INCREASING THE DURABILITY OF ASPHALT MIXTURES BY HYDRATED LIME ADDITION: WHAT MECHANISMS?

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ABSTRACT

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, when moisture damage and frost became some of the most pressing pavement failure modes of the time.

Given its extensive use in the past 40 years, hydrated lime has been seen to be more than a moisture damage additive: It reduces chemical ageing of the bitumen and stiffens the mastic more than normal mineral filler above room temperature. All these properties impact durability and hydrated lime is now seen has an additive to increase asphalt mixture durability.

This article is a literature review on the fundamentals of hydrated lime effect. The reasons why it is so effective lie in the strong interactions between aggregate and bitumen, and a 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 and roughness 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.

Keywords: asphalt mixtures, durability, hydrated lime, ageing, moisture damage

1 INTRODUCTION

Hydrated lime has been known as an additive for asphalt mixtures from their very beginning [1-3]. 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 [4] 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 [5].

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 [3,6-9]. Hydrated lime is known to reduce chemical ageing of the bitumen [3,6-8]. Furthermore, it stiffens the mastic more than normal mineral filler [3,6-8], an effect that is only observed above room temperature [3]. 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 [3]. 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 negative effect on the thermal cracking resistance is reported in the literature [3,6-8].

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. As detailed in a companion paper [10], the field experience from North American State agencies shows 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% [5].

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 [10]. 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 [11]. Similar observations led the Netherlands to specify hydrated lime in porous asphalt [12], 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.

This article reviews the reasons why hydrated lime is so effective in asphalt mixtures. In order to do so, we focus on the interactions between hydrated lime and the major components, i.e. aggregate and bitumen. As a result, the mechanisms of hydrated lime modification can be explained by a combination of 4 effects, two on the aggregate and two on the bitumen.

2 HYDRATED LIME: WHAT IS IT?

2.1 Hydrated Lime: Properties

Hydrated lime is mainly composed of calcium hydroxide $Ca(OH)_2$. It is obtained by hydrating quicklime (essentially calcium oxide CaO) using specific equipments. Quicklime is manufactured by burning limestone of very high purity (made of calcium carbonate $CaCO_3$) at temperatures around 900°C in dedicated kilns [13]. The same cycle can be performed on dolomite $CaCO_3/MgCO_3$, in order to obtain dolomitic lime (CaO/MgO) and then hydrated dolomitic lime ($Ca(OH)_2/Mg(OH)_2$).

Hydrated lime and quicklime for construction and civil engineering applications are specified within the European standard EN 459-1. The principal qualities of the various grades of hydrated products are summarized in Table 1. The grades are for calcium lime (CL) and the number identifies the purity in terms of mass content of CaO + MgO. The letter “S”, standing for “slaked”, identifies hydrated products in powder form.

As far as asphalt mixtures modification is concerned, standard calcic hydrated lime is the mostly used product. Still, hydrated dolomitic lime is also mentioned and was shown to behave in a similar manner [3]. Quicklime, on the opposite, was shown to be detrimental when used as a substitute for hydrated lime [14]. Still, some very specific applications use either quicklime or hydrated lime with porous aggregate (porous basalt, slag...) in order to prevent the so-called soup-phenomenon observed when the water from the aggregate emulsifies the bitumen during mixture transportation [15]. 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, we focus here on standard calcic hydrated lime.

Hydrated lime generally comes in the form of a dry white powder with a particle density close to 2.2Mg/m^3 [3]. Because of a high level of particle porosity (of order 50%), its apparent (bulk) density typically ranges from 0.3 to 0.8Mg/m^3 as measured by EN 459-2.

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

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

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. As a matter of fact, the European standards for hot-mix asphalt (series EN 13108-1 through -7) clearly say: *"filler includes materials as cement and hydrated lime"* (see note 1 in paragraph 4.3.4 of each of the standards). In this sense, hydrated lime can be evaluated using the specifications on aggregates for asphalt mixtures as detailed in EN 13043. More precisely, the relevant part of this standard for hydrated lime is the one dealing with fillers. The case of mixed filler (mixture of filler and hydrated lime) 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 - EN 1097-4) and delta Ring and Ball (EN 13179-1) are measured.

Evaluating the voids of the dry compacted filler consist in measuring the density of a compacted specimen of the studied filler and divide it by the particle density of the filler. Mineral fillers generally have Rigden voids ranging from 28 to 45% [16,17,18], 30-34% being the usual range for many fillers such as most limestone fillers. Hydrated lime has a lot higher Rigden value, generally between 60 and 70%, 65% being a common value [3]. Clearly, this property differentiates hydrated lime from other mineral fillers. Note that the low bulk density of hydrated lime also captures the high porosity of the product. When mixed fillers are concerned, i.e. blends of hydrated lime and mineral filler as defined in EN 13043, 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 [18,20].

The delta ring and ball test consists in measuring the increase in softening temperature of a 70/100 bitumen after addition of 37.5 vol.% of the studied filler. Mineral fillers typically have delta ring and balls between 8 and 25°C, 15°C being a common value [18,20]. As detailed in several studies [20,21], the test cannot be performed on pure hydrated lime. As a matter of fact, the stiffening power of hydrated lime is so pronounced that the 37.5 vol.% blend is not fluid enough to prepare the test specimen.

Still, lower amounts of hydrated lime than the one specified in the European standard allow quantifying the stiffening effect [18,20,21] as pictured in Figure 1. 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 [19,20]. Values for hydrated lime are typically in the 0.7-1.0 range, meaning that hydrated lime contents of 40-50wt.% (23-31vol.%) raise the Ring and Ball value by 20°C. Mineral fillers usually have values in the 1.5-2.5 range [18,19,20]. 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 [18].

Note that the volume fraction used in the standard test for delta Ring and Ball (i.e. 37.5vol.%) is not representative of the typical hydrated lime content in an asphalt mixture. As a matter of fact, typical hydrated lime content in an asphalt mixture is 1-1.5wt.% based on dry aggregate. For a typical binder content of 5wt.% (based on dry aggregate), this amounts to 20-30wt.% or 10-15vol.% hydrated lime in the bitumen.

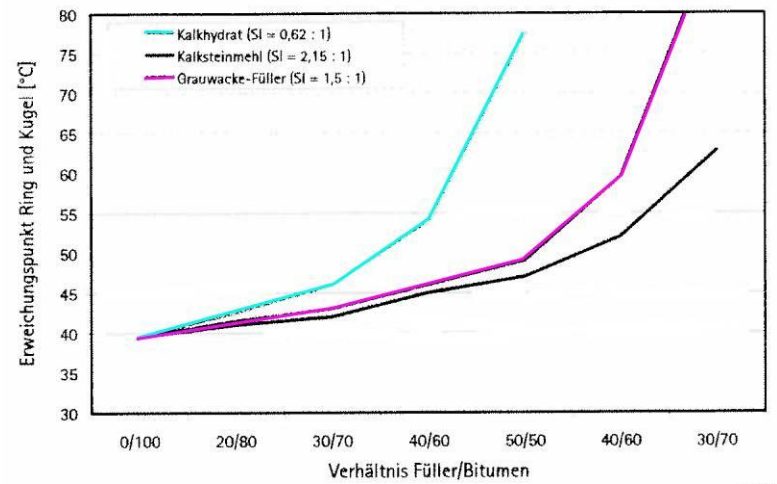

Figure 1: Ring and ball softening temperature of a 200 penetration grade bitumen as a function of filler weight content (expressed in filler/bitumen wt.%/wt.%) for hydrated lime (Kalkhydrat), limestone filler (Kalksteinmehl) and Grauwacke filler (from [19]).

Table 2: Typical properties of hydrated lime compared to mineral fillers.

Property	Method	Unit	Hydrated Lime	Mineral Filler
Particle Density	EN 1097-7	Mg/m^3	2.2	2.6-2.9
Voids in dry compacted filler	EN 1097-4	%	60-70	28-45
Delta ring and ball	EN 13179-1	°C	not measurable	8-25
Bitumen Number	EN 13179-2	-	70-120	40-50
Mass in Kerosene	EN 1097-3	Mg/m^3	0.3	0.5-0.9
Blaine Specific Surface	EN 196-6	cm^2/g	>10,000	7,000
Specific Surface Area	BET with nitrogen adsorption	cm^2/g	150,000-200,000	14,000-95,000
Methylene Blue Value	EN 933-9	g/kg	< 1	0-20

Other properties used to specify mineral fillers for asphalt are also listed in Table 2. It 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 2 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 confused with mineral fillers.

3 HYDRATED LIME IN ASPHALT MIXTURES

As already stated 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 [3]. 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. More precisely, hydrated lime is seen to improve [3,6-9]:

- 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.

It is not the purpose of this article to review the laboratory evidence concerning these effects. Interested readers shall consult the relevant literature where the benefits of hydrated lime on asphalt mixtures are clearly demonstrated with a diversity of materials (aggregate, bitumen, mixture formulas) covering the 5 continents ([3,6-9] and the more than 100 references therein). A thorough literature review is available on the European Lime Association (EuLA) website with a reference list classified by functionalities (www.eula.eu – [3]). Our concern here is to explain why hydrated lime is so effective in asphalt mixtures. In order to do so, we first consider the effects of hydrated lime on the aggregate and then consider the effects of hydrated lime on the bitumen.

3.1 Effect of Hydrated Lime on the Aggregate

Hydrated lime modifies the aggregate surface. Most of the US methods to add hydrated lime consist in putting it directly onto the wet aggregate, sometimes with marination [3,22]. This demonstrates that the surface modification of the aggregate is one key aspect of hydrated lime modification.

3.1.1 Surface Modification

It is well known in asphalt science that siliceous aggregates have worst adhesive properties toward bitumen than limestone aggregates [4,23]. 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 [24]. As a consequence, anionic surfactants are easily displaced by water on siliceous aggregates.

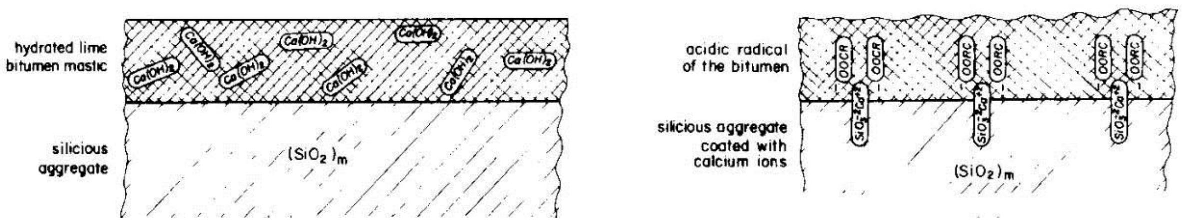

Figure 2: The effect of hydrated lime on the aggregate surface as proposed by I. Ishai and J. Craus (from [25]).

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 2 - [25,26]). As a consequence, a surface treatment with almost no remaining hydrated lime particles already improves the bitumen-aggregate adhesion [27].

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 [28]. This effect can be quite strong to the point that part of the hydrated lime is not recovered after bitumen extraction. 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 [29].

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 [30,31]. So, other mechanisms must operate, and especially those acting on the bitumen as described below.

3.1.2 Clay Flocculation

In the case of clayey aggregates, hydrated lime is known to be highly effective in improving the resistance to moisture damage. This is the reason why hydrated lime is used in such States as California, Colorado, Nevada or Utah which all have aggregates contaminated by large amounts of clays. More specifically, clays are generally present in the form of small inclusions inside the rock and are liberated upon crushing. In this case, the role of hydrated lime is similar as the one used for soil treatment [32]: lime flocculates the clay particles, preventing them to build a water-displaceable barrier between the bitumen and the aggregate. A German study with controlled clay contamination confirmed that hydrated lime efficiently counteracts the effect of clay [19,20].

3.2 Effect on the Bitumen

3.2.1 Chemical Interaction with the Bitumen

The chemical interaction between hydrated lime and bitumen was observed by H. Plancher et al. at Western Research Institute (WY, USA) as early as 1976 [33]. They took four bitumens that varied widely in chemical composition. They prepared 1:1:600 weight solutions of bitumen:hydrated lime: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 [33].

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 [34,35]. When comparing High Performance Gel Permeation Chromatography (HP-GPC) curves in toluene of the bitumens treated either with limestone filler or active filler (Figure 3), 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 [34,35].

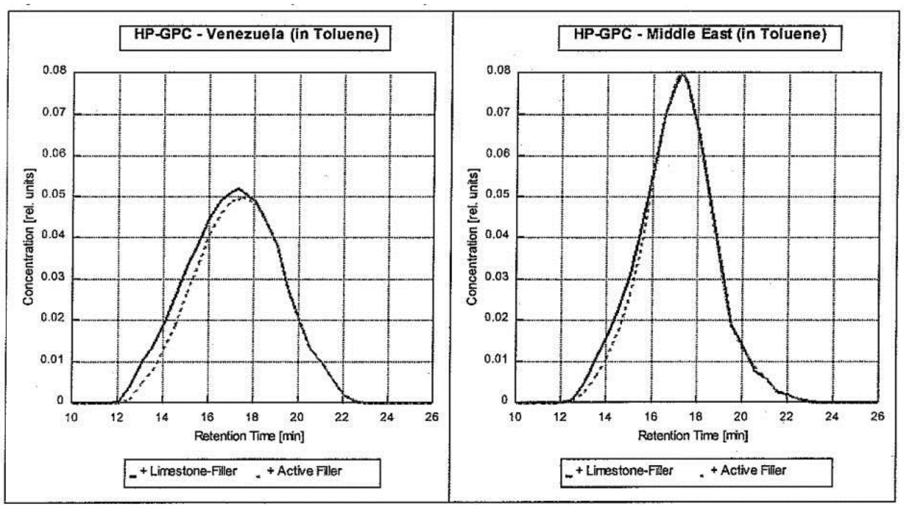

Figure 3: High Performance Gel Permeation Chromatography in toluene for two bitumens from Venezuela or Middle East after contact with either a limestone filler or the same filler with 25wt.% hydrated lime (active filler - from [35]).

Table 3: Concentration of functional groups in four AC-10 bitumens of different chemical composition before and after treatment by hydrated lime (from [33]).

	Concentration, Moles/Liter				
Asphalts	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

Information concerning the bitumen species adsorbed onto the hydrated lime surface can also be found in the literature. As reproduced in Table 3, the lime-treated materials in the study by H. Plancher et al. at Western Research Institute (WRI) in Laramie (Wyoming, USA - [33]) 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 [36] for a review of bitumen structure and chemistry). The ketones were however more numerous. Sulfoxides did not change significantly.

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 [37]. 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 (Figure 4). Note that the effect on bitumen ageing pictured in Figure 4 can not be ascribed to a rheological effect as a consequence of the presence of hydrated lime particles, because the ageing index was computed based on the mastic when hydrated lime was used, and was therefore taken into account. As reproduced in Table 4, the presence of hydrated lime essentially reduces the amount of ketones and most of all of carboxylic acids that form upon ageing.

Table 4: 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 [37]).

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

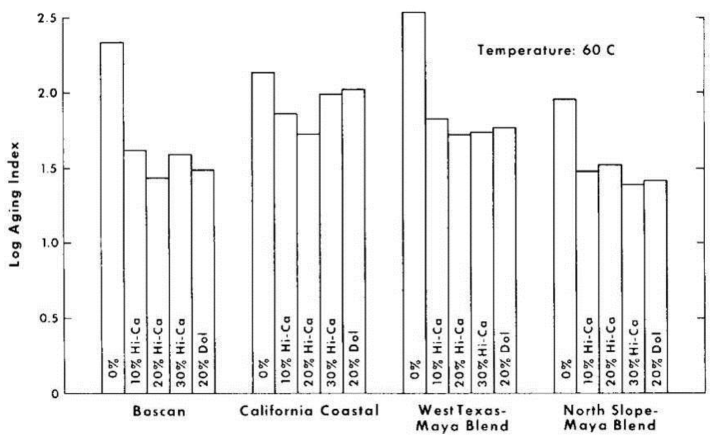

Figure 4: Aging index at 60°C (viscosity after ageing divided by the viscosity before) for various sources of bitumen modified with different weight proportions of hydrated lime (Hi-Ca) and hydrated dolomitic lime (Dol). Ageing was performed in the Thin Film Accelerated Aging Test (TFAAT) corresponding to 3 days at 113°C under air exchange (from [33]).

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 [8]. 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) et al. observed that the anti-ageing effect was not present with $Mg(OH)_2$, a weaker base than $Ca(OH)_2$ [38].
- M. Wisneski et al. at Texas A&M University observed that quicklime had the same anti-ageing effect as hydrated lime [39].

Still, the acid-base reactions are probably not sufficient to explain the whole chemical interactions at stakes. J. C. Petersen et al. at WRI proposed that hydrated lime acts as an inhibitor for the oxidation catalysers naturally present in the bitumen [33,37]. This was in part validated by L. Johansson (KTH) et al., 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 [38]. 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 [33,37,40,41].

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 [8,33,37]. 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 [23,28]. These other surfactants are typically amine-based [42] and are not easily displaced by water, unlike anionic surfactants [23,24]. 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 [43,44,45].

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

3.2.2 Physical Effect on the Bitumen

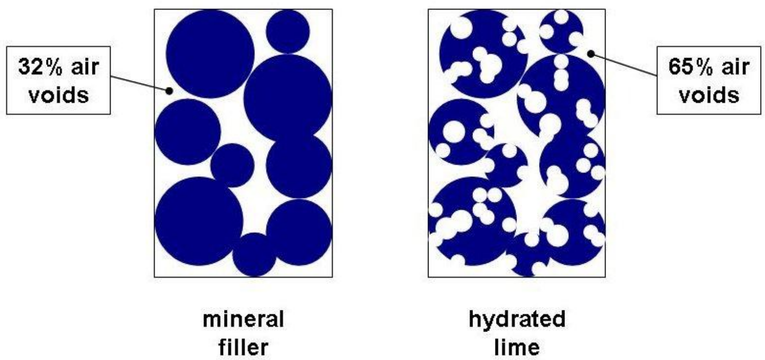

Figure 5: The dry porosity of hydrated lime (right) is higher than that of mineral filler (left) because the porosity inside the particles, which is negligible with mineral filler, sums up to the porosity between particles.

As described earlier, hydrated lime has higher voids of dry compacted filler (Rigden air voids) than mineral fillers, with typical values ranging from 60 to 70% when mineral fillers have values closer to 30-34%. The difference comes from the higher porosity of the hydrated lime particles (Figure 5): 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.

Rigden air voids correlates very well with the stiffening power as measured by the delta Ring and Ball, as illustrated in Figure 6 using data from a study performed by S. Vansteenkiste and A. Verstraeten at the Belgian Road Research Center [17], completed by data from the study by W. Grabowski et al. of Poznan University of Technology [18].

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. The stiffening effect of a porous material is well known in the rheology of suspensions and arises from an increased effective volume fraction of the particles as captured by a low maximum packing fraction (see [36] for a review of suspension rheology in the context of bituminous materials). In other words, the Rigden air voids is similar in concept (but not exactly numerically) to void in the maximum packing fraction.

Note that the build-up of the stiffening effect of hydrated lime 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 7 - [40]). The kinetics of this process might explain, at least partially, why the stiffening of hydrated lime is not always observed when asphalt mixtures are tested [3].

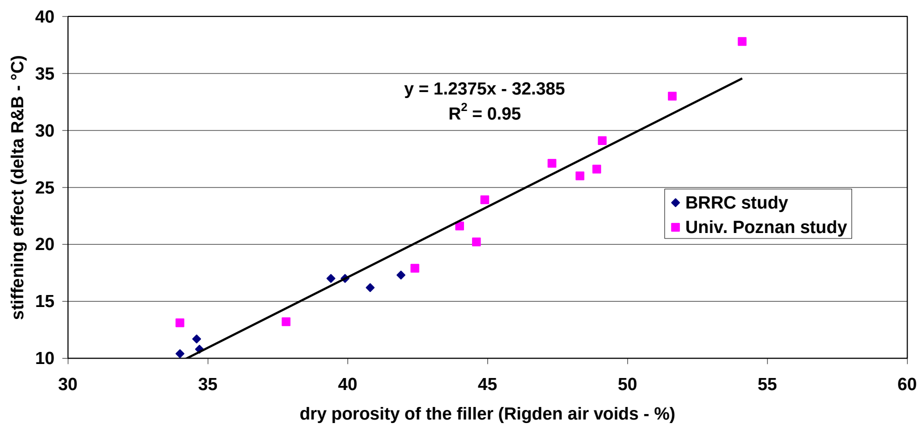

Figure 6: Correlation between the stiffening effect of several fillers with their dry porosity (Rigden air voids). The data are from two studies: one from the Belgian Road Research Center [17] and the other from Poznan University [18].

Still, the contribution of other factors must also be considered. Several papers mention the adsorption of some bitumen components onto the hydrated lime particles [8,41]. 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.

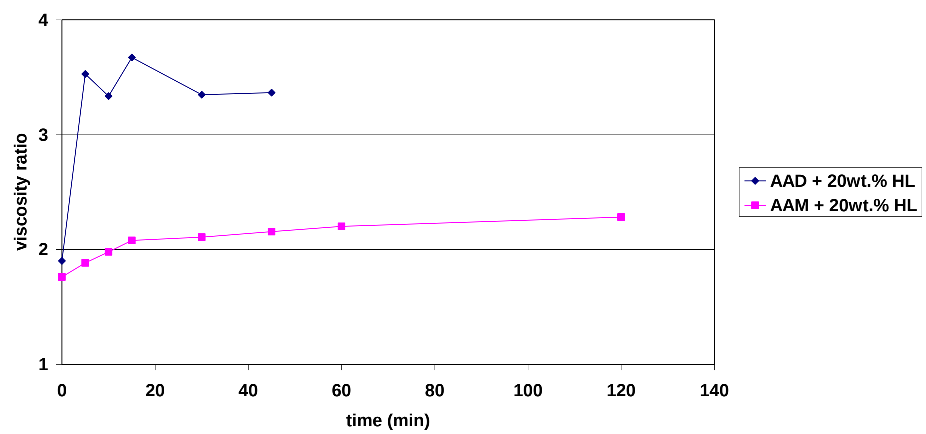

Figure 7: Kinetics of viscosity build-up at 138°C for two bitumens modified with 20% hydrated lime. The viscosity stabilizes quickly for AAD when it keeps increasing after 120min for AAM. The neat bitumen did not show any significant viscosity change in the mean time (after [41]).

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, the high stiffening effect observed with hydrated lime at high temperature disappears below room temperature. This was first observed for 3 different bitumens by J. P. Wortelboer et al. in a joint-study between ESHA (Groningen, The Netherlands) and the French Central Laboratory of Roads and Bridges (LCPC - Figure 8 - [46]). Later studies confirmed 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 [8,35,41,47,48]. This was further evidenced in low temperature studies showing that hydrated lime is similar to other mineral fillers in terms of stiffening effect at low temperature [49,50].

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.

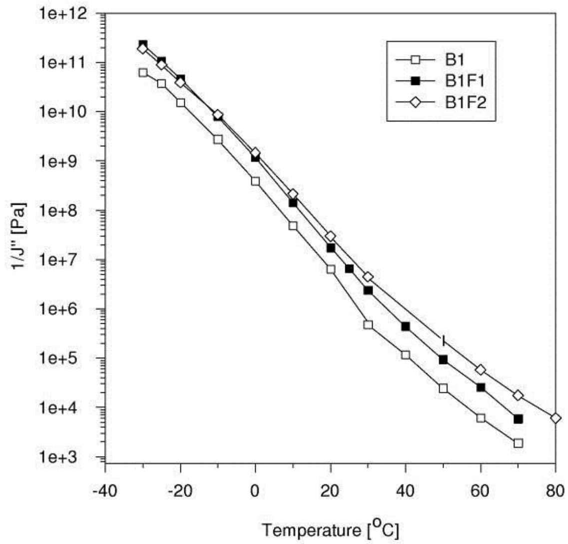

Figure 8: Temperature dependence of the stiffening effect of hydrated lime as compared to limestone filler: inverse of the imaginary compliance (1/J") at 10 rad/s versus temperature for a 70/100 bitumen (B1) and the same bitumen with 50wt.% of limestone filler (B1F1) or mixed limestone filler containing 40% hydrated lime (from [46]).

4 CONCLUSIONS

Over the past 40 years, hydrated lime has become one key additive for asphalt mixtures, with a strong presence in the USA and a growing use in Europe [3]. It is now seen as a multifunctional additive that increases the durability of asphalt mixes through its improvement of [3,6-9]:

- 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.

The way hydrated lime develops its benefits in asphalt mixtures can be separated into different mechanism:

- Aggregate modification, which includes surface precipitation of calcium ions and clay flocculation
- Bitumen modification, which includes an acid-base neutralization of the acidic moieties of bitumen by the (basic) hydrated lime and a physical effect due to its high porosity.

The modification of the surface properties of aggregate explains an improved bitumen-aggregate adhesion. However, the chemical effect on the bitumen also participates in the improvement of the adhesive properties, by neutralizing the "bad" adhesion promoters originally present inside the bitumen.

Then, the chemical effect also results in the slowing down of the age hardening kinetics, enhancing the moisture resistance of the mixture.

Finally, the physical effect on the bitumen, arising from the high porosity of hydrated lime, explains a stronger stiffening effect on bitumen than mineral fillers above room temperature.

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.

Finally, some theoretical aspects remain to be better 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.

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