basalt filler (respectively 5 and 20% hydrated lime); M8 and M9 – with moraine filler (respectively 5 and 20% hydrated lime); M10 – with 67% moraine and 33% limestone filler (25% hydrated lime); M16 – with limestone filler (20% hydrated lime).

The US method was developed by the Federal HighWay Administration (FHWA – [158, 159]). It consists in measuring the Fourier Transform Infra-Red (FTIR) spectrum of the filler and quantify the hydrated lime content from the peak intensity at 3,640 cm^{-1} corresponding to calcium hydroxide (Figure 31). Calcium carbonate peaks at 1,390 cm^{-1} and can be unmistakably separated from the hydrate (Figure 31).

The analysis was shown to be easily performed by using 15-20 g of dust recovered by hammer drilling through an asphalt mixture with a 9.5 mm tungsten carbide bit [158, 159].

Interestingly, measurements on 10years old materials from Nevada showed that no recarbonation or leaching had occurred in the corresponding time frame [158, 159].

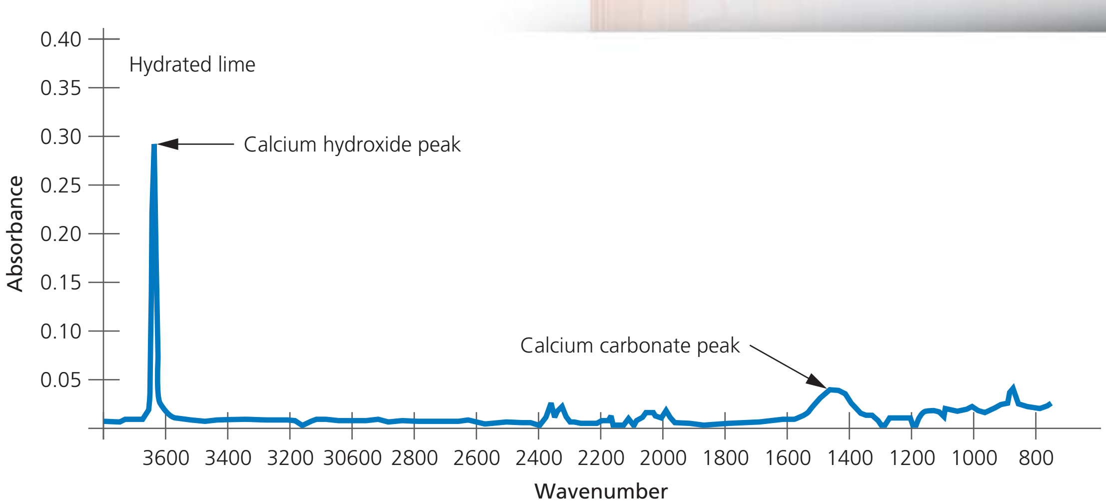


Figure 31. FTIR spectrum of hydrated lime (from [158]).

Summary and conclusions

Hydrated lime has been known as an additive for asphalt mixtures from their very beginning. It experienced a strong interest during the 1970s in the USA, partly as a consequence of a general decrease in bitumen quality due to the petroleum crisis of 1973, when moisture damage and frost became some of the most pressing pavement failure modes of the time. Hydrated lime was observed to be the most effective additive and as a consequence, it is now specified in many States and it is estimated that 10% of the asphalt mixtures produced in the USA now hold hydrated lime.

The effect of hydrated lime on asphalt mixtures has been thoroughly reviewed from 110 documents coming from the 5 continents. Although hydrated lime has been successfully used in asphalt mixtures for a long time, it is still an active research field as demonstrated by the high number of recent publications.

The literature review confirms that hydrated lime is very effective to improve the moisture damage and frost resistance of asphalt mixtures. All available test methods confirm its beneficial effect. However, the most severe test methods such as multiple freeze--thaw procedures or Hamburg Wheel Tracking Device are seen to clearly differentiate hydrated lime from other solutions such as liquid antistrip additives.

Given its extensive use in the past 40 years, hydrated lime has been seen to be more than a moisture damage additive. Hydrated lime is known to reduce chemical ageing of the bitumen. The overall effect consists in decreasing the extent of hardening that the bitumen experiences under prolonged exposure to high temperature in the presence of renewed air. It is observed that hydrated lime essentially reduces the formation of asphaltenes, the viscosifying moieties of the bitumen.

Hydrated lime stiffens the mastic more than normal mineral filler, an effect that is well described in the literature, but it is really observed only above room temperature. This stiffening effect of the mastic impacts the mechanical properties of the asphalt mixture. Strength and modulus, which are generally measured at temperatures around room temperature, are seen to be modified by hydrated lime addition for a little more than half of the mix formulas. However, the rutting resistance, generally measured at temperature in the 45-60°C range, is seen to be improved by hydrated lime addition in about 75% of the mix formulas. In all cases, most of the studies focus on hydrated lime contents of 1-1.5%, and these effects are generally more pronounced for higher hydrated lime contents.

Finally, the few published studies on fatigue resistance indicate that hydrated lime improves the fatigue resistance of asphalt mixtures in 77% of the cases, but no study was found using the European standard protocols. Therefore, the published evidence would be more conclusive if the mixes were tested with a number of cycles to failure above 1 million, and at temperatures below 20°C.

In line with the observation that hydrated lime does not exhibit a higher stiffening effect than mineral filler at low temperature, no improvement of the thermal cracking resistance is reported in the literature.

As a summary, Figure 32 illustrates the efficiency of hydrated lime for the distresses mentioned in the literature.

The reasons why hydrated lime is so effective in asphalt mixtures lie in the strong interactions between the major components, i.e. aggregate and bitumen, and the combination of 4 effects, two on the aggregate and two on the bitumen. Hydrated lime modifies the surface properties of aggregate, allowing for the development of a surface composition (calcium ions) and roughness (precipitates) more favourable to bitumen adhesion. Then, hydrated lime can treat the existing clayey particles adhering to the aggregate surface, inhibiting their detrimental effect on the mixture. Also, hydrated lime reacts chemically with the acids of the bitumen, which in turns slows down the age hardening kinetics and neutralizes the effect of the "bad" adhesion promoters originally present inside the bitumen, enhancing the moisture resistance of the mixture. Finally, the high porosity of hydrated lime explains its stiffening effect above room temperature. The temperature dependence and the kinetics of the stiffening effect might explain why hydrated lime is not always observed to stiffen asphalt mixtures and why it is more efficient in the high temperature region where rutting is the dominant distress.

The way hydrated lime is used in the field is detailed. Ways to add hydrated lime, i.e., into the drum, as a mixed filler, dry to the damp aggregate, as a lime slurry, with or without marination are described. No definitive evidence demonstrates that one method is more effective than the other, and all methods are seen to allow for the beneficial effects of hydrated lime to develop. As far as fabrication control is concerned, hydrated lime can be easily quantified inside the mixture.

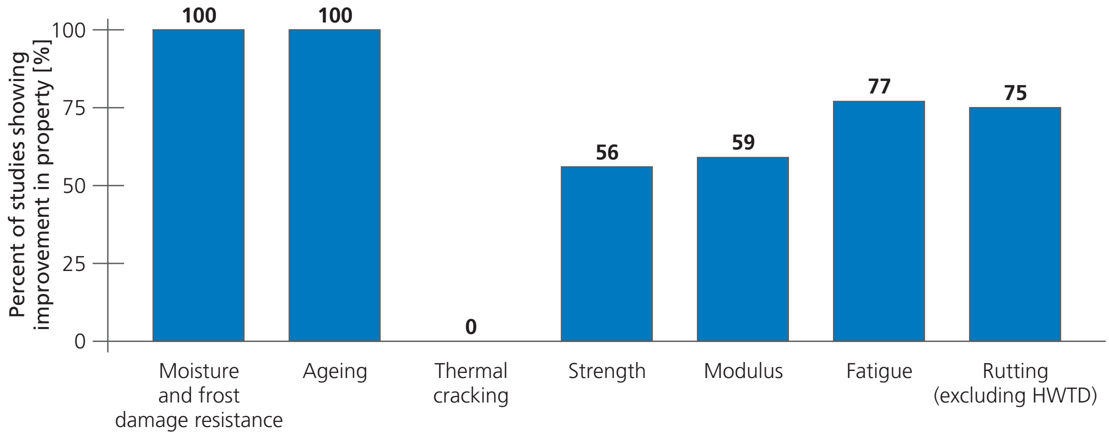


Figure 32. Improvement in selected asphalt mixture properties by hydrated lime addition. The percentage must be understood as the proportion of published studies showing an improvement. Rutting excludes Hamburg Wheel Tracking Device (HWTD) results because they better fit in the moisture damage category.

Given that all the above properties impact the durability of asphalt mixtures, the use of hydrated lime has a strong influence on asphalt mixtures durability. Based on their field experience, North American State agencies estimate that hydrated lime at the usual rate of 1-1.5% in the mixture (based on dry aggregate) increases the durability of asphalt mixtures by 2 to 10 years, that is by 20 to 50%.

The European experience is not yet as developed as in the USA, but the beneficial effects of hydrated lime on asphalt mixture durability have also been largely reported. As an example, the French Northern motorway company, Sanef, currently specifies hydrated lime in the wearing courses of its network, because they observed that hydrated lime modified asphalt mixture have a 20-25% longer durability. Similar observations led the Netherlands to specify hydrated lime in porous asphalt, a type of mix that now covers 70% of the highways in the country. As a result, hydrated lime is being increasingly used in asphalt mixtures in most European countries, in particular in particular Austria, France, the Netherlands, the United Kingdom and Switzerland.

If the benefits of hydrated lime on asphalt mixtures are clearly demonstrated with a diversity of materials (aggregate, bitumen, mixture formulas) covering the 5 continents, the European experience remains somewhat lower than the one coming from the USA. As a consequence, the effect of hydrated lime on asphalt mixtures as measured by several European standard test procedures are not described in the literature. Among those of the highest interest, ITSR and fatigue must be mentioned.

Also, the description of hydrated lime in the European standards for aggregates is not totally appropriate. First, test methods such as the delta ring and ball test can not be performed on hydrated lime, although they are required for mineral fillers. Hydrated lime being considered as filler in the standards on asphalt mixtures, it is critical to resolve this situation. Then, the mixed filler classes appearing in the aggregate standards do not cover all existing products currently used.

Finally, some theoretical aspects remain to be understood. If the chemical effects of hydrated lime on bitumen are well described, the physical ones are barely treated. As a consequence, an explanation for the temperature-dependence of the stiffening effect of hydrated lime in bitumen remains to be validated. Then, the effect on the surface properties of the aggregate, especially the presence of precipitates, is not detailed in the literature and could be the purpose of new research actions.

List of figures

List of tables

Annex 1 (sources)

This report is based on the study of several documents published on the subject all over the world. The full document list is given in Annex 2.

These documents were identified by several means. First, a classical literature search was performed using technical databases such as Hcaplus, ITRD, Compendex, Civileng, NTIS and Dissabs. Then, this search was completed by an internet search on www.google.com with the same keywords. Also, documents known to some members of the Asphalt Task Force working group were added to the list. Finally, relevant documents that appeared in the references of the documents obtained using the above methods but were not detected before, were added to the database.

In the end, 110 documents on hydrated lime in bituminous materials were studied in order to produce this report. The country of origin of the first author (Figure 1) and year of publication (Figure 2) are described in the introduction. Figure 33 gives an idea of the type of documents, mostly research articles.

In terms of content, it is interesting to note that hydrated lime is mostly compared to mineral fillers or other adhesion promoters (mainly liquid antistrip) in the published documents (Figure 34). Other comparison materials include sulfur extended asphalt, lead diamyldithiocarbamate (LDADC – an antioxidant), hedmanite (rockwool natural fiber), dodecaphenone (a model compound for adhesion), coconut fibers, PolyPhosphoric Acid (PPA) and polymers.

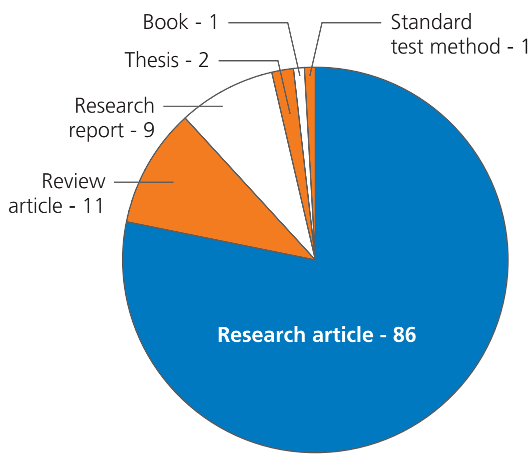


Figure 33. Type of documents in the database (110 documents).

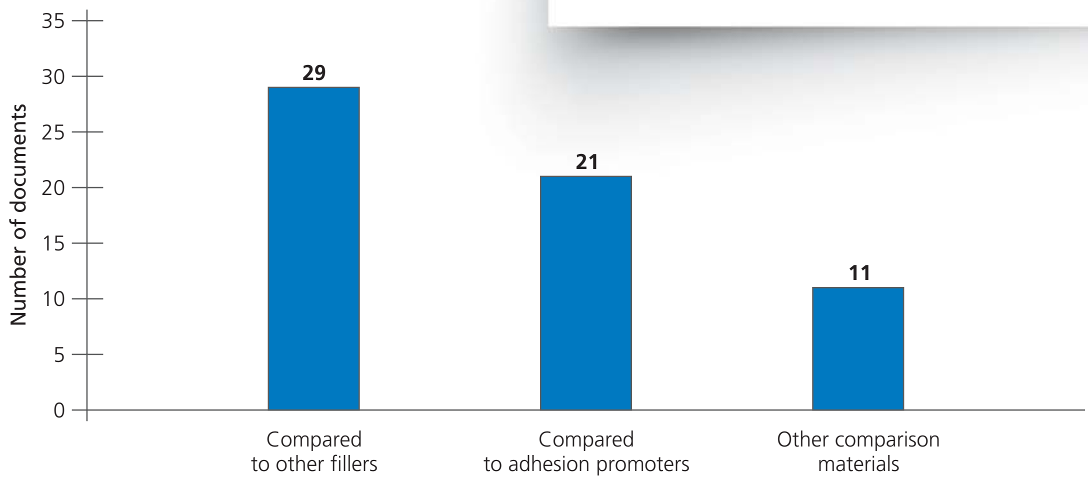


Figure 34. Hydrated lime compared to what?

Finally, the properties that were analyzed in the documents are described in Figure 35. The sum overpasses 110 documents because some publications worked on more than one topic. Clearly, moisture damage and frost is the most studied issue confirming that it is the most widely known functionality of hydrated lime. Mechanical properties (i.e., others than fracture or rutting) are also well documented, given that asphalt mixtures are usually designed based on their mechanical properties. In the column "Other" fall works on hydrated lime properties (filler testing), on mastics and on the quantification method.

A list of references by functionalities is given in Annex 2.

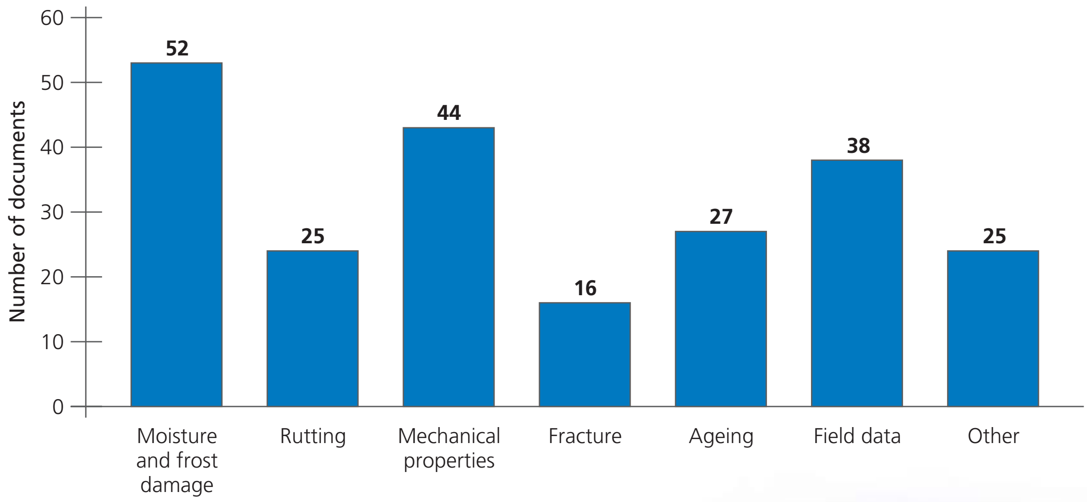


Figure 35. How is hydrated lime evaluated?

Annex 2 (list of documents by type of functionality)

In order to help the reader find appropriate references, the content of the bibliographical database used for this report is disclosed. For each reference, the **topics** covered in the document are listed with the following code:

- **Md** – moisture and/or frost damage including HWTD,
- **Ag** – ageing,
- **Me** – mechanical properties including Marshall stability, modulus, strength (only if the test is done as such, that is, not done as part of a moisture damage test with and without conditioning), ... but excluding rutting and fracture,
- **Ru** – rutting including HWTD,
- **Fr** – fracture including fatigue,
- **Ot** – others including mastic testing, lime quantification, filler testing, ...
- **Fi** – field data.

The analysis of the database based on topics was already given in Annex 1 (Figure 35).

The **most important references** are highlighted in bold.

Reference	Md	Ag	Me	Ru	Fr	Ot	Fi
M. I. Al-Jarallah and K. W. Lee, "Evaluation of hydrated lime as an antistripping additive for asphalt mixtures", J. Eng. Sci. King Saud Univ. 13(1), pp.65-83, 1987	X						
M. Ameri and M. Aboutalebi Esfahani, "Evaluation and performance of hydrated lime and limestone powder in porous asphalt", Road Materials Pavement Design 9(4), pp.651-664, 2008	X		X				
T. S. Arnold, M. Rozario-Ranasinghe and J. Youtcheff, "Determination of lime in hot-mix asphalt", Transportation Research Record 1962, pp.113-120, 2006						X	
T. S. Arnold, J. Rozario and J. Youtcheff, "New lime test for hot mix asphalt unveiled", Public Roads 70(5), March/April 2007						X	
T. Aschenbrener and N. Far, Influence of Compaction temperature and Anti-Stripping Treatment on the Results from the Hamburg Wheel-Tracking Device, Report CDOT/DTD/R-94-9, Denver (Colorado, USA): Colorado Department of Transportation, 1994	X			X			
J. Bari and M. W. Witczak, "Evaluation of the Effect of Lime Modification on the Dynamic Modulus Stiffness of Hot-Mix Asphalt: Use with the New Mechanistic-Empirical Pavement Design Guide", Transportation Research Record 1929, pp.10-19, 2005			X				
G. Baumgardner, J.-V. Martin, R. B. Powell and P. Turner, "Polyphosphoric acid and styrene-butadiene-styrene block copolymer modified asphalt: Evaluation of paved section at the NCAT test track built in 2000 and 2003", Proc. 4th Eurasphalt & Eurobitume Congress, paper 401-029, 2008							X
C. Berthelot, A. Anthony and C. Raducanu, "Mechanistic characterization of anti-stripping additives in Saskatchewan asphalt mixes", Proc. Annual Conf. Transportation Association Canada, Calgary, Sept. 2005			X				
H. D. Bianchetto y A. I. Asurmendi, "Influencia de la temperatura de fabricación y del contenido de cal en el envejecimiento de mezclas bituminosas: Un caso real", Carreteras 16, pp.54-64, 2008		X					
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