



European Lime Association  
Association européenne de la Chaux  
Europäischer Kalkverband

**HYDRATED LIME:**

**A PROVEN ADDITIVE**

**FOR DURABLE ASPHALT PAVEMENTS**

***CRITICAL LITERATURE REVIEW***

Report to the European Lime Association / Asphalt Task Force

**September 2010**

## **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 (<http://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. The following table summarizes the current situation.

Country	Level of experience	Start	[Lime treated HMA] vs [total HMA] (estimate %)	% 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 MF	Stripping, aging, other	AC, SMA, CMA
France	Voluntary	? (> 1945)	1	1 to 1.5	Pure or MF	Stripping, aging, other	AC, CMA, PA, PA (asphalt rubber), BBTM
Germany	Voluntary	2000	< 1	1 to 3	Pure or MF	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	MF	Stripping	SMA, PA
The Netherlands	Compulsory	Mid 90's	7	2	MF	Stripping, Aging, Durability	PA
Poland	Voluntary	1998	< 1	1 to 3	MF	Stripping	AC
Portugal	Voluntary	Beginning 2000's	< 1	1 to 2	Pure	Stripping	PA (asphalt rubber)
Sweden	Voluntary/ compulsory	1998	< 1	1	Pure	Stripping, aging	AC
Switzerland	Preferred	2006	1	1.5	Pure	Stripping, aging, durability	PA, AC, SMA,
Romania	Tests	2007	< 1	2	MF	Stripping, rutting	AC, SMA
Spain	Voluntary	2004	< 1	1 to 2	Pure	Stripping	SMA
Slovakia	Tests	2009	< 1	2	Pure or MF	Stripping	
UK	Voluntary	Early 00's	1	1 to 2	Pure	Stripping	AC

AC: Asphalt Concrete ; SMA: Stone Mastic Asphalt ; PA: Porous Asphalt ; CMA: Cold Mix Asphalt ; BBTM: Very Thin Asphalt Layer ; MF: Mixed Filler

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 (in green, more than 5% of the HMA production is modified with hydrated lime and in yellow, about 1% ).

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.

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 [secretariat@ima-europe.eu](mailto:secretariat@ima-europe.eu).

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## **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 dosificated 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, ITRR 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.

## **1. INTRODUCTION**

Hydrated lime has been used in asphalt mixtures from their very beginning. In the USA, at the end of the 19<sup>th</sup> 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 20<sup>th</sup> 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 1970s 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%.

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 1,740km 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, Belgium, Denmark, France, Germany, the Netherlands, Poland, the United Kingdom, Romania 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.

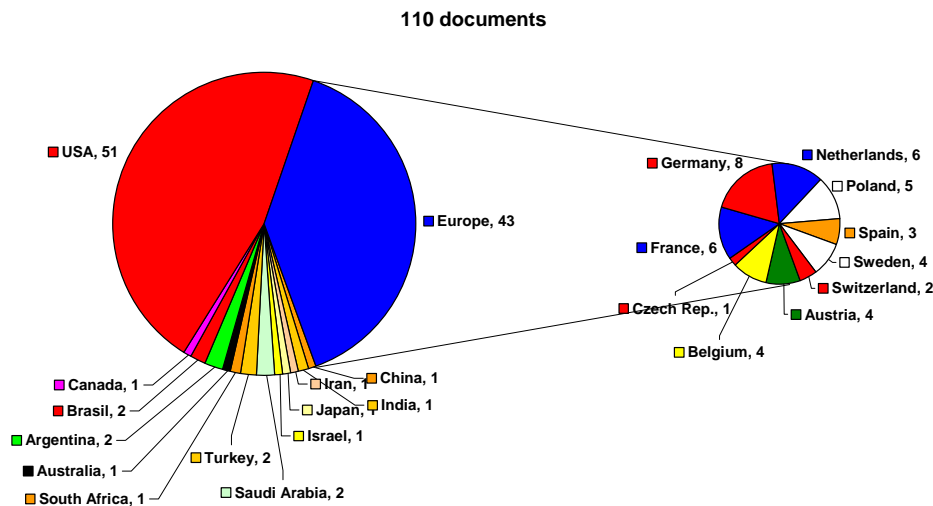


Figure 1: Origin of first author for the documents in the database.

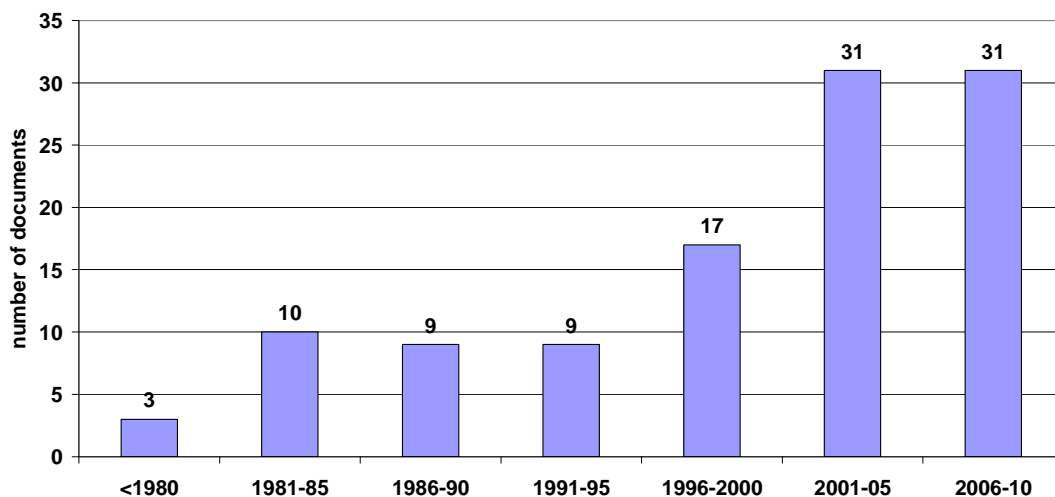


Figure 2: Year of publication of the documents in the database.

The structure of the report is as follows. 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.

## 2. HYDRATED LIME AS AN ACTIVE FILLER FOR ASPHALT MIXTURES

### 2.1 Hydrated Lime: Properties

Hydrated lime is mainly composed of calcium dihydroxide  $\text{Ca(OH)}_2$ . It is obtained by hydrating quicklime (essentially calcium oxide  $\text{CaO}$ ) using specific equipments called hydrators. Quicklime is manufactured by burning limestone of very high purity (made of calcium carbonate  $\text{CaCO}_3$ ) at temperatures around  $900^\circ\text{C}$  in dedicated kilns [4].

The same cycle can be performed on dolomite made of  $\text{CaCO}_3.\text{MgCO}_3$ , in order to obtain dolime or dolomitic lime ( $\text{CaO.MgO}$ ) and then hydrated dolime or hydrated dolomitic lime ( $\text{Ca(OH)}_2.\text{Mg(OH)}_2$  or  $\text{Ca(OH)}_2.\text{MgO.Mg(OH)}_2$  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 are for calcium lime (CL) and the number identifies the purity in terms of mass content of  $\text{CaO} + \text{MgO}$ . 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).

As far as asphalt mixtures modification is concerned, standard 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.

	CaO + MgO	Available lime
	wt. %	wt. %
CL90 S	$\geq 90$	$\geq 80$
CL80 S	$\geq 80$	$\geq 65$
CL70 S	$\geq 70$	$\geq 55$

Table 2: The various grades of hydrated lime according to EN 459-1. Note that the value for available lime will only appear in the revision of EN459-1 to be published probably at the beginning of 2011.

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 dosificate hydrated lime in asphalt mixtures as detailed in Chapter 5.

Hydrated lime hydrated lime generally comes in the form of a dry white powder (Figure 3) with a particle density close to  $2.2\text{Mg/m}^3$  [4]. Because of a high level of particle porosity (of

order 50%), its apparent density typically ranges from 0.5 to 0.8Mg/m<sup>3</sup> as measured by EN 459-2.



Figure 3: Hydrated lime (source: Lhoist).

As will be detailed in Chapter 5, 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.

## 2.2 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.

### 2.2.1 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.

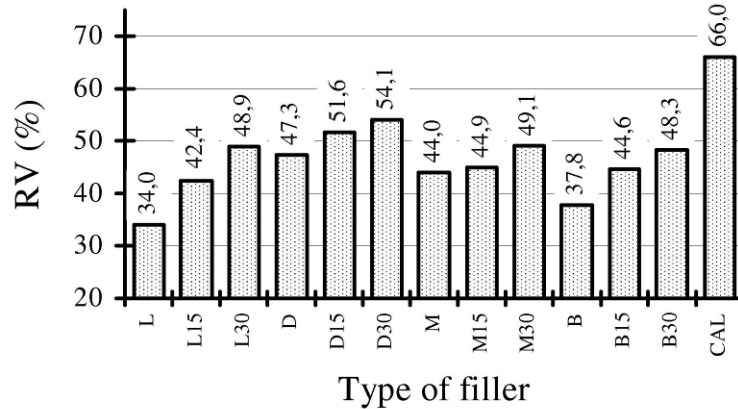


Figure 4: Rigden air voids of several fillers and mixed fillers. L: Limestone, D: Dolomite, M: Melaphyr, B: Basalt, CAL: Hydrated Lime, X15: Filler X with 15wt.% Hydrated Lime, X30: Filler X with 30wt.% Hydrated Lime (from [31]).

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].

### 2.2.2 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).

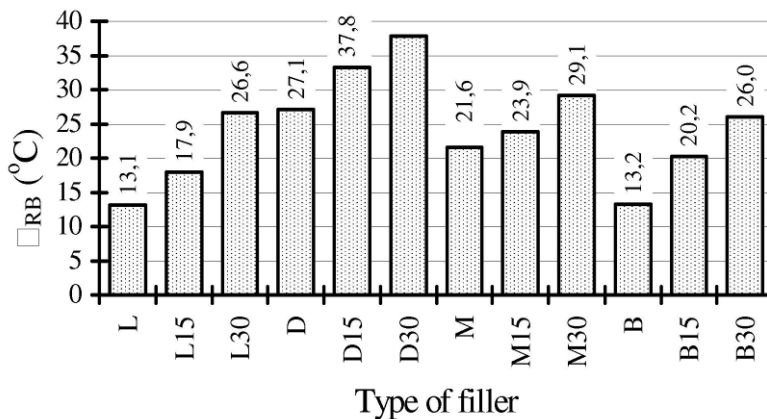


Figure 5: Delta ring and ball of several fillers and mixed fillers. L: Limestone, D: Dolomite, M: Melaphyr, B: Basalt, X15: Filler X with 15wt.% Hydrated Lime, X30: Filler X with 30wt.% Hydrated Lime (from [31]).

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].

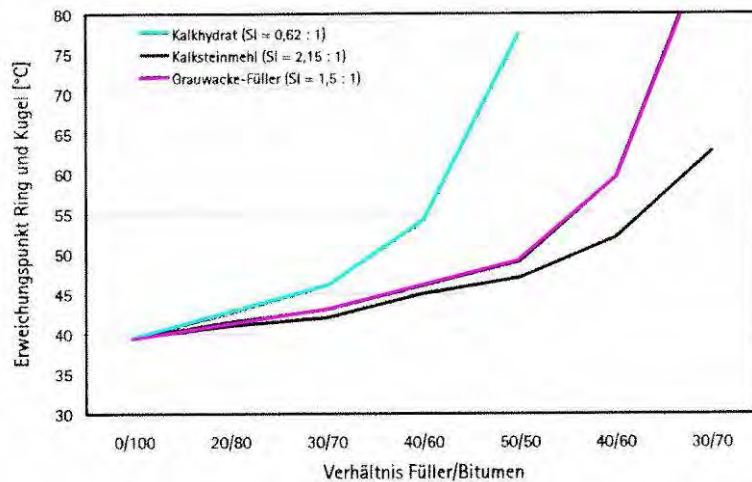


Figure 6: Ring and ball softening temperature of a 200 penetration grade bitumen as a function of filler weight content (expressed in filler/bitumen wt.%/wt.%) for hydrated lime (Kalkhydrat), limestone filler (Kalksteinmehl) and Grauwacke filler (from [38]).

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.

### 2.2.3 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 131791-2 [40]), which consists in measuring the amount of water in ml that needs to be added to 100g of filler in order to reach a reference consistency defined by a penetration value of 5 to 7mm. 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.

Mass in kerosene is also sometimes used to characterize fillers (EN 1097-3 [41]). It measures the so-called apparent density of 10g of filler in 25ml 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 1g 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  $10,000\text{cm}^2/\text{g}$  ( $= 1\text{m}^2/\text{g}$ ) 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  $15\text{-}20\text{m}^2/\text{g}$  [4]. Most fillers have values in the  $1\text{-}5\text{m}^2/\text{g}$  range, but higher values close to  $10\text{m}^2/\text{g}$  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.

Property	Method	Unit	Hydrated Lime	Mineral Filler	Reference
Particle Density	EN 1097-7	$\text{Mg}/\text{m}^3$	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	$^{\circ}\text{C}$	not measurable	8-25	[29,31]
Bitumen Number	EN 13179-2	-	100-120	40-50	[35]
Mass in Kerosene	EN 1097-3	$\text{Mg}/\text{m}^3$	0.3	0.5-0.9	[26]
Blaine Specific Surface	EN 196-6	$\text{cm}^2/\text{g}$	$>10,000$	7,000	
Specific Surface Area	BET with nitrogen adsorption	$\text{cm}^2/\text{g}$	150,000-200,000	14,000-95,000	[4,34]
Methylene Blue Value	EN 933-9	$\text{g}/\text{kg}$	$< 1$	0-20	[34]

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

### 3. 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 the next chapter will cover field behaviour.

#### ***3.1 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.

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.



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

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 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 5 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 5) was found to be one of the most effective among the tests in use in the USA in 1991 (Figure 8).

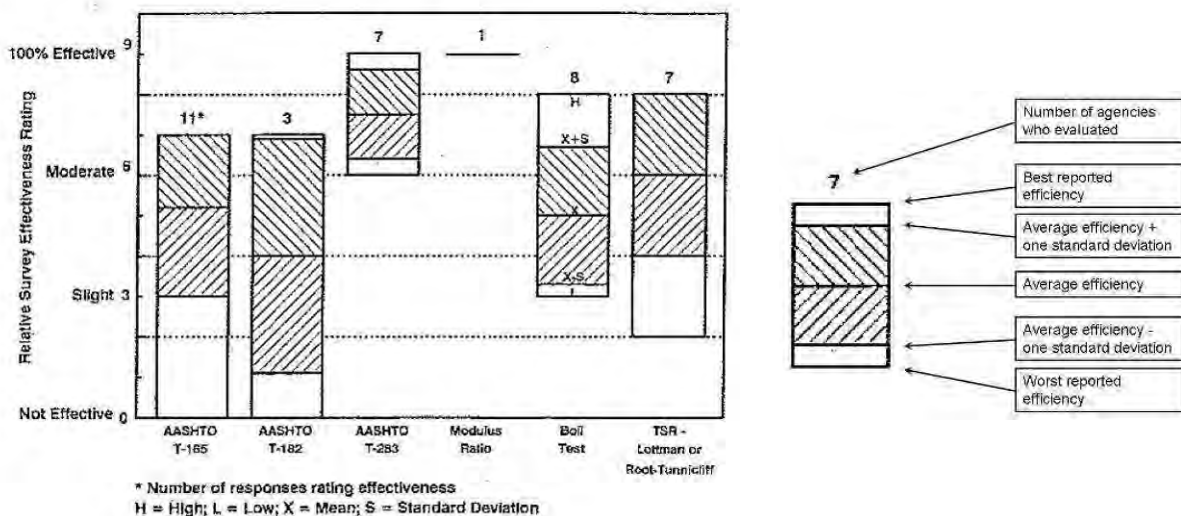
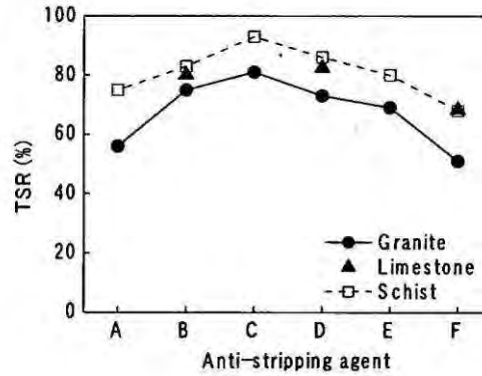


Figure 8: Comparison of the effectiveness of several test methods in order to predict moisture damage as evaluated by State agencies experience (from [8]).

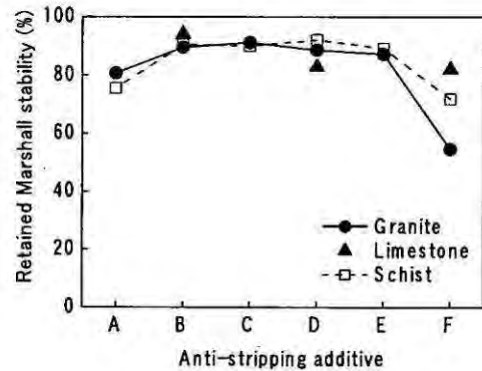
In all cases, the published data confirm that hydrated lime at 0.5-2wt.% on dry aggregate successfully improves the moisture and frost resistance of asphalt mixtures regardless of the testing method. At least 1wt.% is needed in order to fully benefit from this effect [48]. Examples of the potential gain with hydrated lime are listed in Table 6, Table 7, Table 8 and Table 9.

1/ Lottman test



- A: 1% Portland cement
- B: 1% Dry hydrated lime to damp aggregate
- C: 1% lime slurry to damp aggregate
- D: 0.3% (in bitumen) of alkylamidopolyamine antistrip (AST-3)
- E: 0.3% (in bitumen) of alkyldiamine antistrip (PA-1)
- F: reference

2/ Retained Marshall



3/ Hamburg Wheel Tracking Device (HWTD)

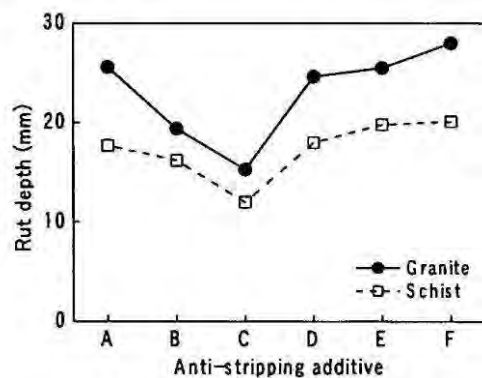


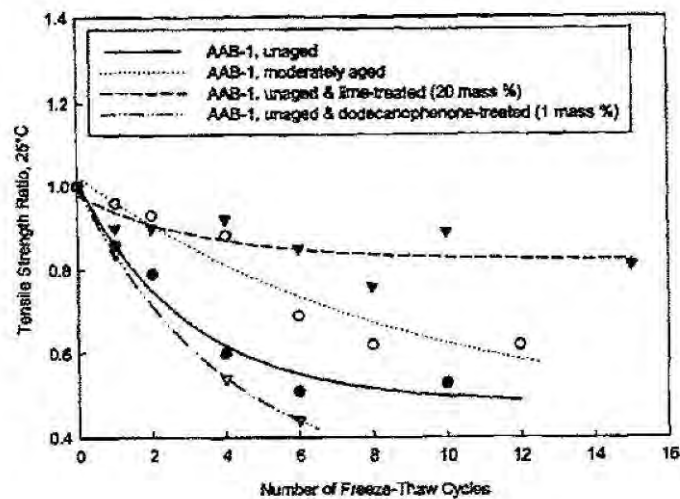
Figure 9: Moisture resistance of 0/20 asphalt mixtures made with different aggregate sources and 4.8% 70/100 penetration grade and several anti-strip additives. The testing was done by the Lottman test (1), Retained Marshall (2) and HWTD at 60°C (3) (from [49]).

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 than other additives in order to increase moisture resistance of asphalt mixtures (Figure 9 – see also section 3.3.4 for a description of the test results).

Clearly, the relative improvement is test-method and materials dependent (Table 6). A good overview of the comparison between liquid antistripping 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 antistrippers. Still, for some specific study with the given raw materials at hand and the type of testing chosen to evaluate them, a liquid antistripping can be observed once to behave better (Table 7 and Table 9 - Figure 9). As a result, multiple freeze-thaw procedures (such as repeated Lottman - Figure 10 or Texas pedestal - Table 8) and HWTD (Table 6) are the most differentiating test methods in order to highlight the beneficial effect of hydrated lime [13,51].

#### A/ Limestone



#### B/ Granite

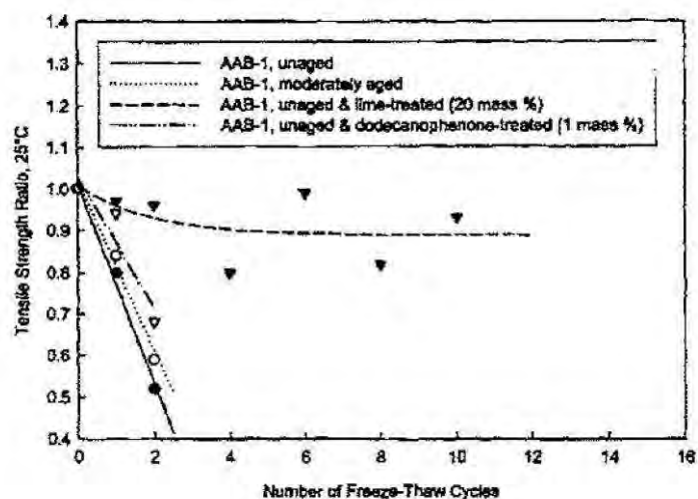


Figure 10: Multiple freeze-thaw test on asphalt mixtures made with limestone (A) or granite (B) aggregate and bitumen AAB-1. The unaged and aged binder were tested, together with the one modified with hydrated lime (20% based on binder with a binder content of 5.5wt.%) and a sample modified with 1% (based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

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 antistripping additives [52]. After 3-4 years, the 3 sections with hydrated lime showed much less stripping than the one with chemical additives [52].

The 15 Federal Highway Administration 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 Pavement Service Index (PSI) except in one case with moderate reduction, when the untreated materials showed moderate (2) or severe (2) reductions in Pavement Service Index (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.

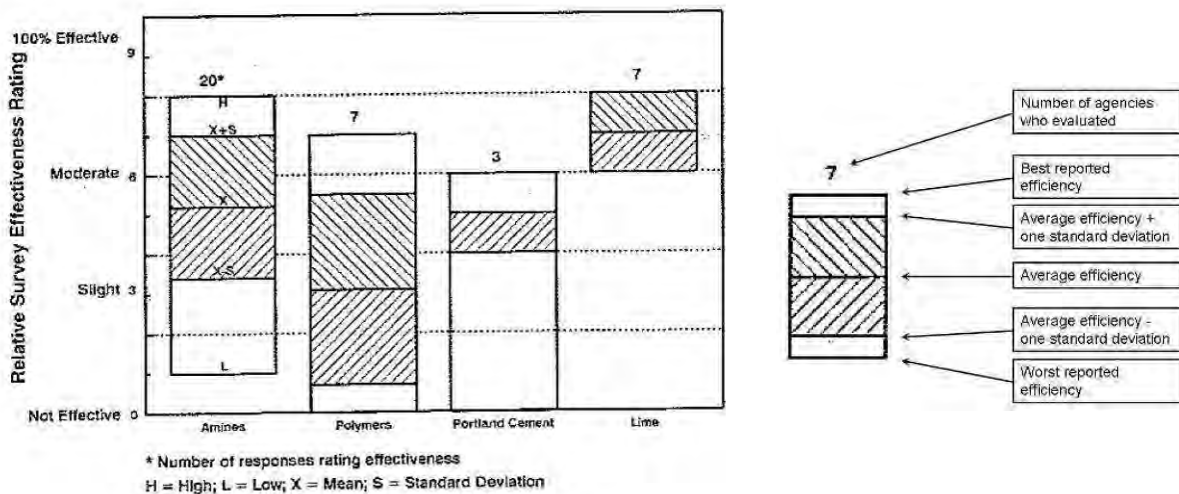


Figure 11: Comparison of the effectiveness of several additives in order to treat moisture damage as evaluated by North American State agencies experience (from [8]).

In the 2003 survey, the State agencies reported that the first reason why they use hydrated lime is because of moisture damage (Table 4 - [10]).

Agency	Resist Stripping	Improve Aging Resistance	Stiffen Binder	Improve Fracture Toughness	Alter Properties of Fines
Arizona	1	3	2	3	2
California	1	2	3	3	3
Colorado	1	3	3	3	1 (when appropriate)
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

Level of importance:  
 1 = very important  
 2 = moderately important  
 3 = less important

*Table 4: Reasons to use hydrated lime as evaluated by USA State agencies experience (from [10]).*

Test method	Standard	Type of specimen	Testing method	Conditioning	Test Result
Hamburg Wheel Tracking	EN 12697-22 – method B under water	260mm x 300mm 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 – méthode A	100mm 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 50mm/min	- specimens in vacuum (7kPa) for 30min - 70hrs in water at 40°C - 2hrs at 25°C	ITS ratio in % (after conditioning / no conditioning)
Duriez	EN 12697-12 – méthode B	100mm diameter (or 80 or 120 or 150 or 160) cylindrical specimen of the asphalt mixture to be tested	Compressive strength at 18°C and 55mm/min	- specimens in vacuum (47kPa) for 120min - 7days in water at 18°C	ITS ratio in % (after conditioning / no conditioning)
Cantabro	EN 12697-17	101.6mm diameter x 63.5mm cylindrical specimen of the asphalt mixture to be tested (generally a porous asphalt)	Mass loss after 300revolutions in the Los Angeles test (without steel balls)	Generally the same as ASTM D1075	Mass loss ratio (after conditioning / no conditioning)
Saturation Ageing Tensile Stiffness (SATS)	UK Specification for Highway Works – Clause 953	100mm diameter x 60mm 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 (55kPa) for 30min - 65hrs at 85°C and 2.1MPa in water saturated vessel - 24hrs at 30°C and 2.1MPa	Indirect Tensile Stiffness ratio in % (after conditioning / no conditioning)
Lottman	AASHTO T283 Tex 531-C	101.6mm diameter x 63.5mm cylindrical specimen of the asphalt mixture to be tested compacted to 6.5-7.5% voids	Indirect Tensile Strength (ITS) at 25°C and 50.8mm/min	- 70-80% pore saturation - 16hrs at -17.8°C - 24hrs in water at 60°C - 2hrs in water at 25°C	ITS ratio (after conditioning / no conditioning)
Repeated Lottman	-	101.6mm diameter x 63.5mm cylindrical specimen of the asphalt mixture to be tested compacted to 6.5-7.5% voids	Indirect Tensile Strength (ITS) at 25°C and 50.8mm/min	Lottman conditioning but with consecutive freeze-thaw cycles (generally from 1 to 20)	ITS ratio vs number of freeze-thaw cycles
Texas Freeze-Thaw Pedestal		41.3mm diameter x 19mm cylindrical briquet of 0.4/0.8 sand coated with bitumen at optimum + 2% compacted by static pressure of 27.58 kN for 20min	Visual (crack)	- briquet immersed in distilled water - 15 hrs at -12°C - 45min in water at 24°C - 9hrs at 49°C then repeat	Number of freeze-thaw cycles to failure

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	101.6mm diameter x 63.5mm cylindrical specimen of the asphalt mixture to be tested compacted by any mean (static / Marshall,...) to 6-8% air voids	Indirect Tensile Strength at 25°C and 50.8mm/min	- 55-80% pore saturation - 24 hrs in water at 60°C - 1hr at 25°C	ITS ratio (after conditioning / no conditioning)
Immersion/Compression	ASTM D1075 AASHTO T165	101.6mm diameter x 101.6mm cylindrical specimen of the asphalt mixture to be tested compacted by static compaction on both sides (3,000 psi during 2min)	Compressive strength at 25°C and 5mm/min	- 4 days in water at 48.9°C or 1 day in water at 60°C	Compressive strength ratio (after conditioning / no conditioning)
Retained Marshall		101.6mm diameter x 76.2mm cylindrical specimen of the asphalt mixture to be tested compacted by impact compaction (50 or 75 blows)	Marshall stability at 60°C – 50.8mm/min	- 24 hours in water at 60°C	Stability ratio (after conditioning / no conditioning)
Texas Boil Test	ASTM D3625 Tex 530-C	(300g + 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 10min	% of retained bitumen after boiling

*Table 5: Most used testing methods in order to evaluate the improvement of the moisture resistance of asphalt mixtures.*

*Hydrated Lime in Asphalt Mixtures*

Materials	Hydrated lime Content and addition method	Criteria	No Hydrated Lime	With Hydrated Lime	Type of Comparison Material	Comparison Material	References
	% based on dry aggregate						
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)	Mix1: (17mm) Mix2: (>20mm) Mix3: (>20mm) Mix4: 8.7mm	Mix1: 1.4mm Mix2: 2.3mm Mix3: 2.5mm Mix4: 2.3mm	0.5% of best Liquid Antistrip (Additive A) in binder	Mix1: 2.2mm Mix2: 8.1mm Mix3: (13.7mm) Mix4: 6.2mm	[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: 10.1mm PG70-22: 3.7mm PG76-22: 3.5mm	PG64-22: 9.5mm (LS) 8.9mm (LM) PG70-22: 2.6mm (LS) 2.9mm (LM) PG76-22: 1.9mm (LS) 1.8mm (LM)			[57]
Mix C Lithonia granite 5% PG67-22	2%	Rut depth at 50°C after 8,000 passes	12mm	4mm	0.5% liquid antistrip LAS2 in the binder	4mm	[58]
Texas DOT mixes 6 different aggregates 4.6-5.5% AC-20 7% air voids		Creep slope (Cycles at 40°C to get 1mm rut depth in the creep region) / Stripping slope (Cycles at 40°C to get 1mm 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 (Ka25)	Rut depth at 50°C after 20,000 cycles	10.9	5.2			[37]

Materials	Hydrated lime Content and addition method	Criteria	No Hydrated Lime	With Hydrated Lime	Type of Comparison Material	Comparison Material	References
	% based on dry aggregate						
0/16 S Asphalt Concrete 50/70 bitumen	1.5% as mixed filler (Ka25)	Rut depth at 50°C after 20,000 cycles	4.6	3.1			[37]

*Table 6: 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 3.3.4 for a description of the test results.*

*Hydrated Lime in Asphalt Mixtures*

Materials	Hydrated lime Content and addition method	Criteria	No Hydrated Lime	With Hydrated Lime	Type of Comparison Material	Comparison Material	References
	% based on dry aggregate						
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 (LAS2) 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 from Unichem 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 from Unichem 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 on damp aggregate with (DLW) or without (DLN) 48 hours marination or lime slurry with (LSW) or without marination (LSN)	retained strength at 25°C	39.8%	DLN: 108.7% DLW: 97.2% LSN: 100.0% LSW: 108.0%			[62]

Materials	Hydrated lime Content and addition method	Criteria	No Hydrated Lime	With Hydrated Lime	Type of Comparison Material	Comparison Material	References
	% based on dry aggregate						
0/25 Type 2C Nevada DOT mixes Lockwood felsite/basalt Polymer-modified PG64-34	1.5% dry lime on damp aggregate with (DLW) or without (DLN) 48 hours marination or lime slurry with (LSW) or without marination (LSN)	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 on damp aggregate with (DLW) or without (DLN) 48 hours marination or lime slurry with (LSW) or without marination (LSN)	retained tensile 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.*

*Hydrated Lime in Asphalt Mixtures*

Test method	Materials	Hydrated lime Content and addition method	Criteria	No Hydrated Lime	With Hydrated Lime	Type of Comparison Material	Comparison Material	References
		% based on dry aggregate						
Repeated Lottman	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	1.5%	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 Teramin 14) 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% 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% 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 Unichem RAA04013 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% voids	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 8: - 10: 310 12: failed	0: 524 1: 473 2: 471 4: 480 6: 446 8: - 10: 466 15: 423			[65]

Test method	Materials	Hydrated lime Content and addition method	Criteria	No Hydrated Lime	With Hydrated Lime	Type of Comparison Material	Comparison Material	References
		% based on dry aggregate						
	Wyoming 0/19 mixture granite 5.5% AAB-1 bitumen 7% voids	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 Freeze-Thaw Pedestal	Texas Asphalt Concrete mix with 62% Pea gravel, 15% washed sand and 23% field sand 5% AC-20 binder	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	lime slurry	Number of freeze-thaw cycles to failure	E: 4 A: 4	E: 22 A: > 25	21 commercial liquid antistrips (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 as measured from the repeated Lottman test or the Texas freeze-thaw pedestal test.*

Test method	Materials	Hydrated lime Content and addition method	Criteria	No Hydrated Lime	With Hydrated Lime	Type of Comparison Material	Comparison Material	References
		% based on dry aggregate						
Duriez	Porous asphalt B40/50 or PMB with 3% EVA	1%	retained compressive strength	B40/50: 62% PMB: 88%	B40/50: 78% PMB: 78%			[68]
Cantabro	0/16 porfire dense mix 6.4% filler 1.9-2.5% voids	1.6% as active filler (Ka25)	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% voids	1.4% as active filler (Ka25)	retained mass loss after 300 turns	Venezuel. crude: 1.6	Venezuel. crude: 1.5			[69]
	Porous asphalt B40/50 or PMB with 3% EVA	1%	retained mass loss	B40/50: 1.02 PMB: 0.99	B40/50: 0.93 PMB: 0.94			[68]
Retained Marshall	0/16 porfire dense mix 6.4% filler 1.9-2.5% voids	1.6% as active filler (Ka25)	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% voids	1.4% as active filler (Ka25)	retained stability	Arabian crude: 97% Venezuel. crude: 111%	Arabian crude: 97% Venezuel. crude: 120%			[69]
Texas Boil Test	undefined Mixes Lithonia granite 5% PG67-22	2%	% covered surface	5%	90%	0.5% liquid antistrip LAS2 in the binder	95%	[58]
	Polish 0/16 Mix w/ Glensanda granite 2/16 and 0/2 Graniczna sand D50 bitumen	1.5%	% covered surface	90%	100%	0.4% liquid antistrip (fatty amine) in the binder	100%	[63]
	River gravel (Gem sand)	calcic lime (c) / dolomitic lime (d)	% covered surface	10%	c: 68% d: 72%			[2]
	Limestone	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.*

### 3.2 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 surprisingly 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.

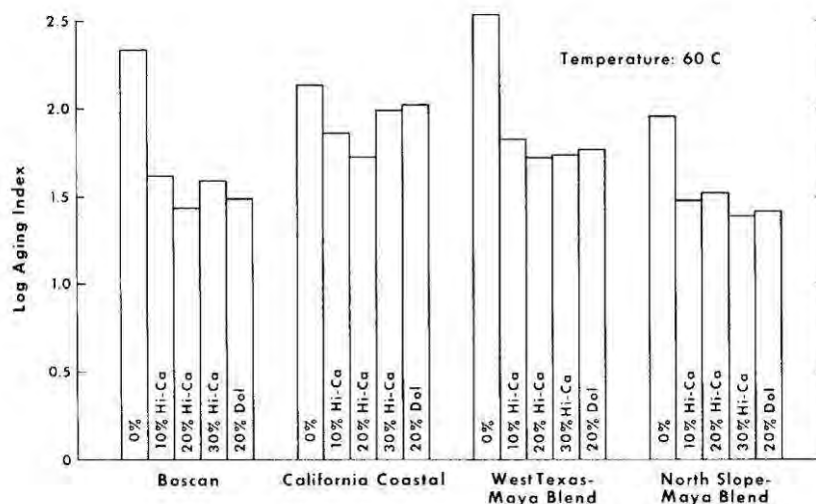


Figure 12: Aging index at 60°C (viscosity after ageing divided by the viscosity before) for various sources of bitumen modified with different weight proportions of hydrated lime (Hi-Ca) and hydrated dolomitic lime (Dol). Ageing was performed in the Thin Film Accelerated Aging Test (TFAAT) corresponding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

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 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 4.

Study	Aging Procedure	Tested Bitumens	Hydrated Lime content (weight % based on bitumen)	Main Conclusions	Reference
Plancher, 1976	<ul style="list-style-type: none"> <li>- Rolling Thin Film Oven Test (RTFOT - EN12607-1 - 75min at 163°C)</li> <li>- Rolling MicroFilm Circulating Oven RMF-C (48hrs at 98.9°C)</li> </ul>	- 4 AC10 from different locations	50 (from 1/1/600 HL/bitumen/benzene solutions then HL and solvent removed)	<ul style="list-style-type: none"> <li>- hydrated lime treatment seen to reduce age hardening (lower stiffening, lower asphaltene content, lower carbonyl-type oxidation products)</li> <li>- bitumen dependent effect but all bitumen benefit from hydrated-lime treatment</li> </ul>	[72]
Edler, 1985	<ul style="list-style-type: none"> <li>- Weatherometer: 65°C with cyclic 102 min UV and 18 min UV+water spray (3bars), 32.5hrs, 73.5hrs, 7 days, 14 days</li> <li>- RTFOT 163°C, 75 min</li> <li>- RTFOT + POB (Pressure Oxygen Bomb 65°C and 2.06 MPa of oxygen pressure, 96 hrs)</li> <li>- RTFOT + TFOT 163°C, 5 hrs</li> <li>- viscosity, IRTE, GPC</li> </ul>	- 60/70 and 80/100	- 6 or 12wt.% hydrated lime	<ul style="list-style-type: none"> <li>- much lower ageing with hydrated lime as noted by viscosity, almost regardless of lime content</li> <li>- lower ratio of C=O abs. (1710 cm<sup>-1</sup>) / C=C abs. (1600 cm<sup>-1</sup>) for lime modified bitumens after ageing</li> <li>- effect much clearer on weatherometer, almost unseen on RTFOT</li> <li>- little effect on molar weight</li> </ul>	[78]
Petersen, 1987	Thin Film Accelerated Aging Test (TFAAT) of hydrated lime-treated materials at 113°C for 3 days	<ul style="list-style-type: none"> <li>- AC10 California Coastal</li> <li>- AC10 Boscan</li> <li>- AC10 North Slope / Maya</li> <li>- AC10 West Texas / Maya</li> </ul>	<ul style="list-style-type: none"> <li>- 10, 20, 30 hydrated lime</li> <li>- 20 dolomitic lime</li> </ul>	<ul style="list-style-type: none"> <li>- ageing procedure similar to 11-13 yrs in the field</li> <li>- 10% hydrated lime enough to neutralize most of the acids of the binders</li> <li>- hydrated lime treatment seen to reduce age hardening (lower stiffening, asphaltene content, and carbonyl oxidation products)</li> <li>- rate of carbonyl formation slows down for hydrated lime-treated bitumens-</li> <li>- rate of sulfides, sulfoxides and ketones formation not modified by hydrated lime</li> <li>- bitumen dependent effect but all bitumen benefit from hydrated-lime treatment</li> <li>- limestone filler does not have any effect on bitumen ageing</li> </ul>	[22,12]

Study	Aging Procedure	Tested Bitumens	Hydrated Lime content (weight % based on bitumen)	Main Conclusions	Reference
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 sulfoxides formation, except for one bitumen (AAK)	[76,70]
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	144hrs 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) <sub>2</sub> not effective as an anti-ageing compound for bitumen - bitumen dependent effect	[80,70]
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 + Little, 1999	TFOT + PAV 100°C 20hrs	- 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]

Study	Aging Procedure	Tested Bitumens	Hydrated Lime content (weight % based on bitumen)	Main Conclusions	Reference
Hopman, 1999	RTFOT (2.5 and 7hrs)	- 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 7hrs)	- 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 100-2000hrs	- 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 + Puiatti, 2004	RCAT 235min at 163°C or 17, 65 and 140hrs 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 <sup>-1</sup> 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: A review of the laboratory studies showing the effect of hydrated lime on the ageing of bitumen.*

Study	Country	Mixture Type	Age	Hydrated Lime content	Main Conclusions	Reference
			years	weight % based on dry aggregate		
Chachas, 1971	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)	<ul style="list-style-type: none"> <li>- the first notice of hydrated lime effect on bitumen aging (lower viscosity)</li> <li>- observation based on bitumen recovery which had lower viscosity for lime-modified mixtures than non-modified ones</li> <li>- the magnitude of the effect was found to be dependent of bitumen source</li> </ul>	[70]
Decoene, 1983	Belgium	2-4cm Porous Asphalts and 5cm 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	Montana – Big timber test sections	One aggregate type, 120/150 bitumen in most sections (except: <ul style="list-style-type: none"> <li>- 85/100 in one section</li> <li>- 200/300 + Chemcrete in one section</li> <li>- 200/300 + carbon black in one section)</li> </ul>	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	<ul style="list-style-type: none"> <li>- no significant effect of HL</li> <li>- maybe due to HL carbonation</li> </ul>	[79]
Jones, 1997	Utah		8		- binder viscosity 50% lower for hydrated lime treated mixes, showing a lower ageing	[11]
Huang, 2002	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]

Study	Country	Mixture Type	Age	Hydrated Lime content	Main Conclusions	Reference
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	0/19 mixture	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.*

### ***3.3 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 2). 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 4).

#### **3.3.1 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 2) 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 4 (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  $\sim 2.5$  and  $\sim 8^\circ\text{C}$  respectively. Note that the difference in R&B temperature range between 2 adjacent paving grades is about  $5^\circ\text{C}$  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:

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

where  $\eta(\phi)$  is the viscosity of the mastic with a volume fraction of filler  $\phi$  and  $\eta_0$  is the viscosity of the base bitumen.

The intrinsic viscosity 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 ( $[\eta] \sim 3-10$ ) is about twice as stiffening as other mineral fillers ( $[\eta] \sim 2.5-5$ ) (Table 12 - [95]).

Filler type	$[\eta]$	Reference
Limestone	3.8	[268]
Limestone	2.6-3.9 (25 °C)	[273]
	3.0-3.7 (70 °C)	
Limestone	2.5 (65 °C)	[270]
	2.4 (135 °C)	
Dolomitic limestone	4.9 (25 °C)	[273]
	4.4 (70 °C)	
Hydrated Lime	3.2-10	[277]
Lime	7	[274]
Sandstone	2.8 (25 °C)	[273]
	4.0 (70 °C)	
Siliceous filler	2.4 (65 °C)	[270]
	2.4 (135 °C)	
Granite	2.7-4.2 (25 °C)	[273]
	3.5-4.1 (70 °C)	
Fly ash	10.2 (25 °C)	[273]
	14.1 (70 °C)	
Slate dust	4.2	[268]
Ball clay	3.2	[270]
Kaolin	6.7	[268]
Carbon black	2.6 (65 °C)	[270]
	3.9 (135 °C)	
Asbestos	16.5	[274]
Polyester fibers	26-34	[281]
Mineral fibers	26	[281]

*Table 12: Intrinsic viscosity 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 3 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].

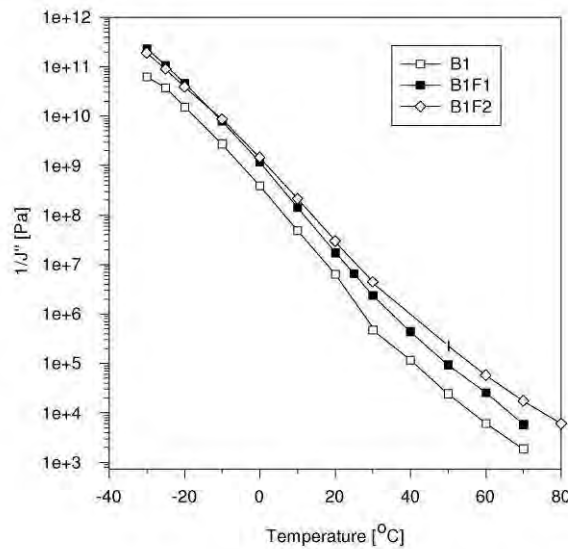


Figure 13: Temperature dependence of the stiffening effect of hydrated lime as compared to a limestone filler: inverse of the imaginary compliance ( $1/J''$ ) at 10 rad/s versus temperature for a reference straight-run 70/100 bitumen (B1) and the same bitumen with 50wt.% of limestone filler (B1F1) or mixed limestone filler containing 40% hydrated lime (from [97]).

Elements of interpretation of these effects are discussed in Chapter 4.

### 3.3.2 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 stress the

measuring conditions when talking about asphalt mixture modulus. A European standard 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  $-10^{\circ}\text{C}$  and  $54.4^{\circ}\text{C}$  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 101.6mm diameter and 152.4mm high cylindrical specimens. The mixes were made with 4.2-5.2% of 4 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.

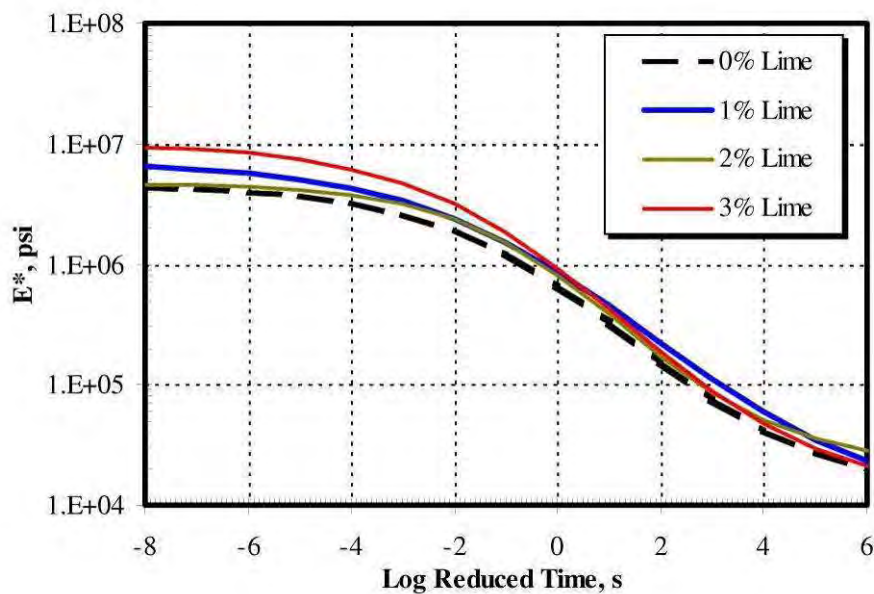


Figure 14: Master curve (norm of the complex modulus versus reduced loading time) at  $21.1^{\circ}\text{C}$  for the 0/18 mixes made of Two-Guns aggregate (4.3% filler) and 4.6% PG64-22 (from [104]).

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 (see previous section) was reported.

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].

Study	Test conditions	Number of Data 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 + Epps, 1987	-28.9 / -1.1 / 25.0 / 40.0°C	10	1.5%	B,D,LS	4	[20]
Pickering, 1992	25°C	4	1-2%		4	[61,13]
Epps, 1992	25°C	8	1-2%		8	[11]
Nevada DOT, 1998	25°C	4			4	[11]
Ghouse Baig + 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 + Sebaaly, 2003	25°C	12	1.5%	D, DM, LS, LSM	1	[62]
Berthelot, 2005	20°C	1	1%		1	[109]
Jaskula + Judycki, 2005	20°C	2	1.5%		1	[63]
Huang, 2008	-10.0 / 4.4 / 21.1 / 37.8 / 54.4°C	1	1%		1	[110]
Mohammad, 2008	-10.0 / 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 + 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 studied 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 and an additional M in case of marination.*

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%. 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 2 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 4.

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.

### 3.3.3 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 3.1). 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: measuring temperature in the low-stiffening zone (Figure 13) and kinetics of the stiffening effect as discussed in Chapter 4.

Study	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	Reference
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 + 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 + Sebaaly, 2003	12	1.5%	D, DM, LS, LSM	4	[62]
Huang, 2005	2	1%	B	0	[65]
Jaskula + Judycki, 2005	2	1.5%	-	0	[63]
Ameri + Aboutalebi, 2008	10	3%	-	10	[114]
Kim, 2008	2	1%	D,LS	2	[60]
Mohammad, 2008	12	1.5%	B, LS	10	[57]
Maldonado + Fee, 2008	1	2%	-	1	[58]
Gorkem + Sengoz, 2009	6	1, 1.5, 2%	-	6	[115]
Vural Kok + 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 studied 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 and an additional M in case of marination.*

### 3.3.4 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.



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

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.

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 (HWTDD) were already listed in the moisture resistance section (Table 6). 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 HWTDD).

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 3.1).

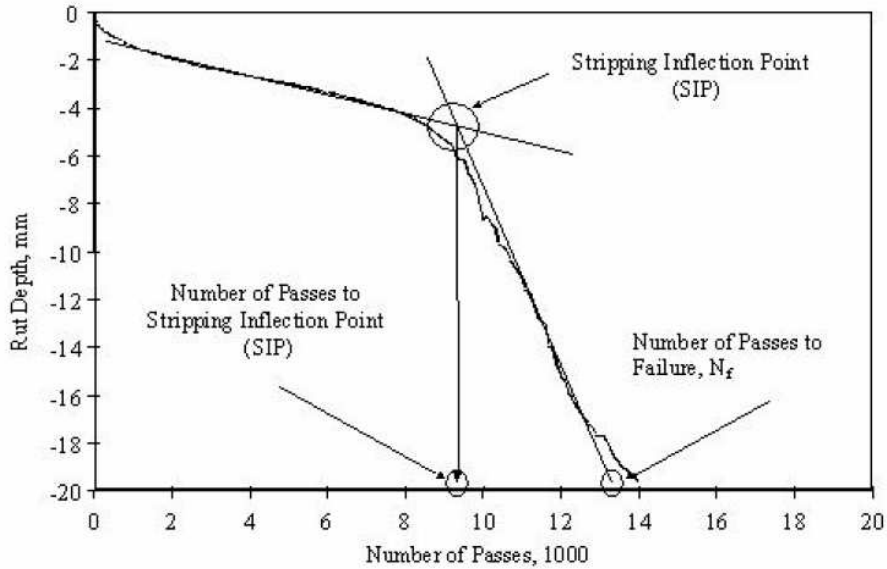


Figure 16: Interpretation of the experimental results from the HWTD (from [13]).

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.

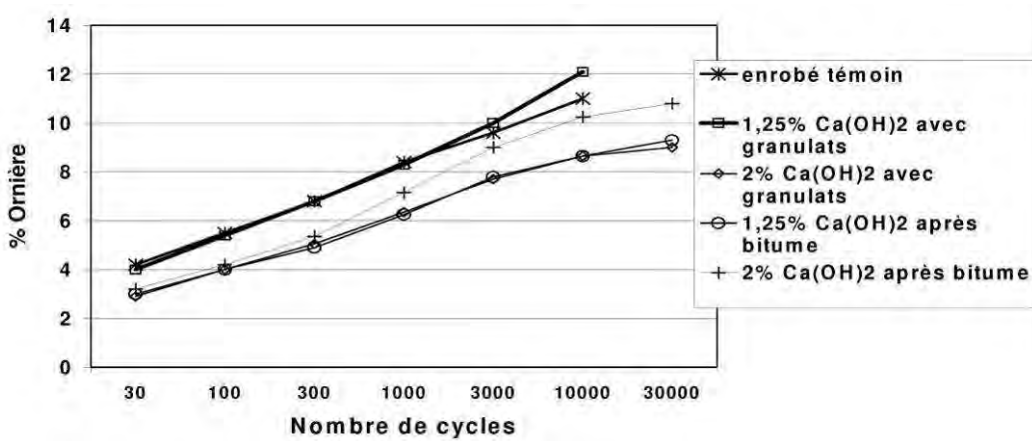


Figure 17: Effect of hydrated lime on the rutting resistance of a French BBSG 0/14 asphalt mixtures: rut depth vs number of load cycles in the French rut tester at 60°C. Enrobé témoin is the reference. 1.25 or 2% hydrated lime were added either to the dry aggregate (avec granulats) or to the mixture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

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.

Study	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 strength than the reference	Reference
Little, 1994		3			3	[12]
Hiérnaux, 1995	French, 60°C	1	1%		1	[23]
Kim, 1995		1			1	[119,11]
Collins, 1997	APA	8			5	[11]
Ghouse Baig + 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 + 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 data. Note that data with the Hamburg wheel tracking device were already described in Table 6. For each publication, the total number of mixes with hydrated lime is given together with the range of studied 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 and an additional M in case of marination, MF for mixed filler.*

### 3.3.5 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].



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

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].

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 exists in order to test asphalt mixtures for fatigue resistance [123].

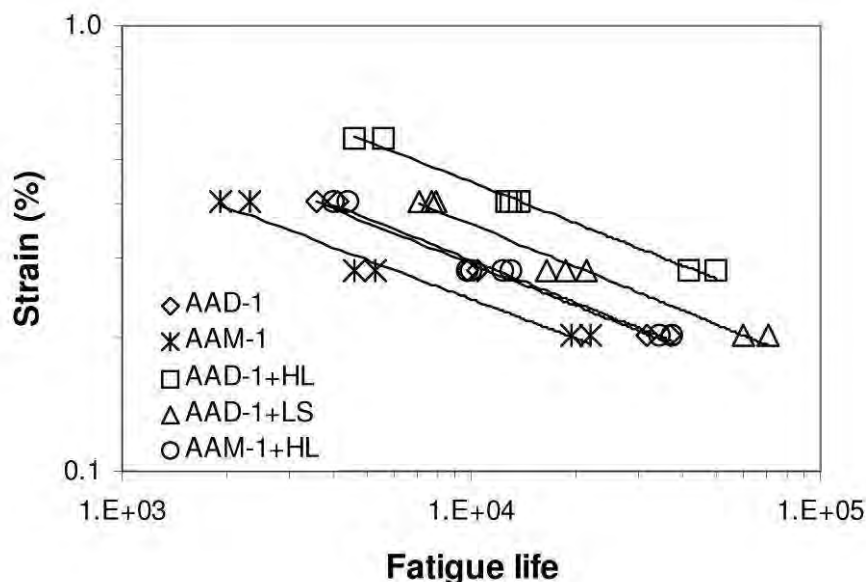


Figure 19: Effect of hydrated lime on the fatigue life of sand asphalt mixtures tested in torsion: Number of cycles to failure vs strain for several sand asphalts containing 10% of hydrated (HL) or limestone filler (LS) in the bitumen for two bitumen sources (AAD-1 and AAM-1 - from [90]).

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.

Study	Testing 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 strength than the reference	Reference
Rhagava Chari + 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	[107]
Mohammad, 2000	25°C	8	1.5%	LS	3	[108]
Little + Petersen, 2005		3	1%	D	3	[13]

*Table 16: A survey of published fatigue data. For each publication, the total number of mixes with hydrated lime is given together with the range of studied 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 and an additional M in case of marination.*

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.

### 3.3.6 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. It 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 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. 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.

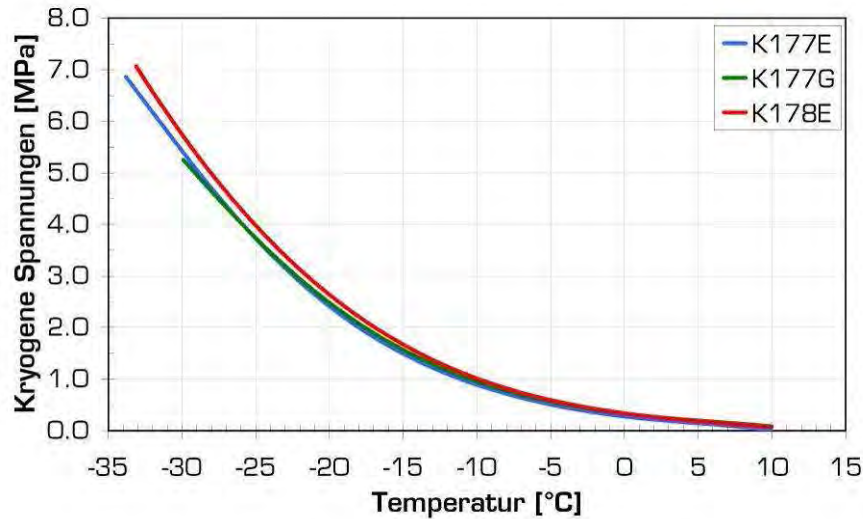


Figure 20: TSRST (thermal stress vs temperature) for 0/22 asphalt concrete with 4.5% polymer-modified bitumen and 2.5% hydrated lime. The curves correspond to repetitions for the same material (from [128]).

A/

	Starttemperatur in °C	Temperaturgradient in K/h	max. th. ind. Spannung in N/mm <sup>2</sup>	Bruchtemperatur in °C
ohne Kalkhydrat	20,0	-10,0	4,296	-24,1
			4,238	-24,5
mit Kalkhydrat	20,0	-10,0	4,279	-24,3
			4,339	-24,6

B/

	Starttemperatur in °C	Temperaturgradient in K/h	max. thermisch induzierte Spannung in N/mm <sup>2</sup>	Bruchtemperatur in °C
ohne Kalkhydrat	20,0	-10,0	4,558	-26,3
			4,523	-26,0
mit Kalkhydrat	20,0	-10,0	4,761	-26,6
			4,573	-26,2

Table 17: TSRST (thermal stress vs temperature) data for: A/ a SMA 0/8 asphalt mixture with 7.3% 50/70 bitumen and with or without 1.6% hydrated lime (in the form of Ka<sub>25</sub> mixed filler). B/ a AC 0/11 asphalt mixture with 6.2% 70/100 bitumen and with or without 1.4% hydrated lime (in the form of Ka<sub>25</sub> mixed filler - 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.

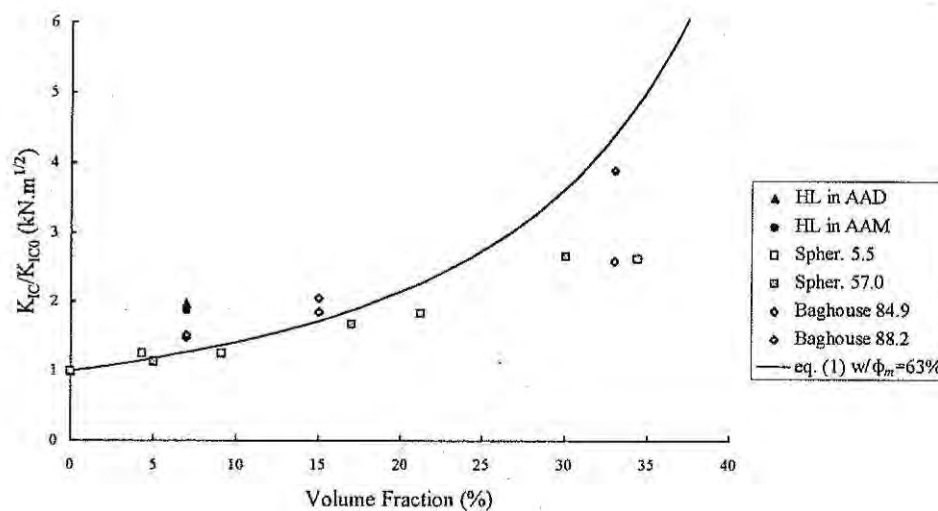


Figure 21: Mastic toughness (reduced to that of the base bitumen) versus filler volume fraction for several mastics made with two bitumens and hydrated lime. The data are compared to published data for mineral fillers (baghouse) or glass beads (spher. - from [81]).

### 3.4 Hydrated Lime Combined to Other Additives

#### 3.4.1 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 (PmB45A) 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]).

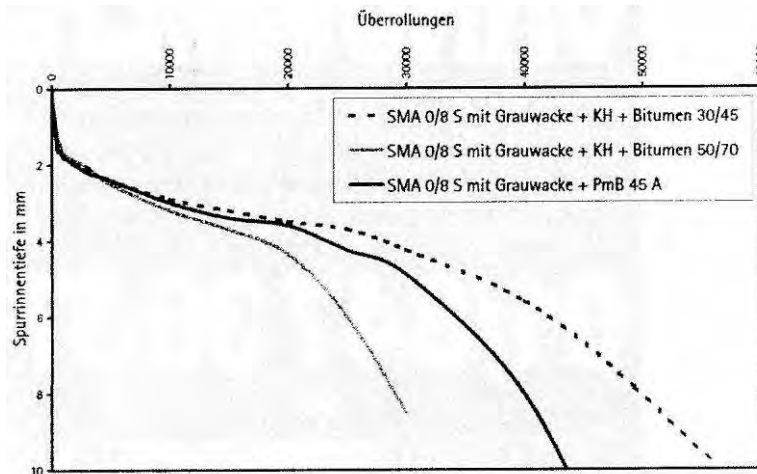


Figure 22: Rutting curves obtained on the HWTD for several SMA 0/8 mixtures made with the same aggregate (Grauwacke) but different binders: polymer-modified bitumen (PmB45A), 30/45 or 50/70 bitumen with 1.4% hydrated lime (in the form of mixed filler). An adequate choice of binder and hydrated lime content 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. Pobochoa 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 5.3.

#### 3.4.2 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].

#### 4. 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 2, 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.

##### 4.1 Effect on the Aggregate

###### 4.1.1 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].

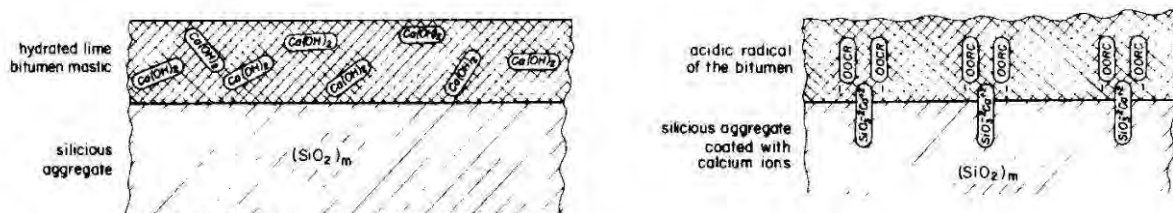


Figure 23: The effect of hydrated lime on the aggregate surface as proposed by I. Ishai and J. Craus (from [139]).

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 5.4. 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.

#### 4.1.2 Clay Flocculation

In the case of clayey aggregates, hydrated lime is known to be highly effective in increasing the 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].

### **4.2 Effect on the Bitumen**

#### 4.2.1 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].

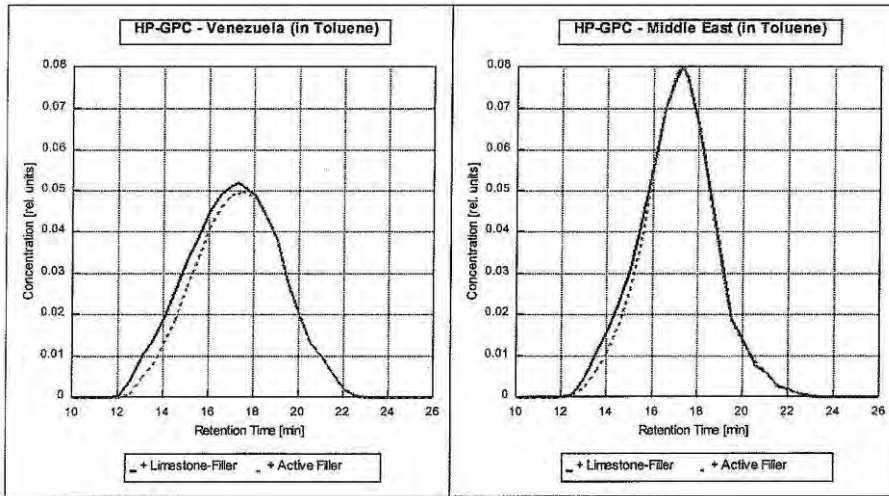


Figure 24: High Performance Gel Permeation Chromatography in toluene for two bitumens from Venezuela or Middle East after contact with either a limestone filler or the same filler with 25wt.% hydrated lime (active filler - from [69]).

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					
Untreated	0.015	trace	0.0014	0.003	0.015
Lime-Treated	.039	*	*	*	.013
B-3036					
Untreated	.021	trace	.0014	.001	.022
Lime-Treated	.039	*	*	*	.019
B-3051					
Untreated	.017	.014	.003	.009	.010
Lime-Treated	.039	*	.001	.004	.008
B-3602					
Untreated	.045	.06**	*	.011	.015
Lime-Treated	.10	.014**	.007	.006	.015

\*Below level of detection  
 \*\*Present as carboxylate salts

Table 18: Concentration of functional groups in four AC-10 bitumens of different chemical composition before and after treatment by hydrated lime (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]. 150g 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.

Lime treatment Type	%	Aging test	Concentration, mol/L				
			Ketones	Anhydrides	Carboxylic acids	2-Quinolone types	Sulfoxides
None	0	Unaged	0	0	0.015	0.017	0.02
		Aged	0.28	0.007	0.015	0.017	0.35
High calcium	10	Unaged	0.03	0	0.005	0.016	0.03
		Aged	0.24	0.005	0.004	0.016	0.32
High calcium	20	Unaged	0.03	0	0.003	0.014	0.03
		Aged	0.22	0.006	<0.002	0.017	0.34
High calcium	30	Unaged	0.03	0	<0.002	0.013	0.03
		Aged	0.21	0.006	<0.002	0.014	0.32
Dolomitic	20	Unaged	0.03	0	0.005	0.013	0.03
		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]).

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].

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:

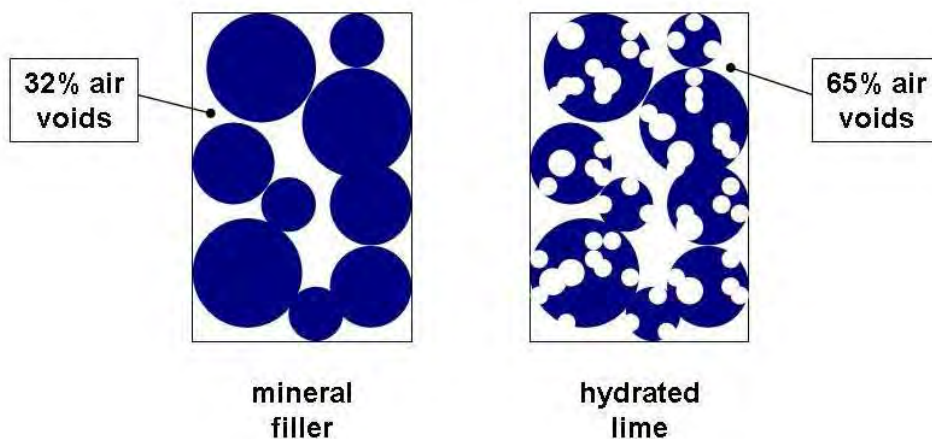
- First, the polar molecules neutralized by the hydrated lime remain strongly adsorbed onto the hydrated lime particles [12,22,72]. This prevents them from further reacting as a consequence of bitumen chemical ageing. Since they are especially prone to ageing, their removal generates an overall slower 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.

#### 4.2.2 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 2 ([31] – see Figure 4 and Figure 5).

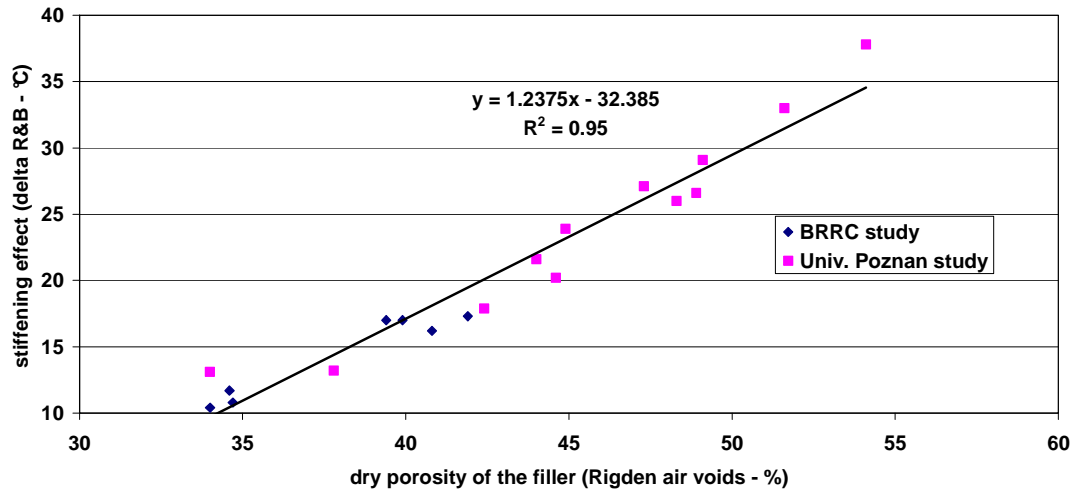


Figure 26: Correlation between the stiffening effect of several fillers with their dry porosity (Rigden air voids). The data are from two studies: one from Poznan University [30] (already described in Figure 4 and Figure 5) and the other from the Belgian Road Research Center [31]).

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 3).

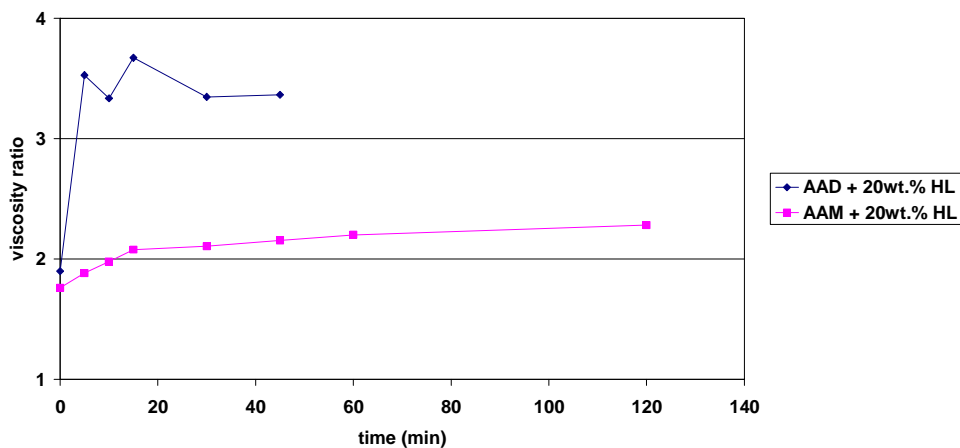


Figure 27: Kinetics of viscosity build-up at 138°C for two bitumens modified with 20% hydrated lime. The viscosity stabilizes quickly for AAD when it keeps increasing after 120min for AAM. The neat bitumen did not show any significant viscosity change in the mean time (after [81]).

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 3.3.1, 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.

## 5. HYDRATED LIME IN ASPHALT MIXTURES IN PRACTICE

### 5.1 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.

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.

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	Marina-tion
<b>Europe</b>							
Austria	1.5-3.5	X					
France	1-1.5	X	X				
Netherlands	2		X				
Switzerland	1.5	X					
UK	1-2	X					
<b>USA</b>							
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).

### 5.1.1 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 1m before the binder injection point [145]. This is a method in use in Europe (Austria, France, Germany, UK) and in 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].

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  $70\text{m}^3$  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].



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

### 5.1.2 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.

Category	Calcium hydroxide content
	wt. %
Ka <sub>25</sub>	≥25
Ka <sub>20</sub>	≥20
Ka <sub>10</sub>	≥10
Ka <sub>declared</sub>	<10
Ka <sub>NR</sub>	No Requirement

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

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<sub>25</sub> with 25% hydrated lime for all their porous asphalts [16]. Germany has also a strong experience with Ka<sub>25</sub>, 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.

### 5.1.3 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].

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].



*Figure 29: Pugmill used to mix hydrated lime with the wet aggregate in South Carolina (from [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 8cm of the stockpile [13].

### ***5.2 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.

Agency	Lime Treated			Non-Lime Treated		
	10%	Average	90%	10%	Average	90%
a) Interstate						
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*	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
b) State and U.S. Highways						
Arizona	18	20	22	15	17	20
California	8	10	12	6	8	10
Colorado*	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
c) Low Volume Roads						
Arizona	20	25	30	15	20	25
California		N/A			N/A	
Colorado*	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

\*Pavement preservation  
N/A = not applicable

Table 22: Life expectancy of hydrated lime treated and untreated mixes in the USA. From [10].

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, Georgia, reported no difference for treated mixes (low volume roads only).

### 5.3 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. 10km 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).

Country	Race Course	Year built	Hydrated Lime +
Brasilien	Rio de Janeiro	1999	PMB
Portugal	Estoril	2001	
Italien	Fiorano	2002	
Bahrain	Manama	2003/04	
China	Shanghai	2004	
Spanien	Barcelona	2004	
Türkei	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)*

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%.

#### **5.4 Hydrated Lime Dosification**

Hydrated lime can be dosified 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:

1. Hydrated lime purity,
2. Hydrated lime content in a mixed filler,

### 3. 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 1g of recovered filler to 150ml of water, 10ml isobutanol and 5ml of a surfactant solution (1g Sodium DodecylSulfate and 1g polyethyleneglycol-dodecylether in 100ml 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 phenolphthalein (0.5g in 50ml ethanol, completed to 100ml 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-robin 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.%.

The method was validated on samples taken out of cores 1.5years 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].

Section	Nominal Hydrated Lime content	Measured Hydrated Lime Content in Recovered Filler
	wt.%	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 (after [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%).

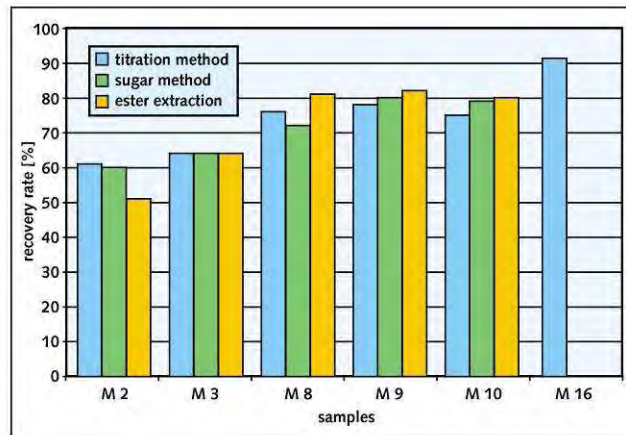


Figure 30: Percentage of hydrated lime eventually detected using three different chemical methods. “Titration” refers to the direct titration following the German method [156] described at length in the text. “Sugar” refers to the titration of a saccharose extract of the filler to be tested and “Ester”, 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) and M16 with limestone filler (20% hydrated lime). The recovery rate is the ratio of dosificated lime over nominal lime content.

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  $3,640\text{ cm}^{-1}$  corresponding to calcium hydroxide (Figure 31). Calcium carbonate peaks at  $1,390\text{ cm}^{-1}$  and can be unmistakably separated from the hydrate (Figure 31).



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

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

## **6. 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 more than 100 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.

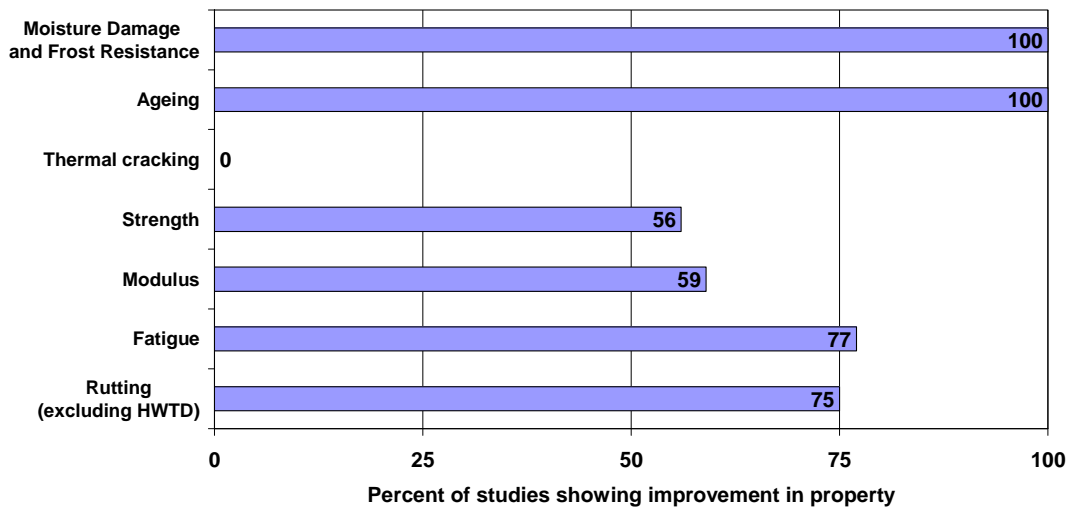


Figure 32: Improvement in selected asphalt mixture properties by hydrated lime addition. The percentage must be understood as the proportion of published studies showing an improvement. Rutting excludes Hamburg Wheel Tracking Device (HWTD) results because they better fit in the moisture damage category.

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 dosificated inside the mixture.

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. 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 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, ITRR 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.

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## 7. 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](http://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.

The following Figures give an idea of the type of documents, mostly research articles (Figure 33).

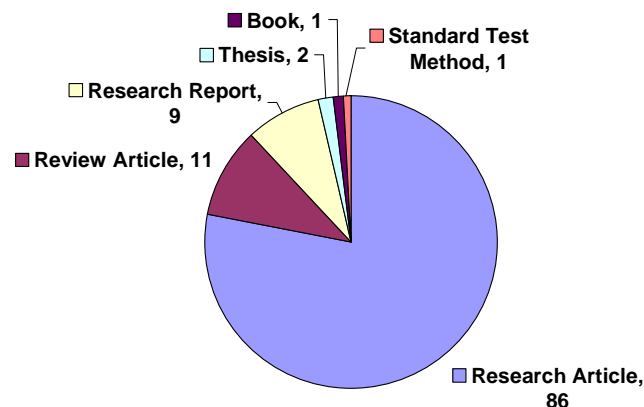


Figure 33: Type of documents in the database.

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.

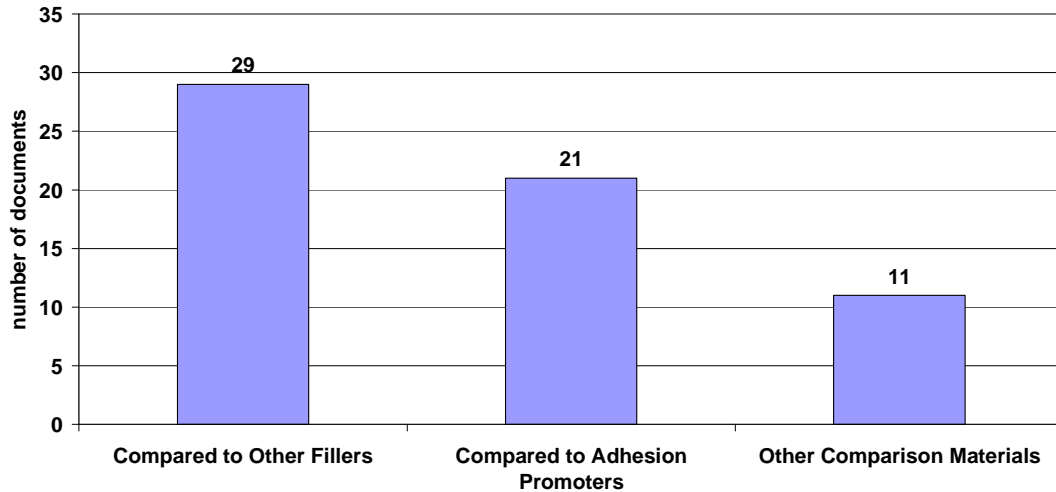


Figure 34: Hydrated lime compared to what?

Finally, the properties that were analyzed in the documents are described in Figure 35. The sum overpasses 110 documents because some publications worked on different aspects. 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 “Other” list fall works on hydrated lime properties (filler testing), on mastics and on the dosification method. A list of references by functionalities is given in Annex 2.

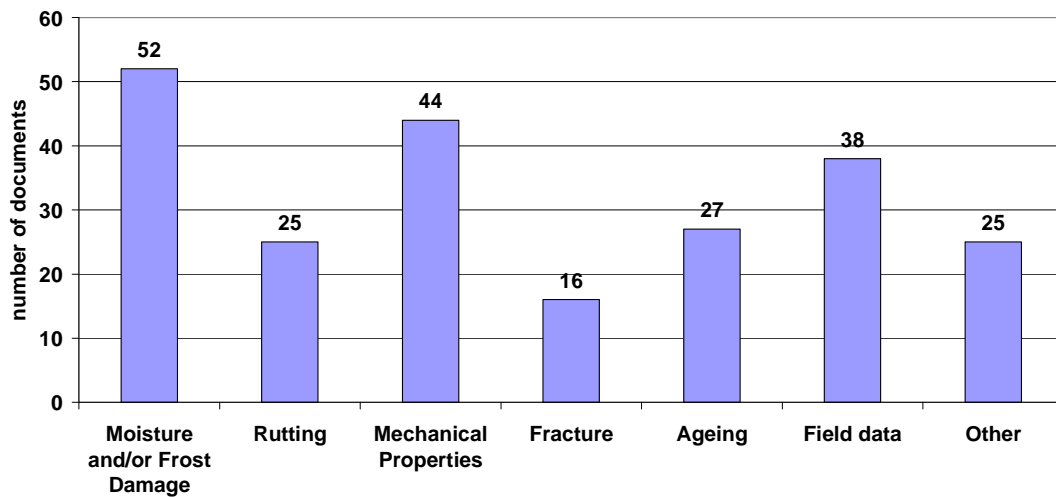


Figure 35: How is hydrated lime evaluated?

## 8. 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 dosification, 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				
<b>T. S. Arnold, M. Rozario-Ranasinghe and J. Youtcheff, "Determination of lime in hot-mix asphalt", Transportation Research Record 1962, pp.113-120, 2006</b>						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	
<b>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</b>	X		X				
J. Bari and M. W. Witzcak, "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. 4 <sup>th</sup> 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				

Reference	Md	Ag	Me	Ru	Fr	Ot	Fi
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					
R. Blab und B. Hofko, Eignung von mit Kalkhydrat und polymermodifiziertem Bindemittel hergestelltem Asphaltmischgut für hoch belastete Verkehrsflächen, Report for Project 0727E, Wien (Austria): Technische Universität Wien, 2008			X		X		
J. Blazek, G. Sebor, D. Maxa, M. Ajib and H. Paniagua, "Effect of hydrated lime addition on properties of asphalt", Petroleum and Coal, 42(1), pp.41-45, 2000	X						
A. L. Bock, D. Hartmann, J. Budny, L. P. Specht e J. A. P. Ceratti, „Estudio laboratorial sobre os efeitos de diferentes formas de adição de cal a concreto asfáltico“, Teoria e Prática na Engenharia Civil 14, pp.59-69, 2009	X		X				
G. Bordonado, « Une expérience d'enrobés drainants sur l'autoroute A1 », Revue Générale des Routes et Aérodrômes 625, pp.47-50, décembre 1985							X
B. Bruce, "Asphalt as a variable – Big Timber test sections", Proc. Association Asphalt Paving Technologists 56, pp.688-710, 1987				X	X		X
B. Brûlé, F. Le Bourlot et B. Simaillaud, « Enrobés drainants : Optimisation de la composition des liants et des mastics », Proc. 5th Eurobitume Congress, Stockholm, paper 3.20, pp.591-595, June 1993	X		X			X	
M. Buchta und C. Kunesch, "Asphaltmodifizierung mit Kalkhydrat - Ergebnisse aus der Praxis", Gestrata Journal 111, pp.7-12, 2005 ( <a href="http://www.gestrata.at/archiv/journal/Journal_111.pdf">http://www.gestrata.at/archiv/journal/Journal_111.pdf</a> )							X
J. W. Button, "Maximizing the Beneficial Effects of Lime in Asphalt Paving Mixtures", ASTM STP 899 pp.134-146, 1984							X
<b>C. V. Chachas, W. J. Liddle, D. E. Peterson and M. L. Wiley, Use of hydrated lime in bituminous mixtures to decrease hardening of the asphalt cement, Report PB 213 170, Salt Lake City (Utah, USA): Utah State Highway Department, 1971</b>		X					X
P. Cramer, G. Herz und M. Radenberg, „Kalkhydrat: Eine Alternative zur Modifizierung des Bindemittels“, Asphalt 6, pp.17-25, 2001	X			X			
<b>Y. Decoene, "Enrobés bitumineux perméables, expériences récentes belges", La Technique Routière 2, pp.20-40, 1983</b>							X
<b>A. C. Edler, M. M. Hattingh, V. P. Servas and C. P. Marais, "Use of aging tests to determine the efficacy of hydrated lime additions to asphalt in retarding its oxidative hardening", Proc. Association Asphalt Paving Technologists 54, pp.118-139, 1985</b>		X					
H.-J. Eulitz, K. Schellenberg, H.-J. Ritter und S.-O. Schmidt, „Verbesserung von Asphalteeigenschaften durch Zugabe von Kalkhydrat“, Report 2/98/B005, Köln (Germany): Forschungsgemeinschaft Kalk und Mörtel e. V., 1998	X	X					X
J. Gallego Medina, "Efectos del hidrato de cal como aditivo de mezclas bituminosas", Carreteras 123, pp.68-80, 2002	X	X		X			

Reference	Md	Ag	Me	Ru	Fr	Ot	Fi
M. Ghouse Baig and H. I. Al-Abdul Wahhab, "Mechanistic evaluation of hedmanite and lime modified asphalt concrete mixtures", J. Materials in Civil Engineering 10(3), pp.153-160, 1998	X		X	X	X		
C. Gorkem and B. Sengoz, "Predicting stripping and moisture induced damage of asphalt concrete prepared with polymer modified bitumen and hydrated lime", Construction Building Materials 23, pp.2227-2236, 2009	X		X				
<b>W. Grabowski, J. Wilanowicz and T. Sobol, "Structural and functional properties of mineral fillers modified with hydrated lime", Proc. 6<sup>th</sup> International Conference on Maintenance and Rehabilitation of Pavements and Technological Control (MAIREPAV6), Torino (Italy), paper 78, July 2009</b>						X	
D. I. Hanson, R. E. Graves and E. R. Brown, "Laboratory evaluation of the addition of lime treated sand to hot-mix asphalt", Transportation Research Record 1469, pp.34-42, 1994	X						
<b>P. Hao and Y. Hachiya, "Moisture susceptibility of asphalt mixture and effectiveness of anti-stripping additives", Proc. Japan Soc. Civil Engineers 61(746), pp.265-273, 2003</b>	X	X		X			
<b>R. G. Hicks, Moisture Damage in Asphalt Concrete, NCHRP Synthesis of Highway Practice 175, Washington (District of Columbus, USA): Transportation Research Board, 1991</b>	X						X
<b>R. G. Hicks and T. V. Scholz, Life Cycle Costs for Lime in Hot Mix Asphalt, 3 vol., Arlington (Virginia, USA): National Lime Association, 2003</b> ( <a href="http://www.lime.org/LCCA/LCCA_Vol_I.pdf">http://www.lime.org/LCCA/LCCA_Vol_I.pdf</a> , <a href="http://www.lime.org/LCCA/LCCA_Vol_II.pdf">http://www.lime.org/LCCA/LCCA_Vol_II.pdf</a> , <a href="http://www.lime.org/LCCA/LCCA_Vol_III.pdf">http://www.lime.org/LCCA/LCCA_Vol_III.pdf</a> )						X	X
P. C. Hopman, Hydroxide in Filler, Netherlands Pavement Consulting Report n°97316, Utrecht (The Netherlands): Netherlands Pavement Consulting, 1998	X	X				X	
<b>P. C. Hopman, A. Vanelstraete, A. Verhasselt and D. Walter, "Effects of hydrated lime on the behaviour of mastics and on their construction ageing", Proc. 5<sup>th</sup> Int. Conf. on Durable and Safe Road Pavements, Kielce, vol. 1, pp.59-68, May 1999</b>	X	X				X	
J. F. Huang, S. P. Wu, L. Pan and Y. Xiao, "Effects of hydrated lime on the dynamic properties of gneiss asphalt mixtures", Proc. 2 <sup>nd</sup> Int. Conf. on Heterogeneous Material Mechanics (ICHMM), Huangshan (China), pp.1057-1060, 2008			X				
S.-C. Huang, J. C. Petersen, R. E. Robertson and J. F. Branthaver, "Effect of hydrated lime on long-term oxidative aging characteristics of asphalt", Transportation Research Report 1810, pp.17-24, 2002		X					
<b>S.-C. Huang, R. E. Robertson, J. F. Branthaver and J. C. Petersen, "Impact of lime modification of asphalt and freeze-thaw cycling on the asphalt-aggregate interaction and moisture resistance to moisture damage", J. Materials in Civil Engineering 17(6), pp.711-718, 2005</b>	X						

Reference	Md	Ag	Me	Ru	Fr	Ot	Fi
<b>I. Ishai and J. Craus, “Effect of the filler on aggregate-bitumen adhesion properties in bituminous mixtures”, Proc. Association Asphalt Paving Technologists 43, pp.228–258, 1977</b>	X		X				
R. P. Izzo and M. Tahmoressi, “Use of the Hamburg wheel-tracking device for evaluating moisture susceptibility of hot-mix asphalt”, Transportation Research Record 1681, pp.76-85, 1999	X			X			
M. Iwanski and M. Pabocha, “Water and frost resistance of gap-graded asphalt modified with the SBS polymer and hydrated lime”, Foundations of Civil and Environmental Engineering 11, pp.29-39, 2008 ( <a href="http://www.ikb.poznan.pl/fcee/2008.11/full/fcee_2008-11_029-039_water_and_frost_resistance_of_gap-graded.pdf">http://www.ikb.poznan.pl/fcee/2008.11/full/fcee_2008-11_029-039_water_and_frost_resistance_of_gap-graded.pdf</a> )	X		X				
P. Jaskula and J. Judycki, “Evaluation of effectiveness of hydrated lime additive in protecting asphalt concrete against water and frost”, Proc. 6 <sup>th</sup> Int. Conf. on Environmental Engineering, Vilnius, May 2005	X		X	X			X
P. Jaskula, “The effectiveness of hydrated lime as asphalt concrete additive”, Foundations of Civil and Environmental Engineering 10, pp.99-109, 2007 ( <a href="http://www.ikb.poznan.pl/fcee/2007.10/full/fcee_2007-10_099-109_the_effectiveness_of_hydrated_lime.pdf">http://www.ikb.poznan.pl/fcee/2007.10/full/fcee_2007-10_099-109_the_effectiveness_of_hydrated_lime.pdf</a> )	X		X	X			X
R. A. Jimenez, “Methods and treatments to control debonding”, Proc. Association Asphalt Paving Technologists 59, pp.94–137, 1990	X						X
L. S. Johansson, J. F. Branthaver and R. E. Robertson, “A study of rheological properties of lime treated paving asphalts aged at 60°C in a pressure aging vessel”, Fuel Science Technology Int. 13(10), pp.1317-1343, 1995		X				X	
<b>L. S. Johansson, J. F. Branthaver and R. E. Robertson, “The influence of metal-containing compounds on enhancement and inhibition of asphalt oxidation”, Fuel Science Technology Int. 14(8), pp.1143-1159, 1996</b>		X					
L. S. Johansson and U. Isacson, “Effect of filler on low temperature physical hardening of bitumen”, Construction Building Materials 12 pp.463-470, 1998						X	
L. S. Johansson, Bitumen ageing and hydrated lime, Ph. D Thesis, Royal Institute of Technology, Stockholm (Sweden); 1998		X				X	
<b>P. S. Kandhal and I. J. Rickards, “Premature failure of asphalt overlays from stripping: Case histories”, J. Association Asphalt Paving Technologists 70, pp.301-349, 2001</b>							X
<b>T. W. Kennedy, F. L. Roberts and K. W. Lee, “Evaluation of moisture susceptibility of asphalt mixtures using the Texas freeze-thaw pedestal test”, Proc. Association Asphalt Paving Technologists 51, pp.327–341, 1982</b>	X						
<b>T. W. Kennedy, N. Turnham, J. A. Epps, C. W. Smoot, F. M. Young, J. W. Button and C. D. Zeigler, “Evaluation of methods for field applications of lime to asphalt concrete mixtures”, Proc. Association Asphalt Paving Technologists 52, pp.508–534, 1983</b>	X						X
<b>T. W. Kennedy, Use of Hydrated Lime in Asphalt Paving Mixtures, National Lime Association Bulletin 325, 1984</b>	X						X

Reference	Md	Ag	Me	Ru	Fr	Ot	Fi
T. W. Kennedy and W. V. Ping, "An evaluation of effectiveness of antistripping additives in protecting asphalt mixtures from moisture damage", Proc. Association Asphalt Paving Technologists 60, pp.230-263, 1991	X						X
M. J. Khattak and V. Kyatham, "Viscoelastic behavior of hydrated lime-modified asphalt matrix and hot-mix asphalt under moisture damage conditions", Transportation Research Record 2057, pp.64-74, 2008			X		X		
O. K. Kim, C. A. Bell and R. G. Hicks, "The effect of moisture on the performance of asphalt mixtures", ASTM Special Technical Publication 899, Philadelphia (Pennsylvania, USA): American Society for Testing and Materials, pp.51-72, 1985	X			X	X		
<b>Y.-R. Kim, D. N. Little, I. Song, "Effect of mineral fillers on fatigue resistance and fundamental characteristics", Transportation Research Record 1832, pp.1-8, 2003</b>			X		X		
Y.-R. Kim and D. N. Little, "Linear viscoelastic analysis of asphalt mastics", J. Materials in Civil Engineering 16(2), pp.122-132, 2004						X	
Y.-R. Kim, J. Sudo Lutif, A. Bhasin and D. N. Little, "Evaluation of moisture damage mechanisms and effects of hydrated lime in asphalt mixtures through measurements of mixture component properties and performance testing", J. Materials Civil Engineering 20(10), pp.659-667, 2008	X			X		X	
<b>C. Kunesch und S. Neumann, "Kalkhydrat – Mischgut für das hochrangige Strassennetz", Gestrata Journal 126, pp.20-24, 2009 (<a href="http://www.gestrata.at/archiv/journal/Journal_126.pdf">http://www.gestrata.at/archiv/journal/Journal_126.pdf</a>)</b>							X
R. Lackner, M. Spiegl, R. Blab and J. Eberhardsteiner, "Is low-temperature creep of asphalt mastic independent of filler shape and mineralogy? Arguments from multiscale analysis", J. Materials in Civil Engineering 17(5), pp.485-491, 2005						X	
<b>D. Lesueur and D. N. Little, "Effect of hydrated lime on rheology, fracture and aging of bitumen", Transportation Research Record 1661, pp.93-105, 1999</b>						X	
<b>D. N. Little and J. A. Epps, The Benefits of Hydrated Lime in Hot Mix Asphalt, Arlington (Virginia, USA): National Lime Association, 2001 (<a href="http://www.lime.org/Abenefit.pdf">http://www.lime.org/Abenefit.pdf</a>)</b>	X	X	X	X	X	X	X
<b>D. N. Little and J. C. Petersen, "Unique effects of hydrated lime filler on the performance-related properties of asphalt cements: Physical and chemical interactions revisited, J. Materials in Civil Engineering 17(2), pp.207-218, 2005</b>		X		X	X	X	
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