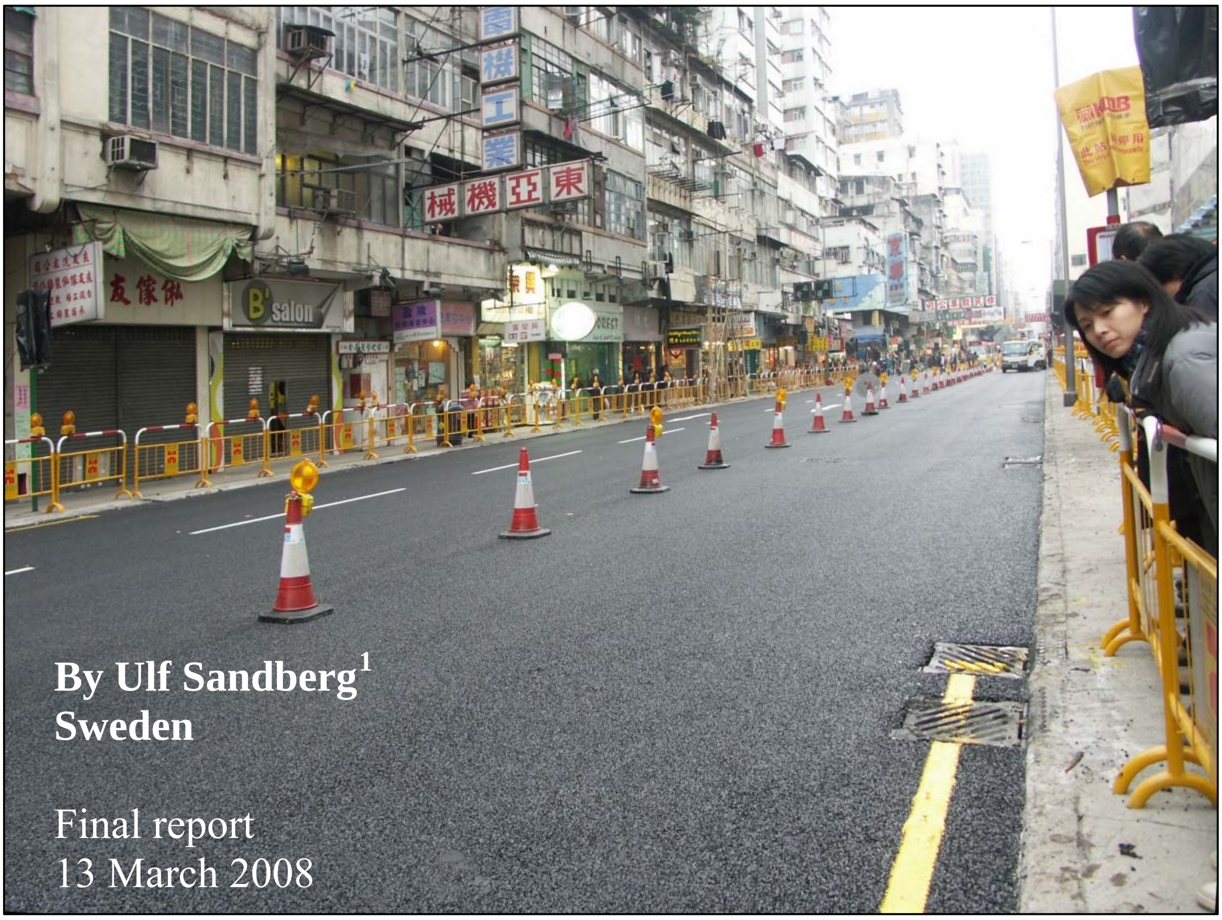
Review and evaluation of the low-noise road surface programme for low-speed roads in Hong Kong



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"Reviewing the Trial of Low Noise Road Surface (LNRS) in Hong Kong and Benchmarking the Experience on the Use of LNRS in Overseas Countries"

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SUMMARY

In Hong Kong, trials to use low-noise road surfaces (LNRS) started in 1987 and a programme for resurfacing high-speed roads with such material has been in force since the early 1990's. Nowadays the use of LNRS on high-speed roads in noise-exposed areas is common practice, given certain traffic and road conditions. In 2002 a new programme started aiming at trying such surfaces also on medium- and low-speed roads and streets in urban areas. In 2006, the Environmental Protection Department (EPD) of Hong Kong published a "Comprehensive Plan to Tackle Road Traffic Noise in Hong Kong". An important part of this plan is an increased and widened use of low-noise road surfaces (LNRS) on low-speed roads and streets. In order to evaluate the LNRS programme, to review international experience and to obtain ideas and proposals for making the use of LNRS more efficient in the future it was decided to sponsor a project in which international expertise would be engaged to conduct the review and evaluations. After a tendering procedure, the author was selected to conduct this project. The project results are presented in two reports, of which this is the first one.

The purpose of the work reported herein is to review the results of trials of low noise road surface (LNRS) materials being carried out at about 30 road sections in Hong Kong on noise reduction and durability aspects and to propose the possible way forward on trials of LNRS materials in Hong Kong.

Due to the uniqueness of the Hong Kong trials, it was not easy to find relevant information and experiences overseas which are directly applicable and useful to Hong Kong, with its hot climate, topography, dense population, high-rise buildings and intensive bus traffic.

This report, and especially its sister report "The Benchmark Report" (under production), attempt to collect, compile and analyze the most relevant information and experiences overseas, which is useful for and applicable to the Hong Kong situation. However, for the evaluation and conclusions, the results and experiences of the trials made and still ongoing in Hong Kong are the most important ones.

The evaluation of the LNRS trial programme at this time suggests that it has been both successful and not successful; indicating that the risks of failures have been well balanced against the opportunities of progress.

In the evaluated part of the LNRS trial programme so far, the only type of LNRS tried is the polymer-modified friction course (PMFC), which in Europe would be called (polymer-modified) single-layer porous asphalt.

The trials have been essentially successful since they have indicated that LNRS may reduce noise emission by about 2 dB(A) in comparison to the conventional paving materials used in Hong Kong and seen as an average over two years, without any major problems with technical durability. The loss of noise reduction with time has been only about 0.3 dB(A) over the two-year studied period. In some cases one may even achieve about 4 dB(A) of noise reduction. The potential noise reduction was found to be about 1.7 dB higher for low proportions of heavy vehicles than for high proportions, and about 1.4 dB higher at speeds in the range 50-55 km/h than at speeds in the 20-25 km/h range

In a long-term perspective, the noise reduction potential is greater since the development towards quieter power units of vehicles will make the LNRS more effective with time. The lessons from the trials will also make future application of LNRS more effective and less costly.

There are also unsuccessful parts of the trial programme; for example poor noise reduction (or none at all) for some test sections. The risk of obtaining poor noise reduction increases with the proportion of heavy vehicles in the traffic and inversely with the average vehicle speed. From this one can learn how to apply the LNRS on road sections in the future where they are more effective and avoid using them on sections where they are ineffective.

The main subject of this report is the application of LNRS on low-speed roads. However, an outlook at the situation on high-speed roads is made. It is found that the low noise surfaces have performed well on high-speed roads in Hong Kong. However, it is also noted that it seems possible to improve them in such applications, since the noise reduction which can be credited to the porosity is not as high as have been obtained internationally, when considering that the surfaces they replace mostly are relatively "noisy" ones. The reasons for this is that the PMFC used are not of optimum construction in accordance with international experience. Suggestions are made on how the high-speed low noise road surface policy can be improved.

The methodology in parts of the test programme has some serious flaws, which could have been avoided if the level of knowledge had been higher at the start of the programme. The design of the trial programme could also have been better; most importantly by testing not only the PMFC type of LNRS but also including a number of other potential low-noise road surface types, and even including a few conventional wearing courses. But the latter flaws are still possible to correct in the still on-going part of the trial programme.

By learning from the results and experiences so far, the author thinks that the 2 dB(A) of average noise reduction obtained for the first 21 sections analyzed here, can become 3-4 dB(A) of average noise reduction in a future regular application of LNRS on Hong Kong low-speed roads. This would correspond to an effect similar to cutting traffic volume by 50 % and as such be an improvement which is extremely difficult to achieve in other ways. In addition, a wide application of "semi-low-noise road surfaces"; i.e., road surfaces which reduce noise only by 0-2 dB(A), but with only a small cost increase in comparison to the traditional paving policy, one may achieve further improvement of the acoustical quality of life in Hong Kong. The author thinks that the latter is possible in the near future after trying so-called thin layers on a wide scale. Even conventional SMA surfaces which are known to be durable may have such an effect in comparison to the traditional paving materials used in Hong Kong.

When estimating the advantages and disadvantages of the LNRS, one shall not forget other effects than reduced noise. This includes lower rolling resistance (which will occur at least when old concrete pavements are re-surfaced), which will reduce fuel consumption and CO_2 emissions, but it also includes improved skid resistance which may reduce accidents. Two very important advantages of the PMFC type of LNRS is the water storage capacity of such pavements, which reduces the need for high-capacity subsurface drainage systems, and the reduced heat island effect caused by the porous structure and water-retaining capacity of PMFC. When such effects are counted in terms of saved dollars and saved tons of CO_2 emissions, one may find that using PMFC is a win-win situation. Other advantages include less splash and spray and better anti-glare characteristics and in some cases also less emission of particulates; the latter being a serious health effect in many large cities.

The report contains a very comprehensive chapter with recommendations. These deal with the methodology and design of the trial programme, but most of all with possibilities to improve the low-noise road surfaces and their application. Further, recommendations for new research and experiments are given, which may improve the efficiency of LNRS in the future. One of the most important parts of the recommendations chapter is a comprehensive proposal for a new policy for the use of low-noise road surfaces in Hong Kong.

It is hoped that this report will aid the Hong Kong environment and highway authorities in implementation of a more effective low-noise road surface policy in the future.

ACKNOWLEDGEMENTS

This work has been conducted as part of the project "Reviewing the Trial of Low Noise Road Surface (LNRS) in Hong Kong and Benchmarking the Experience on the Use of LNRS in Overseas Countries" (No. AN 06-004) for the Hong Kong Environmental Protection Department (EPD).

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The author is Senior Research Scientist at the Swedish Road and Transport Research Institute (VTI), in Linköping, Sweden, and also Adjunct Professor at Chalmers University of Technology, Division of Applied Acoustics, in Gothenburg, Sweden. However, this project was conducted independently by the author by special agreements. Nevertheless, the author is grateful to VTI and Chalmers for making this work possible.

1. INTRODUCTION

In Hong Kong trials to use low-noise road surfaces (LNRS) started in 1987 and a programme for resurfacing high-speed roads with such material has been in force since the early 1990's. Nowadays the use of LNRS on high-speed roads in noise-exposed areas is common practice, given certain traffic and road conditions. In 2002 a new programme started aiming at trying such surfaces also on medium- and low-speed roads and streets in urban areas. In 2006, the Environmental Protection Department (EPD) of Hong Kong published a "Comprehensive Plan to Tackle Road Traffic Noise in Hong Kong" [EPD Plan, 2006]. An important part of this plan is an increased and widened use of low-noise road surfaces (LNRS) on low-speed roads and streets. In order to evaluate the LNRS programme, to review international experience and to obtain ideas and proposals for making the use of LNRS more efficient in the future it was decided to sponsor a project in which international expertise would be engaged to conduct the review and evaluations. After a tendering procedure, the author was selected to conduct this project. The project results are presented in two reports, of which this is the first one.

2. PURPOSE

The purpose of the work reported herein is to review the results of trials of low noise road surface (LNRS) materials being carried out at about 30 road sections in Hong Kong on noise reduction and durability aspects and to propose the possible way forward on trials of LNRS materials in Hong Kong.

3. METHODS USED IN THIS STUDY

This study has been conducted in the following ways:

- Review of documents from Hong Kong describing road construction technology and policy
- Review of test site descriptions and test surface descriptions obtained from Hong Kong
- Discussions with experts at the Highways Department (HyD) and the Environmental Protection Department (EPD)
- Seminar in Hong Kong in October 2006 with participation by EPD and HyD
- Meeting in Hong Kong with experts from EPD and HyD in October 2006
- Study on-site at several of the test sections (selection of sections made by the EPD), at three occasions: February 2005, October 2006, December 2006
- Some supplementing information was gained at a visit in December 2007
- Communication by e-mail
- Discussion of some issues with road surface experts at the Swedish Road and Transport Research Institute (VTI)
- Study visit to quarry and asphalt lab in Hong Kong
- The author has collected more than a thousand photos from the various test sections

4. ROAD SURFACES USED FOR REDUCTION OF ROAD TRAFFIC NOISE

4.1 General overview

4.1.1 The role of the road surface

The role of the road surface is to provide a safe, economic, efficient, comfortable and environmentally friendly drive of the vehicles travelling on it and also to be economic and environmentally friendly when being constructed. Therefore, a number of surface characteristics must be favourable, such as skid resistance (both in dry and in wet weather), tyre wear, surface wear, durability, visual guidance, drainage, splash and spray generation, emission of particulates, rolling resistance and noise generation. It follows that the parameter of particular interest in this report, i.e. noise characteristics, is just one of many parameters to observe in the design and construction process.

In many situations the effect of the surface on noise emission is very important. The difference in road traffic noise for a range of road surfaces, given the same traffic and speed, may amount to as much as 10-15 dB(A) in rare cases and 5-8 dB in common cases. This can be compared with the noise reduction of a noise barrier, which in the most favourable cases (covered roads excluded) may amount to around 15 dB(A) but as an average may be around 8 dB(A) behind the barrier as seen from the road.

Due to the topography and the large number of high-rise residential buildings in Hong Kong, noise barriers are effective only in few cases; unless they are constructed to cover a substantial part of the road width. Low-noise road surfaces may be effective in many cases where noise barriers fail and in any case might be a good supplement to noise barriers. Therefore, Hong Kong has embarked on a way to repave substantial parts of its road network with surfaces providing a noise reduction compared to the regular surface materials used.

It must be pointed out that as far as we know, the road surface itself does not generate noise[2]. Therefore, in a physical sense, it cannot be "noisy". On the contrary, any road surface is always quiet. It is the tyre which emits noise when running on the road surface. Even the tyre is absolutely quiet when it does not roll. However, since the noise is generated in a tyre/road interaction process, and this noise is much influenced by the surface characteristics, it is common practice to speak about "noisy", "quiet", or "low-noise" surfaces, meaning that it is the traffic travelling on this road surface which may be "quiet" or "noisy", as affected by the road surface.

The following sections intend to give as an introduction a brief overview of both "noisy" and "quiet" road surfaces in rather general terms.

[2] One should also be aware of that "noise" is defined as "unwanted sound" and as such is not a physical parameter; instead it is a subjective parameter. However, it has become common practice in environmental engineering to use the term "noise" as a synonym for "sound" with the implication that this type of sound is unwanted by most people. Therefore, the term "noise" is used in this report to represent the physical parameter sound, where it is understood that the sound is unwanted.

4.1.2 Road surfaces to be avoided

First it should be mentioned what kind of surfaces that one should avoid because of their noise characteristics. Some of them are actually among the most popular ones; mostly for durability and safety reasons. The following surfaces should be avoided; listed from the worst to the more moderate ones:

- **Paving stones:** Paving stones of the old types create of lot of tyre/road noise. They are justified mainly for historical and/or cultural reasons, and often on streets where there should be little traffic. The author has not seen any surfaces of this kind in Hong Kong, but they are frequent in old towns in Europe.
- **Transversely tined cement concrete (TTCC):** Cement concrete surfaces with transverse tines produced by dragging steel tines in a comb-like structure in the non-cured concrete are second in noise emission only to old types of paving stones. If the spacing between tines is not randomized, such a surface may create a whistling and extremely annoying tonal noise. Randomized tine spacing will not reduce the noise level but will reduce annoyance to some extent. Although the noise problem has been widely recognized since the early 1970's, these pavements are still used extensively in the USA but have been abandoned in Europe for noise reasons. The brushed concrete (see below) frequently used in Hong Kong, looks similar to a tined surface but may not be as "rough" as is often the case in USA.
- **Brushed cement concrete (BRCC):** Instead of using steel tines one can use a softer material (a "brush") to brush the concrete transversely to the driving direction while the surface is still uncured. Depending on the brush material and exact brushing technique used, these surface may range in noise characteristics from being equal to the noisiest SMA:s up to the "noisiness" of the TTCC. The BRCC was used in Hong Kong as the traditional paving material on high-volume roads and streets, but is not used any longer in new constructions.
- **Hot rolled asphalt (HRA):** The HRA has been widely used in the UK, but is now being phased-out due to noise reasons. A revision of the U.K. traffic noise prediction method, the CRTN, specifies a difference between HRA and SMA as large as 4-5 dB[3] for high-speed highways and motorways [Abbot & Nelson, 2001].
- **Surface dressing with large chippings:** Surface dressings (chip seals) are unfavourable if maximum chipping sizes are above about 11 mm. These were very popular in Europe on low-volume roads in the 1970's, not the least in Sweden, but are nowadays rarely used on roads where traffic noise is a significant problem.
- **Very smooth surfaces:** Surfaces, in particular cement concrete, with a very smooth macrotexture are "noisy". These should be avoided, anyway, for safety reasons.
- **SMA and DAC with large chippings:** Stone mastic asphalt (SMA) or dense asphalt concrete (DAC) with maximum chipping sizes in the range above about 13 mm. These are dominating on roads in the Scandinavian countries since they are highly resistant to the studs used on tyres in wintertime.

[3] A change of 10 dB in noise level is generally considered to correspond to a doubling or halving of the subjective perception; although some experts argue that even a 3-5 dB change may have such effects under certain conditions.

4.1.3 Low noise road surfaces

The following surface types are useful for reduction of traffic noise (in order from moderate to the best):

- **Diamond grinding:** For existing cement concrete surfaces, be they transversely tined or very smooth-textured, diamond grinding which creates narrow longitudinal grooves is a useful measure. Durability is fine, except if studs are used on tyres in wintertime. Potential noise reduction: 1-2 dB in relation to a dense asphalt concrete, 3-5 dB in relation to a tined cement concrete.
- **Exposed aggregate cement concrete (EACC):** An alternative solution, for a new cement concrete, is to use the exposed aggregate technique, provided a maximum aggregate size of 8 mm is used. Swedish experience with this (e.g. wet friction, durability and noise) is very positive. On roads for medium and low speeds, this author would recommend a maximum aggregate size of 5 or 6 mm. Potential noise reduction (for 8 mm): 1-2 dB in relation to a dense asphalt concrete[4], 3-5 dB in relation to a tined cement concrete.
- **Small-aggregate surface dressings:** An alternative measure at medium and low speeds, either on a smooth cement concrete or a smooth asphalt surface, is to lay a surface dressing (chip seal) which has very small chippings (preferably in the range 1-5 mm). There are several proprietary methods of this type, such as Shellgrip, Epoxygrip and Italgrip, many of which have the major object of increasing friction. For example, the Wisconsin DoT recently presented excellent improvements in accident rates in a trial with Italgrip [Hitec, 2004]. If, and only if, such surfaces are laid on a very smooth base without becoming depressed, they may almost compete with porous surfaces in terms of noise reduction. Potential noise reduction: 1-5 dB in relation to a dense asphalt concrete or SMA 0/11.
- **Thin surfacings:** There is now a multitude of thin surfacings offered on the market; most of which have good acoustic characteristics. In the EU projects SILVIA[5] and SILENCE[6] such surfaces have appeared to reduce noise by 3-6 dB in new or fairly new condition in comparison to dense asphalt concrete with medium aggregate size [Bendtsen & Andersen, 2005]. Improved concepts were recently proposed by a Danish road contractor [NCC, 2005] and this is just one of many examples. Part of these favourable values is due to a moderate porosity in new condition, part is due to macrotexture being optimized for low noise. What the performance is when they become older is not yet sufficiently tested, but it is clear that they will gradually become noisier with time, almost like porous surfaces. Thin surfacings are most useful on low- or medium-speed roads and streets, presently being widely applied in for example the UK, France and the Netherlands, but some of them may also be used on motorways. Potential noise reduction: 3-6 dB in relation to a dense asphalt concrete when new, gradually reduced with time.
- **Asphalt rubber friction course (ARFC):** In Arizona, and also in California, Texas and some other US states with warm climate (but also in Portugal and Japan), adding a large proportion of rubber particles obtained from recycled tyre rubber to the binder and applying a very high content of binder to a dense asphalt mix has been reported to give excellent noise, friction and durability properties. There are two variants: one with a low air voids content ("gap-graded") and another one with a high air voids content ("open-graded"). A pilot program in the US is underway to evaluate these surfaces for a possible

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[4]The reference here is a mix of dense asphalt concrete (DAC) and SMA with max. 11 mm chippings

[5] See http://www.trl.co.uk/silvia/

[6] See http://www.silence-ip.org

wider use [Anon., 2005]; although they have been in successful use already quite a long time and on a large scale in the Phoenix valley in Arizona [Donavan et al, 2005]. Potential noise reduction: 2-5 dB in relation to a dense asphalt concrete, 8-12 dB in relation to a tined cement concrete. The noise reduction effect seems to deteriorate somewhat with time [Donavan et al, 2005]. Recent research in Sweden has shown that the noise reduction is not primarily due to the rubber, the rubber inclusion has a marginal effect.

- **Single-layer porous surfaces:** This is the “traditional” low noise road surface, being tested for noise purposes since the late 1970’s, the first report on this by the author was published in 1979. Noise reduction in new condition is excellent provided the air voids exceed about 20 % and thickness exceeds about 40 mm, see Fig. 9. However, the problem is the reduced efficiency due to clogging. The pores are “self-cleaned” in the wheel tracks for high-speed traffic in wet conditions. Potential noise reduction: 1-7 dB in relation to a dense asphalt concrete, diminishing by about 1 dB per year; but faster on low-speed roads. Some road authorities consider this surface type as approximately 50 % more expensive as conventional dense asphalt surfaces over a life-cycle. In Japan and the Netherlands this surface type is very widely applied. In Hong Kong, the commonly used variant is called Polymer Modified Friction Course (PMFC).

- **Double-layer porous surfaces:** By putting a second porous layer with smaller chippings on top of a first porous layer with large chippings the acoustic efficiency is increased further. These surfaces are currently under trial in several countries; most of all in the Netherlands. For example, an ongoing motorway trial in Sweden has indicated excellent performance during the first three years of operation, which is remarkable in the Swedish climate. Yet, the maximum chipping size in the Swedish top layer is 11 mm; whereas many countries make attempts with much smaller chippings, such as a maximum aggregate of 4 mm. A Danish experiment on a 50 km/h city street has also been very favourable for one of the three tested variants; namely the one with the largest chippings [Bendtsen et al, 2005a]. A German experiment has indicated that it is in principle possible to obtain very favourable effects also with porous double-layer cement concrete [Sliwa, 2005], although those attempts so far have stumbled over problems with friction, which are believed to be possible to solve by further research. Part of the favourable acoustic effect comes from the increased thickness by applying two layers, part of it from the combination of narrow and wide pores in the layers. The unfavourable side is the high cost of this surface type; it is substantially more expensive than the single-layer surface. A recent state-of-the-art paper gives more information [Goubert et al, 2005]. Potential noise reduction: 4-8 dB in relation to a dense asphalt concrete. As far as this author is aware, the double-layer technique has been tried in Hong Kong only once, namely as "Material D" listed in [Ng & Tse, 2005].

Finally, it shall be stressed that different road surfaces change characteristics with time and wear in different ways. It means that a surface which is very good in new condition might be poor after a few years of operation. One shall, therefore, study the noise characteristics over the lifecycle of the surface.

4.2 Road surfaces commonly used in Hong Kong

The author has not managed to get any road surface statistics for Hong Kong, but the impression from several visits in 2005-2007 is as follows.

A dominant surface type on the high-volume network and on city streets a couple of decades ago seems to have been cement concrete, with a transversely brushed macrotexture to increase skid resistance. The macrotexture was shaped by a broom of steel tines that was swept across the surface before curing. The designation BRCC is used here. The author thinks that its texture looks more like the US tined concrete than the European brushed concrete. This type of surface is being phased out, which more or less seems to be completed already on high-speed roads, but there is still a considerable length of cement concrete surfaces on city streets. The slabs are rather short, length not known, and the joints are in many cases in poor condition. The BRCC surfaces are generally considered to be quite "noisy" surfaces. The author estimates that these surfaces on the average would be 2-3 dB(A) "noisier" than a DAC 0/11, see also [Roovers & Doorschot, 2005]. Figs. 1-2 show illustrations of such surfaces.

Fig. 1. Illustrations of a common brushed cement concrete (BRCC) surface on city street (Junction Road) often being the type of surface on which a PMFC is laid.

Probably the most common surface (by lane length) is dense asphalt concrete (DAC) with 20 mm maximum aggregate size. The author uses the designation DAC 0/20. There are also some roads with 10 mm aggregate size, DAC 0/10. The former would normally be 2-3 dB(A) noisier than the DAC 0/10, according to a model practiced by the author (see below). However, the DAC surfaces in Hong Kong are different from the ones in Europe. The author has not seen grading curves, but from visual observations of paved surfaces the Hong Kong DAC in general has a much smoother texture than expected from a 20 mm max aggregate size. The texture depth (by the volumetric patch method) is usually 0.3-0.4 mm, which would normally not be accepted in Europe because of too poor wet skid resistance. The author has seen also DAC surfaces with a "normal" macrotexture; i.e. around 0.5-0.6 mm; so the range of DAC surfaces in Hong Kong is extremely large. An example of extremely low macrotexture appeared as the EcoPark reference surface (see later in this report) where texture depth was measured at 0.2 mm [Road Research Group, 2007], and where the surface looked like an industrial hall floor.

Such smooth-textured surfaces (texture depth below 0.4 mm) are normally not included in tyre/road or traffic noise studies in Europe, Japan or USA, since they are considered as non-acceptable, but according to some basic research studies they should be relatively "noisy" due to the poor drainage and creation of substantial "air pumping noise" [Sandberg & Ejsmont, 2002]. This and the lack of Hong Kong studies on such pavements makes it very difficult to evaluate the Hong Kong LNRS trial sections.

A number of experiments have been made recently with SMA surfaces, based on the (incorrect) rumour that such surfaces would be substantially quieter than DAC surfaces. However, the total length of SMA surfaces in Hong Kong is probably not yet significant. The grading would normally be max 10 mm, thus the designation would be SMA 0/10, but also 20 mm max aggregate size has been used. The author's model estimates an SMA to be 0.6 dB(A) noisier than a DAC with similar maximum aggregate.

Fig. 2. Close-up of brushed cement concrete slabs. This is sometimes the type of surface being repaved with PMFC to reduce noise (Lomond Road intersection).

The PMFC surfaces are rapidly increasing in length and are now covering a considerable length of the high-speed roads. It is now the standard surface for use in resurfacing on high-speed roads, given certain traffic and road conditions, see Chapter 7. By 1999, 11 km of high-speed roads had a PMFC material. Starting in 2002, a number of local roads/streets have also been resurfaced with PMFC, the total length unknown. By February 2006, 25 out of 72 suitable streets had been resurfaced in this way. If each case would be 200 m long (an estimate by this author), this would mean 5 km of local streets, but rapidly increasing until the programme is expected to be finished in 2010 [EPD Plan, 2006]. The PMFC normally has a maximum aggregate size of 10 mm ("PMFC 10"), but 20 mm sections ("PMFC 20") have been tried too. Thickness is normally 30 mm, but 50 mm has been tried too. The target air voids (new) is 20 %. The PMFC is normally pre-blended. There is also a variant without the polymer modification of the binder, which is not used any longer.

Finally, it is common to see a special kind of "anti-skid" surface laid on a cement concrete surface; in particular at intersections or at sharp bends or grades where friction may be a critical factor. It is a surface dressing with a very small aggregate of calcined bauxite from Guyana bound with epoxy resin onto the concrete. It is a proprietary material called "Sho-Bond non-skid paving material" laid manually. Recently, other types of binder have been used in lieu of the epoxy as there have been some concerns with excessive cracking of the epoxy base. The thickness of the completed dressing shall be 4-6 mm which will indirectly require an aggregate which is between 1.4 mm and 4.75 mm[7]. This surface should be a relatively quiet surface provided the chippings could be laid close together and in a uniform way (which is not always the case). The laying process could be improved. Figs. 3-4 illustrate this type of surface.

As will be discussed further below, the number of aggregate gradings is limited in Hong Kong. It is common practice to use the 5, 10 and 20 mm sieves, which means that the maximum aggregate size will normally be 10 mm, but with a smaller amount of 5 and 20 mm material also being laid.

Fig. 3. Sho-bond surface dressing laid on cement concrete slabs (Lai Chi Kok Road).

[7] US standard sieve size # 4

Fig. 4. Sho-bond surface dressing laid on BRCC slabs; close-up of surface with some damages (Lai Chi Kok Road). The underlying BRCC texture is seen in the lower right corner.

4.3 How do Hong Kong LNRS compare to international state-of-the-art LNRS?

The PMFC normally has the following main noise-influencing features:

Thickness: 30 mm
Target air voids (new): 20 %
Max. aggregate size: 10 mm

As is shown below, these three parameters are the determining factors for a PAC in new condition. Thickness and air voids should be as high as possible, aggregate size as small as possible.

Internationally, the above data are not "impressive"; i.e. the noise reduction of such a surface will not be among the good examples on an international state-of-the-art level. For example, in the Danish city street experiment, running 1999-2006, which was rather successful, the best surface over the lifetime (which was a double-layer PAC with SBS-modified binder) had the following data:

Thickness: 70 mm
Target air voids (new): 25 %
Max. aggregate size (top layer): 8 mm

The noise reduction measured as SPB Index ranged from 5 dB(A) in new condition to 1 dB after 6 years in comparison to a DAC 0/11 of similar age [Ellebjerg et al, 2008]. Nominally, these reductions are similar to the ones recorded in Hong Kong [Ng & Tse, 2005] but the reference surface is much quieter so the Danish results are significantly better.

In the Swedish experiments currently running, a double-layer PAC presently applied on two motorways and a number of smaller highways, has the following main data:

Thickness: 80 mm
Target air voids (new): 25 %
Max. aggregate size (top layer): 11 mm

The noise reduction measured as SPB Index was 7-8 dB(A) initially, reduced to about half after 3 years, compared to a reference of SMA 0/16, the latter of which is probably somewhat quieter than the Hong Kong cement concrete reference surface.

A single-layer PAC used in Sweden, somewhat similar to the Hong Kong PMFC has the following main data:

Thickness: 50 mm
Target air voids (new): 25 %
Max. aggregate size: 16 mm

In Germany it is common to use on high-speed roads the following single-layer porous surface:

Thickness: 45 mm
Target air voids (new): 22-28 %
Max. aggregate size: 8 mm

It seems to this author is if the German surface could be the presently most effective single-layer porous asphalt (see the Benchmark report). Compared to this one, the Hong Kong PMFC can be improved in all three respects.

Consequently, given the same thickness as currently is common (30 mm), the PMFC in Hong Kong could be improved by switching to an 8 mm aggregate and aiming at somewhat higher air voids. Alternatively, the thickness can be increased from 30 mm to (say) 45 mm. The latter costs a little more, the former may be somewhat less durable against ravelling at critical points. Therefore, increased noise reduction may be obtained at the possible cost of shorter lifetime or at the cost of more material.

The above discussion neglects the possibility to increase noise reduction by using an increased amount of rubber, see the discussion about asphalt rubber friction course in the previous chapter.

Chapter 12 in this report contains recommendations for improved surfaces in Hong Kong.

5. WHAT IS A LOW-NOISE ROAD SURFACE (LNRS)?

As far as this author has understood it, a low-noise road surface (LNRS) in Hong Kong is usually assumed to be a porous asphalt concrete (PAC) surface; more commonly referred to as Polymer Modified Friction Course (PMFC). On the high-speed roads on which LNRS has been applied extensively in the past the noise reductions have been measured initially at approximately 5 dB(A) falling to 1-2 dB(A) at the end of service life [Ng & Tse, 2005].

In the Hong Kong situation where a brushed cement concrete (BRCC) is commonly the surface type to be replaced by a LNRS material, also other surface types than PMFC may be effective, and in low-speed urban situations sometimes even more effective than PMFC when considering the whole lifetime.

In the Tyre/Road Noise Reference Book, a LNRS is defined as a material which gives at least 3 dB(A) of vehicle noise reduction in relation to a "conventional" and "most common" road surface [Sandberg & Ejsmont, 2002]. Also, recent work in Denmark has defined LNRS in a similar way [Kragh, 2006]. Now that there is a definition of a (virtual) reference surface in Europe [Sandberg, 2006], it is suitable that the 3 dB(A) are counted against the reference surface defined there.

It follows that a LNRS material would be a paving material which gives a reduction of vehicle noise of 3 dB(A) or more in comparison to an average of an SMA 0/11 and a DAC 0/11. In practice it will mean that SMA:s would not really qualify as a LNRS since the potential noise reduction by this class of surfaces would rarely exceed 2 dB(A). Nevertheless, since Hong Kong extensively uses BRCC surfaces (although these are being phased out), which are perhaps 2-3 dB(A) "noisier" than the proposed reference surfaces, according to the author's estimation, this does not mean that SMA:s shall not be considered for noise reduction purposes in Hong Kong. But the definition suggested here would make the terminology more consistent with international practice and probably be more appropriate in the near future.

See further the sub-chapter about Reference surfaces below.

6. DESIGN OF LOW-NOISE ROAD SURFACES

6.1 The major options

The noise generation mechanisms are described in Chapter 7 of the Tyre/Road Noise Reference Book [Sandberg & Ejsmont, 2002]. A more modern and compact description appears in [Bernhard & Sandberg, 2005]. The ways to optimize noise reduction are described in Chapter 21 of the same book.

There are three major ways to design a quiet road surface:

- Optimize its macro- and megatexture to reduce texture-excited tyre vibrations while at the same time provide adequate drainage of air entrapped in the tyre/road interface
- Make it porous, which gives two effects: (1) providing air drainage to eliminate the so-called air pumping mechanism, and (2) providing sound absorption in order to absorb sound when it propagates over the surface
- Make it soft, in order to make the surface texture more "flexible"

6.2 Texture optimization

An attempt to produce an illustrative description can be found in [Sandberg, 2004a]. An abridged part is included below.

A very effective way of describing road surface texture is to use texture spectra, just as in acoustics and vibration work. Fig 5 shows a typical texture spectrum for a common asphaltic surface. One may mention the following features:

- The peak is determined by the dominating stone fraction. If the maximum and dominating stone fraction is 13 mm, the peak usually falls at about 16 mm. This is because all large stones are not located immediately close to each other, but there is usually some extra spacing of mortar or of smaller stones in-between.

- The peak is more pronounced, the more gap-graded the aggregate grading is (the more uniform the dominating stone size is) and the closer together the larger stones are located.

- The area above the peak, to the right on the wavelength scale, is dominated by “harmonics” to the dominating profile component (the max aggregate size), for example the sharpness of the stones, and by aggregate in the size range 2-6 mm.

- The area below the peak, to the left on the wavelength scale, is dominated by “inhomogeneities” in the surface, such as uneven spacing between the largest stones, a mix of areas where there are no large stones and areas where there are large stones.

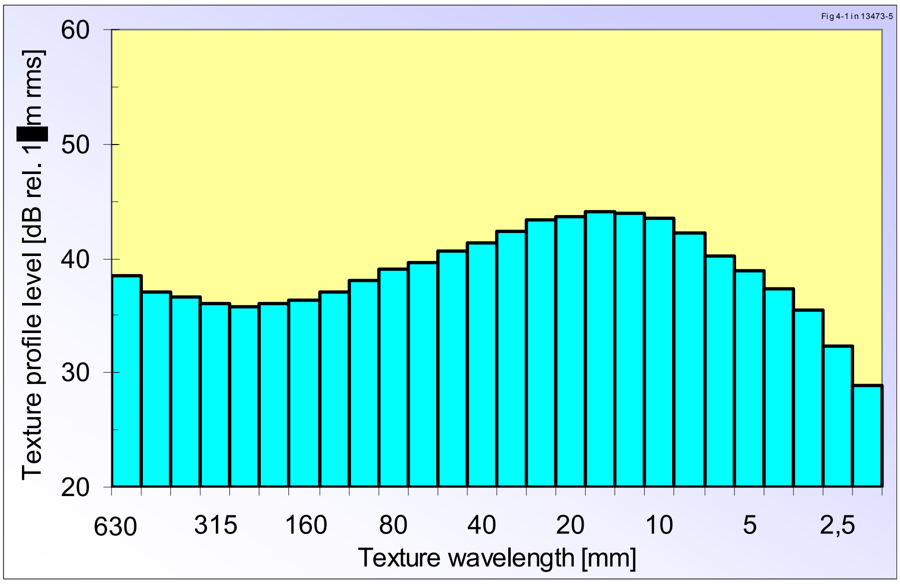

Fig. 5 Typical texture spectrum of an asphaltic surface obtained by spectrum analysis of a profile curve. See ISO 13473-2 for further information about texture spectra.

For example, in a porous asphalt surface a single stone size is dominating, and there is a relative lack of smaller stones and sand; therefore, these stones are generally located rather close to each other. This gives a fairly pronounced texture spectral peak. The contrary is a smooth, dense cement concrete pavement, or the British Hot Rolled Asphalt (HRA). The latter surfaces sometimes show no peak at all and instead show a continuously falling spectrum from large to small wavelengths.

The most effective texture measures to reduce noise emissions from the tyres are [Sandberg & Ejsmont, 2002][Sandberg, 2004a]:

- Maximize the texture levels in the texture wavelength range 2-8 mm
- Minimize the texture levels in the texture wavelength range 20-250 mm
- In order to reach the above objectives, one may “push” the peak in the spectrum as much to the right as possible; this may be made by choosing a smaller maximum aggregate size
- It follows from [Sandberg & Ejsmont, 2002] and [Sandberg, 2004a] that it is slightly more efficient to affect the wavelengths 20-250 mm than the ones at 2-8 mm

Fig. 6 attempts to illustrate all of the points above.

The above provides a simple way of describing texture for noise characterization, since one can limit it to two single-value parameters: the texture levels (amplitude) at around 80 mm of texture wavelength (named megatexture) and the texture levels at around 5 mm of texture wavelength (named macrotexture). These two parameters can be affected by for example pushing the texture spectral peak in the left or right direction, but also by the absolute levels of the texture amplitude. Practical ways to achieve this are the following:

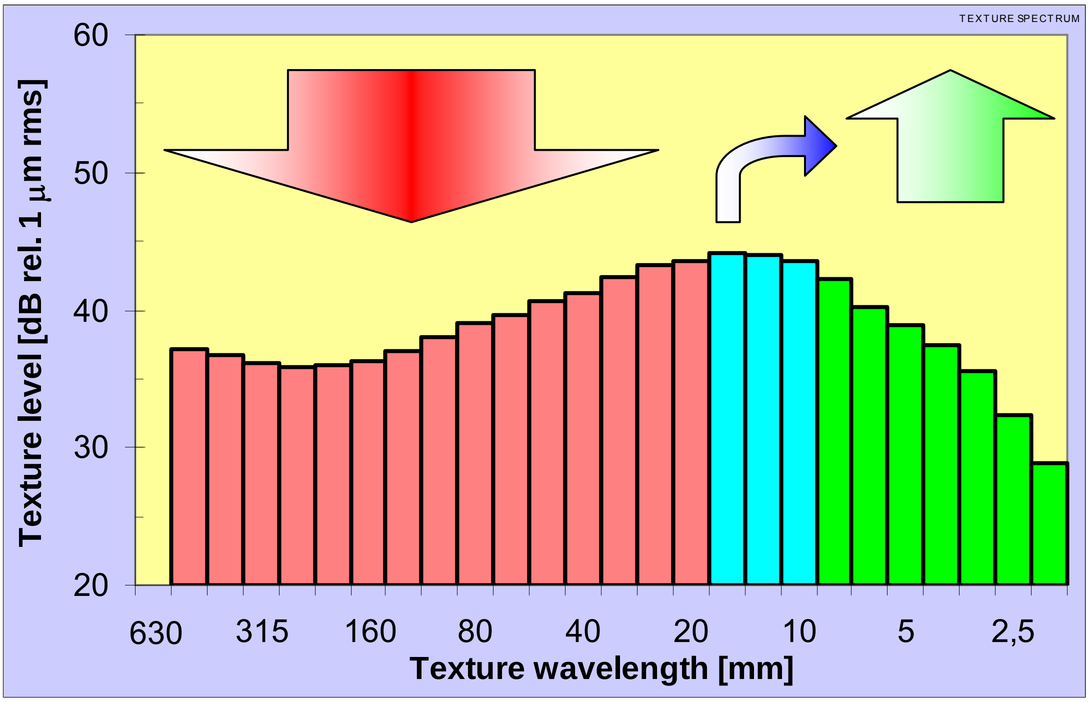

Fig. 6 Typical texture spectrum of an asphaltic surface and the desired actions to optimize it for lowest tyre/road noise emission.

- The peak may be shifted in the right direction by choosing a smaller maximum aggregate size in the mix. Usually, this automatically is favourable to the two following items.
- The megatexture may be reduced by designing and laying the surface with a rather uniform aggregate size and making sure that the chippings are compacted (horizontally) in order to come as close together as possible. The length of the "valleys" between chippings should be minimized. Also, careful rolling of the surface will be favourable.
- The macrotexture around 5 mm texture wavelength may be increased by designing an open surface with a rather uniform small aggregate size (max 4 mm would be fine) and making sure that there will be "valleys" between chippings with a high amplitude (but the length small be minimum). A surface dressing with small chippings (2-4 mm) is an example of such a surface.

For a quite narrow range of surfaces, it has been found empirically that the simple model of Table 1 may be used to compare the "noisiness" of SMA and DAC surfaces over a range of maximum aggregate sizes [Sandberg, 2006].

The normalizations have been developed for SMA and DAC surfaces with a maximum aggregate size from 8 to 16 mm and with texture depths at 0.5 mm or above. However, the author believes that it will not work well with the Hong Kong DAC surfaces, due to the extremely low macrotexture of the majority of Hong Kong DAC surfaces. It should, however, work for the Hong Kong DAC surfaces with texture depths at 0.4-0.5 mm and above and for the SMA surfaces. The age influence has been developed based on northern and middle

European conditions. It is possible that it will be somewhat different in the hot Hong Kong climate.

Table 1. Corrections to be made to the measured levels to normalize from the actually used DAC or SMA surface to the virtual reference surface which is an average of a DAC 0/11 and an SMA 0/11, according to [Sandberg, 2006]. See illustrations in Figs. 7-8.

Type of influence	**Corrections for light vehicles**	**Corrections for heavy vehicles**
Age influence **y** for an age of **m** months	See Fig. 8	None
Surface type influence	Subtract 0.3 dB for SMA surfaces and add 0.3 dB for DAC surfaces	None
Max. aggregate size influence	Subtract 0.25 dB per mm (of max chipping size) that exceeds 11 mm; add 0.25 dB per mm below 11 mm	None

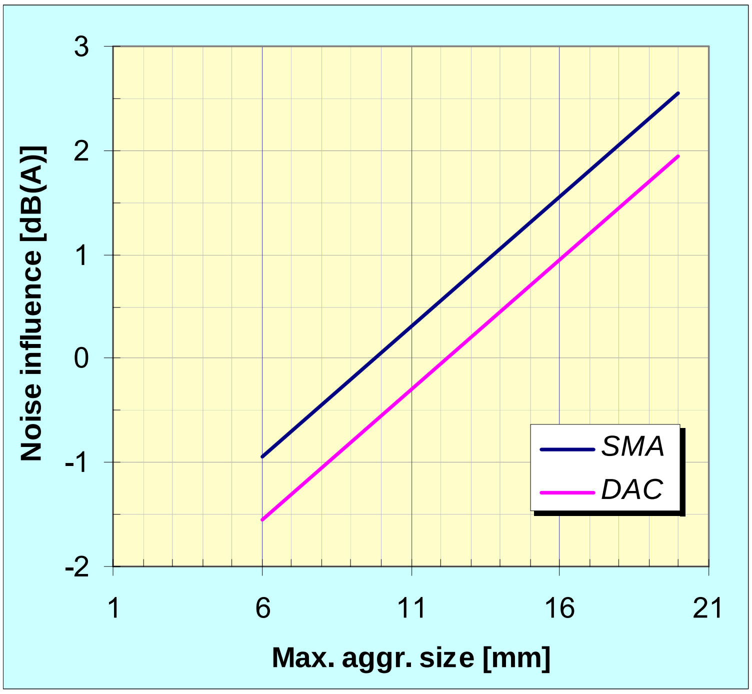

Fig. 7. Influence of road surface maximum aggregate size on noise, according to [Sandberg, 2006]. According to the same source it is also assumed that SMA surfaces are on the average 0.6 dB "noisier" than DAC surfaces. Note that the relation is a crude approximation, less accurate the further away from 11 mm aggregate size one gets. However, tests against newer data have invariably come out well.

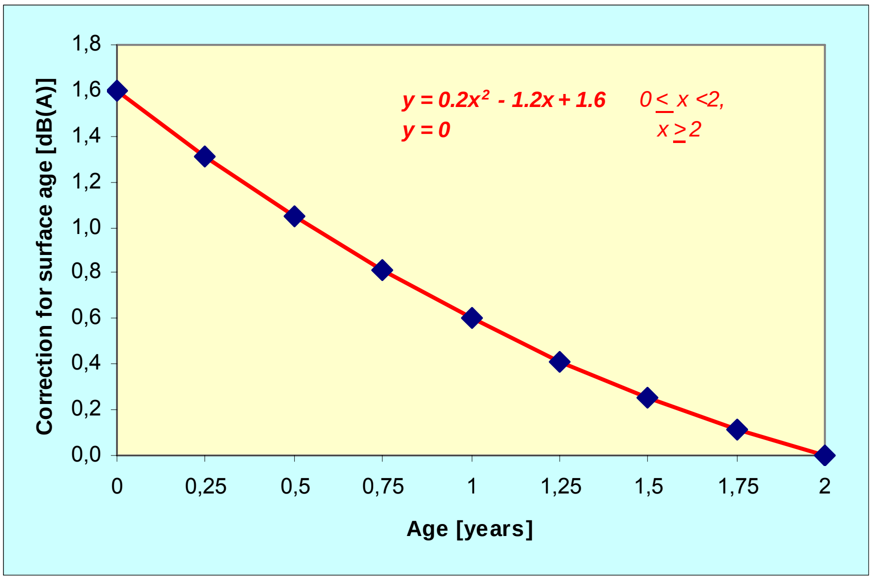

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Fig. 8. Correction for road surface age, according to this author; but only useful for DAC and SMA surfaces with max. aggregate sizes 6-20 mm. Note that the correction for surfaces less than 2 years of age should be added to the measured value in order to normalize it to a surface age of 2 years or older. Age is expressed in decimals of year.

The model may be used to calculate the difference between common Hong Kong DAC and SMA surfaces for light vehicles; provided macrotexture is not lower than approx. 0.4 mm. For example, Fig. 7 will predict the following noise level differences:

- From DAC 0/10 to DAC 0/11: Add 0.25 dB to the value measured on DAC 0/10
- From SMA 0/10 to SMA 0/11: Add 0.25 dB to the value measured on SMA 0/10
- From DAC 0/10 to SMA 0/10: Add 0.6 dB to the value measured on DAC 0/10
- From DAC 0/10 to SMA 0/8: Add 0.1 dB to the value measured on DAC 0/10
- From DAC 0/10 to SMA 0/6: Subtract 0.4 dB to the value measured on DAC 0/10
- From DAC 0/10 to DAC 0/20: Add 2.5 dB to the value measured on DAC 0/10

6.3 Porosity

The porosity provides two advantages:

- Air drainage to eliminate the so-called air pumping mechanism
- Sound absorption in order to absorb sound when it propagates over the surface

The exact processes are very complicated and depend on a number of factors such as:

- The air voids content (air volume of the entire volume)
- The thickness of the porous layer
- How well the pores are interconnected (closed air voids are ineffective)
- The shape of the pores (the "winding" character and the "thickness" of the pores)

Empirically, a relation has been found between noise reduction and the “equivalent thickness of air” in the porous layer below the tyre/road interface. The "air thickness" is the product of the layer thickness (in mm) and the air voids content (by fraction of 1). The relation is presented in Fig. 9, which is based on an idea originally by Descornet and data collected by Sandberg and Descornet.

The relation is rather good, explaining ¾ of all the variance, but it is based on rather similar aggregate sizes; maximum aggregate sizes range between 8 and 16 mm with a dominance of 11 mm. Most of the residuals are probably due to the neglect of aggregate size; i.e. surface texture.

A more elaborate model for porous and semi-porous surfaces such as PAC and thin surfacings has been developed recently by this author, based on data measured in the Netherlands in 2005-2006. This model is based on three parameters:

- Maximum aggregate size ("aggr") in mm
- Air voids content ("voids") in fraction of 1
- Thickness of the porous layer ("thick") in mm

In case of a double-layer surface, the maximum aggregate size is determined from the top layer, the air voids is the average of the two layers and the thickness is the total thickness of the two layers. The model is based on 24 surfaces having a max. aggregate size 4-16 mm.

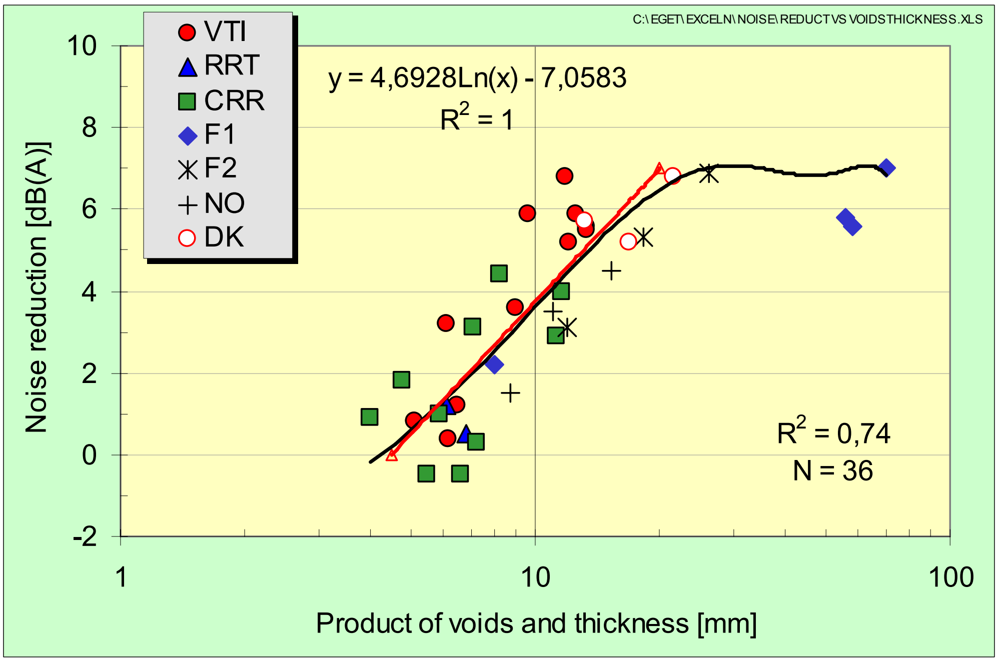

Fig. 9. The relation between noise reduction of porous surfaces in relation to a DAC 0/11 and the “equivalent thickness of air” in the porous pavement, i.e. the product of air voids content (in fraction, i.e. 20 % = 0.20) and pavement thickness in mm. Based on data from various countries. From [Sandberg & Ejsmont, 2002].

The equation of the model is:

$$\text{Noise reduction} = 0.3*\text{voids}*\text{thick} + 0.039*\text{aggr}^2 - 1.275*\text{aggr} + 7.6 \qquad [\text{dB(A)}]$$

Some illustrations of effects of parameter variations are presented in Fig. 10. Note that the model predicts better noise reduction for smaller aggregate size, but experience shows that below 8 mm the ravelling may be too cumbersome, so current best-practice is 8 mm.

The model has a reference level (0 dB noise reduction) corresponding to approximately a DAC 0/10 and is based on surfaces in new condition. It is assumed that the "correction" from new to old condition would change the noise level equally much in the reference case as for the low-noise surfaces (Fig. 8), so the model would tentatively be suitable also for the noise reduction considering also old surfaces. However, clogging might distort the model, since it is not sure that a clogged surface having a voids content of 15 % after clogging would give the same noise reduction as a surface designed with 15 % voids and which would not be clogged.

This may be supplemented by the model to predict the noise relations between various SMA and DAC surfaces described above; in fact the two models fit rather well for air voids = 0 over the common range of aggregate sizes.

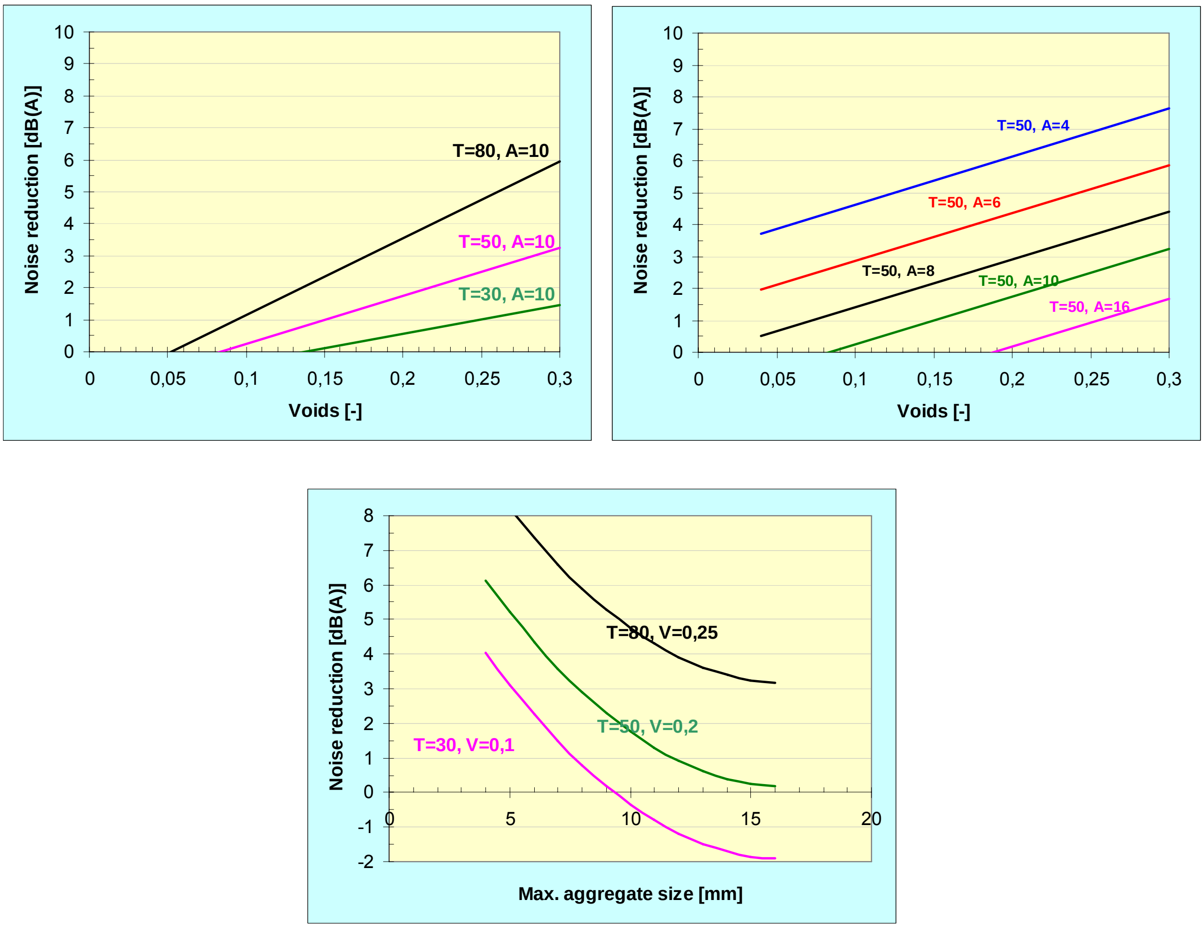

Fig. 10. Example of noise reductions coming out of the model, for various input parameters.
T = Thickness (in mm)
V = Voids content (in fraction of 1)
A = Maximum aggregate size (in mm)

6.3 Stiffness reduction

The relation between road surface stiffness and noise emission is poorly studied and no "safe" relations have been presented. However, it is obvious from research on poroelastic road surfaces that there is a substantial extra noise reduction effect attributable to the softer surface [Sandberg & Kalman, 2005][Meairashi, 2006].

Such surfaces are not yet ready for application on a trafficked road. However, there are some road surface types that includes sufficient amount of rubber, albeit just a small fraction of the poroelastic ones, for which the rubber content seems to affect the noise emission. The authors' best estimation when this is written, based on own measurements and measurements by others, is that a rubber content of approximately 2 % by weight of the total mix may reduce noise by 1-2 dB(A) extra.

Further studies on this are needed. However, the concept is promising and is really worth exploring more. Both VTI and Hong Kong EPD are working on this matter.

7. SPECIAL CONDITIONS IN HONG KONG OF IMPORTANCE TO LNRS EFFICIENCY

There are some conditions typical of Hong Kong which makes the road surface policy and effects of LNRS different than in most European countries.

Hong Kong is one of the most densely populated areas in the world. As some parts of the land area are mountainous, the large population is concentrated to certain parts of the already small land area. Residential houses have been built as high-rise buildings with typically 40-60 floors, mostly located close to each other in something which a visitor might want to describe as a "skyscraper park". The distance between major roads and residential areas is very small; for a visitor sometimes "shocking".

This has the effect that traditional noise barriers are ineffective in most situations. The noise will just propagate over the barrier tops to the high-rise buildings nearby. Nevertheless, there are several locations where noise barriers have an effect and have been constructed, but it is not at the extent which would be the case in an urban area in a "western" country. Instead the need of source abatement by using LNRS on the roads and streets is increasingly interesting since these reduce noise not only behind a barrier but in all directions from the source.

Traffic is very intense, almost always and everywhere. Congestion is normal and causes interrupted traffic flows. The vehicle noise standards have lagged a little behind Europe and Japan with the effect that there is a higher proportion of vehicles not meeting the latest noise emission standards. This means that there is a higher proportion of power unit noise from the vehicles compared to the tyre/road noise than one would hear in many other countries.

The proportion of heavy vehicles in the traffic, most of all buses, is abnormally high on most streets and roads. The author cannot prove it, but it is the impression that bus density in Hong Kong is higher than in any other major city or area in the world. There are two basic kinds of busses: large city busses (mostly double-decker busses) and a smaller type called "public light bus". The buses travel most of all close to where people live and work, where they brake and accelerate at the bus stops causing extra noise. This is the basic need of this type of traffic, so it is impossible to improve it significantly by traffic management. Streets such as, for example, Nathan Street in Kowloon are exposed to an almost constant "din". The heavy vehicle traffic, unfortunately, limits the noise reduction effect of LNRS, because of power unit noise dominating the noise emission and this type of noise not being controlled by LNRS. The acceleration, braking, and turning in corners of the heavy buses and delivery trucks also mean an extra strain on the PMFC surfaces which are weak regarding horizontal forces. To alleviate this problem, extra durable and dense surfaces need to be laid on bus stops. On the low-speed roads included in the LNRS program, heavy vehicle proportions are generally 20-50 %.

Another special condition is the extremely hot and humid climate. This puts constraints on the type of binders in the surfaces and increases ravelling and probably also rutting. This in combination with the high traffic volumes and high heavy vehicle proportions creates extra needs of road surface maintenance and limits the lifetime of the surfacing. Typically, resurfacing is needed approximately each 6th year for a normal road surface and more frequently for an LNRS. This is much more frequently than in most European cities. It is even considered that LNRS materials on some streets may need resurfacing with a frequency of 2-3 years [Ng & Tse, 2005]. These limited lifetimes are comparable to those of Swedish road surfaces exposed to high traffic volumes, but in Sweden the limitations are caused mainly by the use of studded tyres; i.e. a "too" cold climate.

Since a "low-noise road surface" (LNRS) by definition means a comparison with some "normal-noise road surface", the normal (reference) surface which is used for comparison is equally important as the LNR itself. In Hong Kong, the "normal" dense asphalt surfaces are extremely smooth-textured in the majority of cases, as was described in the previous chapter. Such surfaces are very "noisy". The other type of common surfaces which LNRS replaces is the brushed cement concrete (BRCC) which also is a very "noisy" surface type. Thus, in Hong Kong, mostly replacing a very noisy surface with a new low-noise one should give relatively high "noise reductions"; nominally significantly higher than those measured in Japan or in Europe.

For reasons unknown to the author, the available aggregate gradings are limited in Hong Kong. It is common practice to use only the 5, 10 and 20 mm sieves, which means that the maximum aggregate size will normally be 10 mm, but with a smaller amount of 5 and 20 mm material also being laid. In most countries in Europe it is common to produce aggregate classes with maximum sizes of 4, 6, 8, 11, 14 and 16 mm (rounded values); i.e. approximately twice the number of classes in Hong Kong. It means that the number of degrees of freedom in the design of an asphalt mix is much higher in Europe than in Hong Kong and the mix may be better optimized for a special purpose.

Finally, it shall be mentioned that the typical aggregate in Hong Kong is not of very high quality; in particular the polished stone value is not very high.

8. POLICY WITH RESPECT TO THE USE OF LNRS IN HONG KONG

8.1 General concerns

The Environmental Impact Assessment (EIA) process is a statutory requirement in Hong Kong since 1998. Under the EIA process, the noise impact shall be assessed at the outset of planning of road projects. Direct mitigation measures, in particular those that can reduce noise at source, should be considered. Application of noise reducing road surfacing is considered one of the measures for noise mitigation.

The Highways Department has published guidelines for the application of low noise road surfaces [HyD GN, 2001]. The types of surfacings mentioned are:

- Polymer modified friction course (PMFC), 30 mm thick, 10 mm max aggregate size
- Stone mastic asphalt (SMA),
- Exposed aggregate cement concrete (EACC)[8]
- Proprietary thin layers

The EACC has not been used so far since it requires an aggregate with very high polished stone value, which is not available in Hong Kong. The thin layers have not been tried either, for unknown reasons. SMA has been tried at a few places; but so far with questionable success.

However, the PMFC has been tried rather successfully in several experiments, and has now become the standard surfacing for all new high speed roads in Hong Kong, i.e. at 70 km/h and above. Its use is recommended generally in the Transport Planning & Design Manual for its favourable performance with respect to water spray, texture depth, aquaplaning and skid resistance at high speeds; apart from its noise-reducing potential.

The cross-slope of roads in Hong Kong is usually 2.5 % by design.

8.2 Application on high-speed roads

The highest speed limit in Hong Kong is 110 km/h, but 70 km/h is a common speed limit which is also considered as being a high-speed road. According to the guideline [HyD GN, 2001] on high-speed roads the noise reducing surfacing, i.e. the PMFC, should be applied with the following compositions:

When concrete is the existing pavement:
30 mm thick, max. 10 mm aggregate, polymer modified porous friction course, laid over a 20 mm thick, max. 3.35 mm aggregate, polymer modified dense cushion course. The cushion is used to provide an intermediate layer to avoid reflective cracking from the joints between the

[8] HyD uses the designation EACS (Exposed aggregate concrete surface)

concrete slabs. To accomplish this, there is also a "glass grid" laid between the PMFC and the cushion course over each joint.[9]

When the existing pavement is bituminous:
30 mm thick, max. 10 mm aggregate, polymer modified porous friction course, laid over a 25 mm thick, max. 10 mm aggregate, regulating wearing course (dense), or laid on a max. 20 mm aggregate wearing course of newly constructed pavement.

8.2 Application on low-speed roads

As concerns low-speed roads; i.e. posted speed of 50 km/h or below, the guideline says in summary:

Under existing policy for new local roads, low noise surfacing materials should be used under exceptional circumstances where noise reduction is an absolute necessity but cannot be achieved by any other means. For existing local roads, 72 road sections have been identified for resurfacing with low noise materials, subject to detailed feasibility study to be carried out by HyD in consultation with EPD.

The following noise reducing road surface may be applied on low-speed roads:

When concrete is the existing pavement:
The guideline says "not applied as further study and trials have yet to be carried out." However, the author knows that low-noise surfaces are indeed applied on cement concrete on several low-speed roads.

When the existing pavement is bituminous:
30 mm thick, max. 10 mm aggregate, polymer modified porous friction course, laid over a 45 mm thick wearing course (dense).

The application is, however, subject to conditions as listed below (which are based on the results presented in Chapter 11.2):

1. Not to be applied on inclined roads
2. No to be applied where there is a sharp bend in road geometry
3. Average annual daily traffic must not exceed 18,500 in traffic volume and percentage of commercial vehicles shall not exceed 35 %
4. Not to be applied on roads where a minimum crossfall of 2.5 % cannot be practically achieved to drain water to the roadside gullies effectively (for minimizing occurrence of flooding in the porous friction course material)

There are also special guidelines regarding detailed applications for joints to adjacing dense pavements, bridges, flyovers, rodding eye covers and gully gratings, aiming at providing a smooth ride, avoiding excessive structure loading, avoiding standing water and avoiding the build-up of too high pavement surfaces in relation to barriers and kerbs.

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[9] The author is very impressed by the efficiency of this arrangement, which in other countries is a huge problem. The author has not at any place in Hong Kong with such a construction noticed any reflective cracking.

8.3 Detailed composition

The cushion layer is specified in detail in [HyD GN, 2001], but as it is not important for noise emission, it is not reported further here.

The PMFC is important, though. In the guidelines from 2001 it is specified as shown in Table 2; however, which it is stated as subject to change. Table 3 was obtained in January 2007 and gives some alternative specifications apart from the one of Table 2. In Table 3 there are four variants specified:

1. Conventional 10 mm Friction Course (without polymer)
2. Conventional 10 mm Polymer Modified Friction Course (same as Table 2)
3. Pre-blended Type 10 mm Polymer Modified Friction Course
4. Pre-blended Type 20 mm Polymer Modified Friction Course

Of these, it is the 2nd one that is generally used. The two pre-blended variants have been used only on Chui Tin Street and then they were 50 mm thick, not 30 mm as the regular one is.

Fig.10 shows the grading in Table 3 (conventional PMFC) compared to the Dutch ZOAB and Swedish ABD11.

Table 2. Specification of the PMFC material in [HyD GN, 2001]

Properties		**Friction course**
Nominal maximum aggregate size (mm)		10
	BS test sieve	Percentage by mass passing
Particle size distribution	14 mm	100
	10 mm	85 - 100
	5 mm	20 - 40
	2.36 mm	5 - 15
	75 µm	2 - 6
Bitumen content as % of total mass including binder, but excluding polymer	min	5.5
	max	7.0
Dosage of polymer, % of solid content by weight of binder content (see Note 1)		min 3
Air voids in mix as a percentage of total bulk volume		min 17

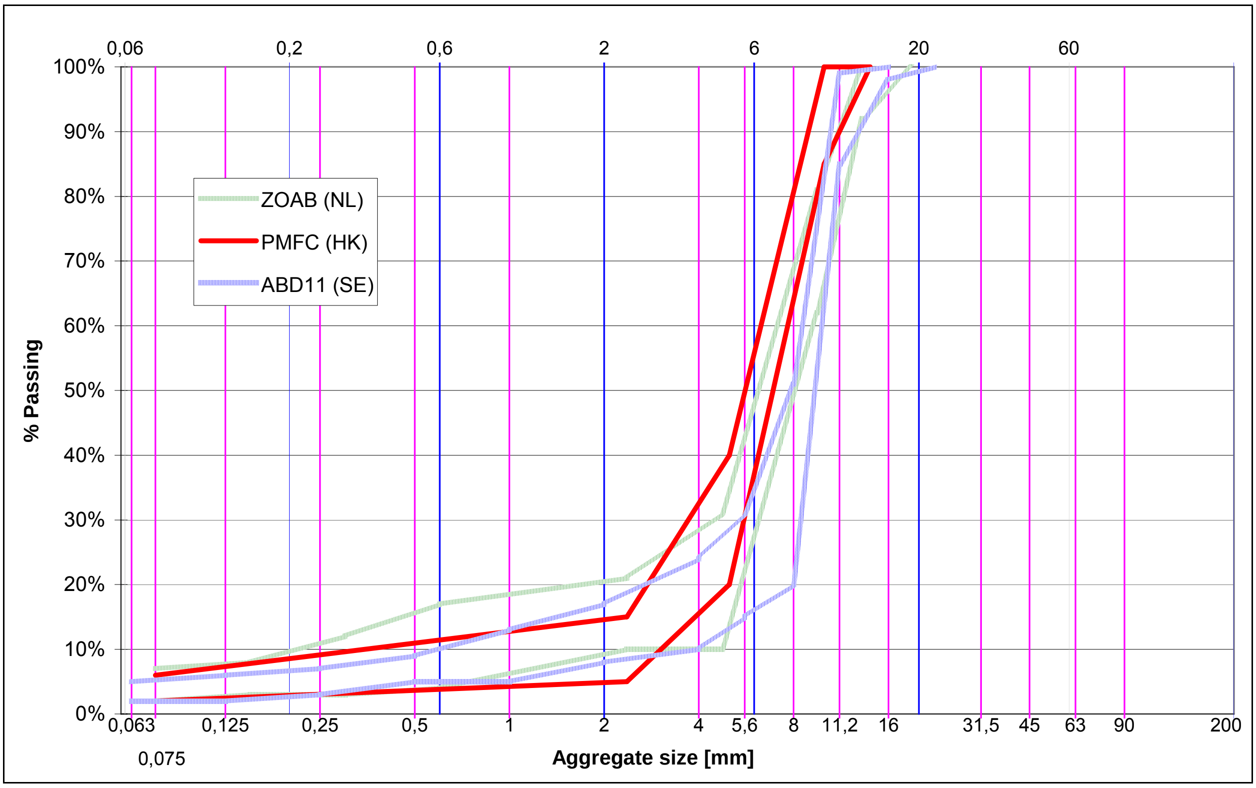

Fig.11. Grading of the conventional PMFC (Table 3); here compared to the corresponding "standard" PAC surfaces in the Netherlands ("ZOAB") and Sweden ("ABD11"). ZOAB means very open asphalt concrete and ABD11 means drainage asphalt concrete 11 mm.

Table 3. Specifications for LNRS according to table obtained in January 2007 from HyD/EPD

Low Noise Surfacing Materials	Conventional 10 mm Friction Course (without polymer)		Conventional 10 mm Polymer Modified Friction Course		Pre-blended Type 10 mm Polymer Modified Friction Course		Pre-blended Type 20 mm Polymer Modified Friction Course	
Usage	Mainly used in high speed roads		Mainly used in local roads for noise reduction Also for application in high speed roads		On trial for noise reduction in local roads		On trial for noise reduction in local roads	
	Design Grading	Mix Design Requirement	Design Grading	Mix Design Requirement	Design Grading	Mix Design Requirement	Design Grading	Mix Design Requirement
Polymer modified binder content (%)	--	--	5.7	--	5.5	5.5 - 7.5	4.5	4.5 - 6.5
Binder content (%) [excl. polymer]	4.5	4.5 - 5.5	5.5	5.5 - 7.0	--	--	--	--
Dosage of Polymer	--	--	3 %	≧ 3 %	--	--	--	--
B.S. Sieve (mm)	% passing		% passing		% passing		% passing	
28	--	--					100	100
20	--	--					96	96 - 100
14	100	100	100	100	100	100	78	72 - 88
10	96	85 - 100	96	85 - 100	96	85 - 100	--	--
6.3	--	--	--	--	--	--	--	--
5	27	20 - 40	27	20 - 40	26	20 - 40	18	13 - 34
3.35	--	--	--	--	--	--	--	--
2.36	11	5 - 15	11	5 - 15	10	5 - 15	12	10 - 20
1.18	--	--	--	--	--	--	--	--
0.3	--	--	--	--	--	--	--	--
0.075	4.0	2.0 - 6.0	4.0	2.0 - 6.0	4.0	2.0 - 6.0	4.0	3 - 7
	(including 1.5 % hydrated lime)		(including 2 % hydrated lime)		(including 2 % hydrated lime)		(including 2 % hydrated lime)	
Marshall Properties								
Air voids in mix, VIM (%)	20.4	18 - 25	19.1	≧17	20.5	≧20	21.3	≧20
Marshall quotient (kN/mm)	--	--	--	--	--	--	--	--
Binder drainage test	--	--	Pass	Tmax > Binder cont.	Pass	Tmax > Binder cont.	Pass	Tmax > Binder cont.
Voids in mineral aggregate, VMA (%)	28.5	≧25	--	--	--	--	--	--

9. EVALUATION AND METHODOLOGY ISSUES RELATED TO LOW-NOISE ROAD SURFACES IN HONG KONG

9.1 Introduction

The low noise resurfacing programme in Hong Kong has required quite large investments. It is important that the evaluation of the program is made professionally and with due regard to the best international knowledge, with the aim to get as accurate and as much information as possible from it. In order to draw the correct conclusions it is a great advantage if all results are evaluated and assessed in a consistent, logical and scientifically justified way. If this is not made the results will just be a mess and conclusions will be ad hoc statements.

The conditions in Hong Kong are far from ideal for testing road surfaces. The traffic is intensive on almost all locations, buildings mostly lie very close to the street and road, often small but lively businesses are located along the streets, and population density is exceptionally high; all of this contributing to high noise emissions. To distinguish the noise emission coming from the tyre/road interaction, or from the road traffic but influenced by the road surface, under such conditions requires special considerations. What would be normal in many countries in Europe would not automatically work fine in Hong Kong. The several issues of importance identified in the following sections relate to both experiments (measurements) and to the evaluations to be made based on the data collected.

The following sections present and discuss issues related to the evaluation of the Hong Kong low noise resurfacing programme and present suggestions aiming at optimizing this part of the programme.

9.2 Noise measurement methods

9.2.1 General

In the Hong Kong low noise resurfacing programme the following noise measurement methods should be considered for use:

- Statistical Pass-By (SPB) method
- Measurement of the equivalent noise level before and after repaving
- "Normalized Leq" method
- Close-Proximity (CPX) method

These four methods are more or less suitable on a certain location and give different types of results. The following sections discuss issues of importance related to these methods.

9.2.2 Statistical Pass-By (SPB) method

For comparison of noise characteristics of road surfaces, the Statistical Pass-By (SPB) method specified in ISO 11819-1 is the most recognized and commonly accepted premium method.

Wherever possible, it is suggested to use the SPB method in this program. The SPB method has some problems in urban traffic, however. The most serious one is the need for freedom from acoustically reflecting surfaces within 50 m from the microphone. Clearly, in urban locations, such a requirement is hard to meet. In the low noise resurfacing programme it is particularly useful to implement an extra option in the method which is not yet standardized but which is already sufficiently tested to justify its use in this program[10], namely the backing board principle [Goubert, 2006]. In this method, where a special microphone is placed flush with a backing board with an area of a couple of square meters, it becomes acceptable with reflecting surfaces behind the backing board. For example, it may be placed adjacent to a building façade. See Fig. 12 for an example of a backing board.

Fig, 12. Example of backing board used by the Belgian Road Research Centre [Goubert, 2006].

It is suggested that the SPB method supplemented with a backing board is used, with a measuring distance of 7.5 m from the centre of the nearest lane paved with LNRS. This distance may be somewhat negotiated (down to 5.0 m) in cases where the facades are closer to the street than 7.5 m from the lane centre, with a correction being made to the 7.5 m standard distance. This author will supply the information necessary to manufacture the backing board, about the special microphone needed, about its placement (which is very critical), about correction from backing board to free-field conditions, etc.

[10] It is currently being standardized by the working group ISO/TC 43/SC 1/WG 33

The measurement of speed of all vehicles subject to noise measurement is mandatory.

The SPB method has not been used earlier in the resurfacing programme which means that few data will be available as reference cases (surfaces) and for LNRS in new condition. However, starting from 2007, the final data collection in the programme should include SPB measurements on as many sites as possible, and hopefully these will include a few reference cases (before repaving) and some LNRS in new condition. It is recognized that SPB measurements are relatively expensive. One must expect that one can measure one or two surfaces per day with a staff of two and data evaluation will take at least one day for one person. Thus, SPB measurements cost 2-4 person-days per site. On streets carrying a high volume of traffic and where there are businesses close to the street, measurements may have to be made in evening and night time in order to get undisturbed vehicle pass-bys to measure.

The resulting SPB noise levels may be compared from site to site and over time as well.

9.2.3 Before-After Leq (BALeq) method

A measurement method which can be relatively accurate if conducted well, even in an acoustically reflective environment, is the measurement of the equivalent noise level at an occasion before repaving and at a comparable occasion after the repaving, using exactly the same microphone position. Wherever such a measurement has been made before repaving, it is suggested that it is made also after repaving, and then repeated after some time (say one, two or three years). It is then of course important to record traffic data sufficiently accurate to be able to normalize levels to a common standard, with a specified number of vehicle passes per time and a specified percentage of heavy vehicles. Ideally would be also to normalize for differences in speed, and if significant speed differences before-after are expected, it is absolutely necessary to make such normalization.

Only measurements where one has used exactly the same microphone position are meaningful to compare; i.e. one can only study the change in noise level with time at a certain test site. If the microphone positions are not identical, the effect of the position may well exceed any changes due to the introduction of the LNRS. It may be tempting to use such measurements to compare results at various test sites, but this author thinks that it is meaningless if not the same microphone position was used.

In this method one measures the Leq during a set time period and normalizes the level to a standard traffic volume, heavy vehicle content and vehicle speed. All these factors should be measured. If speeds are not measured, it must be noted that a 5 km/h change in speed between two occasions will lead to a systematic error of 0.5-1.0 dB. Time periods would ideally be spread over the day and night, say 30 minutes in the morning, 30 minutes in the afternoon, 30 minutes in the evening and 30 or 60 minutes at night. To measure the Leq over a full day-night cycle (24 h) is meaningful for surface comparisons if and only if traffic data are recorded simultaneously. If the measurements cannot be made at the four suggested periods, it is important to make the before-after measurements at as similar traffic conditions as possible, in order to minimize the corrections for varying traffic for the normalization.

The normalization should preferably be made based on the latest European noise prediction models (IMAGINE or HARMONOISE) or the Nord2000 model, rather than on the CRTN model used so far in Hong Kong, since the latter is out-of-date. Not even the British use it any longer. An example is shown later in which it seems that the CRTN normalization procedure seems to have given a very strange result (Shanghai Street, see chapter 11).

Note that what is written about Leq above applies equally well to L_{10}. As appears in 9.2.7, this author recommends the use of L_{10} rather than Leq in the Hong Kong LNRS programme.

If desired, the author may give further advice on how the normalization to standard traffic conditions shall be made.

The resulting "BALeq" noise levels may be compared only within the site and over time.

9.2.4 Normalized Leq (NMLeq) method

In cases where the acoustical environment can be consistent from site to site; namely when there are no large reflective objects within 30-50 m from the microphone (depending on the size and angle of these one may negotiate this distance), or if a backing board is utilized (see SPB method), the "Normalized Leq" method can be used. It is inexpensive and fast.

As in the previous case, one measures the Leq during a set time period and normalizes the level to a standard traffic volume, heavy vehicle content and vehicle speed. All these factors should be measured. Time periods would ideally be spread over the day and night, say 30 minutes in the morning, 30 minutes in the afternoon, 30 minutes in the evening and 30 or 60 minutes at night. To measure the Leq over a full day-night cycle (24 h) is meaningful for surface comparisons if and only if traffic data are recorded simultaneously. If the measurements cannot be made at the four suggested periods, it is important to make the before-after measurements at traffic conditions which are as close to the normalized conditions as possible, in order to minimize the corrections for varying traffic for the normalization.

If this is made accurately, the resulting NMLeq noise levels may be compared from site to site and over time as well, just like the SPB levels, but less accurately.

Note that what is written about Leq above applies equally well to L_{10}. As appears in 9.2.7, this author recommends the use of L_{10} rather than Leq in the Hong Kong LNRS programme.

9.2.5 Close-Proximity (CPX) method

For comparison of noise characteristics of road surfaces, the Close-Proximity (CPX) method specified in a draft ISO/CD11819-2 is the most commonly used method internationally. It is rather critical to conduct in many respects if valid comparisons between sites and over time are to be made. It is therefore, absolutely necessary to follow the recommendations in the draft. If this is not done, the inaccuracies will be unacceptable.

Hong Kong now has a CPX trailer, namely the one at the Department of Civil and Structural Engineering at the Hong Kong Polytechnic University, see Fig. 13. In 2006, tyres of two types were acquired which have a potential of being standardized by the ISO group working on this issue, see Fig. 14.

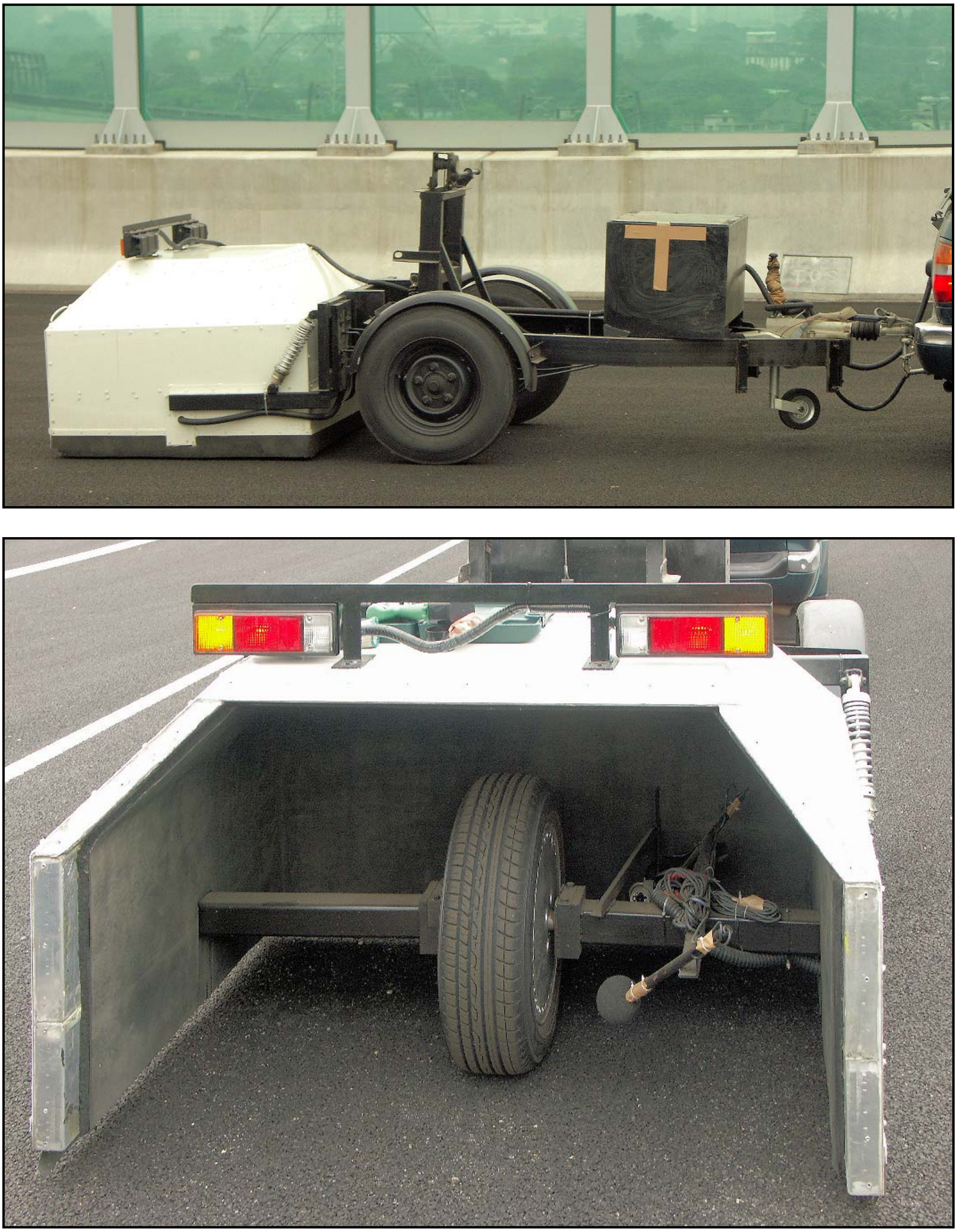

Fig. 13. The CPX trailer developed at the Hong Kong Polytechnic University under direction of Prof Wing-tat Hung. The top photo shows the exterior and the bottom photo the interior.

Fig. 14. Two tyres suitable for use as temporary "reference tyres" in the CPX trailer developed at the Hong Kong Polytechnic University. The left one is the ASTM Standard Reference Test Tire (SRTT) (new version) and the right one is the Goodrich MudTerrain tyre. The ASTM tyre is intended to respond to road surfaces typical of a car tyre, whereas the MudTerrain tyre is intended to respond to road surfaces typical of a truck tyre.

The SRTT tyre has recently been decided by the ISO group to be one of the two reference tyres, and the Goodrich MudTerrain is one of two candidate tyres presently considered as the second reference tyre. Even if the latter will not be standardized finally, the data will still be useful for wide comparison, since the same tyres have been and are being used in 2006, 2007 and 2008 in many measurements in Europe and in USA. It is therefore strongly recommended to use the CPX method on all test sites where measurements can be made in 2007 and later and to make measurements with both the SRTT and the MudTerrain tyres.

This author has given some advice regarding improvements to the Hong Kong CPX trailer, based on the visit to see the trailer in October 2006. It is known that some of the recommended work has been carried out. However, in case the following things have not already been carried out, it is recommended that they are made as soon as possible (citations are copied from an e-mail sent by this author to Prof Hung):

"Add a load cell to the CPX trailer:
Until it has been demonstrated that the test tyre load in the CPX trailer is totally stable when the trailer is run on surfaces which are uneven; for example having ruts and some undulations (running over different concrete slabs may be one test), I suggest that the trailer is supplemented with a load cell which can measure the tyre load while the trailer is in operation in order that test tyre load can be monitored.

Add sound absorbing material on the inside of the CPX trailer:

The enclosure of the CPX trailer should be covered on the inside with sound absorbing material of the type common on European CPX trailers. Also the bars holding the test tyre should be covered.

Remove the flat cover on the rim of the test wheel in the CPX trailer:
The flat plate that covered the rim of the test tyre in the CPX trailer should be removed in order to expose the normal irregular rim surface instead. The reason is that a flat surface there tends to increase the risk of getting acoustic standing waves in the enclosure."

Common test speeds shall be selected; for example 30, 50 and 80 km/h. For each site measurements shall be made at a minimum of two of these speeds (or slightly different speeds if speed limits or safety so require), at least 20 km/h apart. Then, the results may be interpolated and even to some extent extrapolated in terms of speed.

However, one shall note that for the CPX method only tyre/road noise is measured; no noise coming from the power units of vehicles will influence the results.

These results would then be the only ones that can be used to compare all test sites with each other (from 2007 and onwards) and which would potentially have the best resolution. These results may then be the most valuable of all in the low noise resurfacing programme.

It must be stressed that a crucial factor in the CPX method is the rubber hardness of the reference tyres. Unless test tyres are stored in a cold place, they rapidly deteriorate and change their noise properties [Sandberg & Ejsmont, 2007]. In the Hong Kong climate, such tyre rubber deterioration is likely to occur within half a year if tyres have not been stored properly. Therefore, the CPX method is reproducible in Hong Kong only if these facts are observed.

9.2.6 Summary of properties of the methods

Table 4 summarizes the characteristics and usefulness of the mentioned methods. The number of + symbols describe the good properties of the method while the - symbols describe the poor properties.

Table 4. Positive (+) and negative (-) properties of the four methods considered useful. It is assumed that SPB and NMLeq use backing board wherever appropriate.

Characteristics	**CPX method**	**SPB method**	**NMLeq method**	**BALeq method**
Compare test sites with each other	+++	+++	++	---
Compare noise changes with time & when repaving	++	++	+	++
Considering tyre/road noise only	+++	---	---	---
Considering typical vehicle noise emission	--	++	+++	+++
Relevance to typical traffic noise	+	++	+++	+++
Resolution & accuracy (detect small differences)	+++	++	-	+
Control/check of homogeneity	+++	---	---	---
Time consumption and cost for measurement	+++	---	+	+
Comparison with international studies	++	+	--	---
Number of test sites to be measured with the method	+++	+	++	+

9.2.7 Metrics

The A-weighted sound pressure level shall be measured. So far, no other weighting has been demonstrated to be superior to the A-weighting. The time constant shall be in accordance with the respective standards or drafts for them. Frequency spectra shall be measured in the CPX method, and it is recommended to be made also in the BALeq and NMLeq methods. It is an advantage if frequency spectra are measured in the SPB method too but it may be considered too expensive here.

In the noise monitoring programme of the low-noise resurfacing trial on low-speed roads (see Chapter 11) it appears that the type of sound level used for reporting noise reductions is the L_{10}. Internationally, it is the L_{eq} that is used (or L_{DEN} or L_{DN} which are L_{eq} levels but where increased weight is given to noise during night and evening hours). It was only the U.K. and some commonwealth states that used L_{10}. Nowadays, even the U.K. has switched to L_{eq}.

Should one then use L_{eq} for the evaluations instead of L_{10}? First, consider what these metrics are mainly influenced by:

The L_{10} is the level exceeded 10 % of the time (18 minutes of the 3 h monitored in the past and present programmes). This level will have the following features:

- Passages of heavy vehicles will influence the level, during most of the passage
- Passages of light vehicles will influence the level, but mostly when the vehicles are closest to the microphone
- Extremely noisy events such as people shouting, blowing in horns, illegal motorcycle driven in noisy mode, poor exhaust systems, release of air from heavy vehicles, etc (which are mostly short events) will not contribute with their high noise level, just with the time during which they occur
- Background noise will not at all influence results

The L_{eq} is a kind of time "average", but which puts much higher weight to noisy events than to the "average" events. This level will have the following features:

- Passages of heavy vehicles will influence the level for the entire passage, but in particular when they are closest to the microphone
- Passages of light vehicles will influence the level too, but only when the vehicles are closest to the microphone
- Extremely noisy events such as people shouting, blowing in horns, illegal motorcycle driven in noisy mode, poor exhaust systems, release of air from heavy vehicles, etc (which are mostly short events) will have a major influence on the final level
- Background noise will not at all influence results

Due to the characteristics of many of the local streets, it is likely that there are many very noisy events which will influence the L_{eq} levels but not the L_{10} levels. The road surface will not affect these very noisy events at all, and it will affect the heavy vehicle noise just marginally. Thus the L_{eq} is not a good measure of the effect of the surface. Therefore, the author suggests in this particular case to use the L_{10} instead of the L_{eq} for the main evaluations.

The author has made a comparison of L_{10}, L_{90} and L_{eq} noise reductions on two road sections in the low-speed resurfacing programme. The results appear in Table 5. The L_{90} values look very different from the others and are probably much influenced by occasional activities at the road by businesses and customers. The author believes that the most relevant values are the L_{10} values.

Table 5. Comparison of noise reductions measured with L_{10}, L_{90} and L_{eq}

Road	Occasion	Noise reduction based on L10	Noise reduction based on L90	Noise reduction based on Leq
Castle Peak Road	Immed. after resurf.	2.65 dB	5.07 dB	2.22 dB
Castle Peak Road	3 mths after resurf.	3.01 dB	4.05 dB	2.58 dB
Wu Shan Road	Immed. after resurf.	2.16 dB	-1.35 dB	2.15 dB
Wu Shan Road	3 mths after resurf.	2.39 dB	0.95 dB	2.39 dB
Average		2.55 dB	2.18 dB	2.33 dB

9.2.8 Surface homogeneity and variability

It has been detected in measurements in Sweden, Germany and Denmark that there is often, if not always, a systematic variability in noise level on a porous asphalt surface along the test section. This occurs after some time of operation of the surface, sufficiently long to create some clogging of the surface. Near the joint to the dense surface on the road/street immediately ahead of the test section (as seen from vehicles driving along the road/street), it is typical that the noise level is relatively high close to the joint, but drops down with increasing distance from the joint until reaching a steady-state minimum after approx. 100 m. See Fig. 15 for an example.

The reasons are believed to be

- a gradual clogging due to transportation by vehicles of dirt from the adjacent dense road section, and this effect is worse the closer to the dense section one is. This effect can occur up to 100 m from the beginning of the test section
- a gradual clogging due to transportation by running water during rainfall containing dirt from the adjacent dense road sections, and this effect is worse the closer to the dense section one is. This effect can occur up to perhaps 20 m before the end of the test section
- it could also partly be a matter of adjustment of the paving machines. This effect can occur until 10-20 m from the beginning of the test section.

Porous surfaces are rarely homogene; a large point-to-point variability in air voids and thickness and surface texture is normal. The above phenomenon is a kind of systematic inhomogeneity which is also time dependent. However, there is also a random-type inhomogeneity built into the surface during the paving operation; possibly becoming amplified later due to traffic. Such variability was clearly seen on some sites inspected during rainy weather in December 2006. This makes measurements that rely on a spot measurement uncertain; such as the SPB method and the Leq-based methods, where the microphone is located on one location per test section and the area under study will be just a "spot" effectively from about 10 m before and 10 m after the position in the lane closest to the microphone position. It is not feasible to repeat measurement at several locations to compensate for this due to the high time consumption and costs.

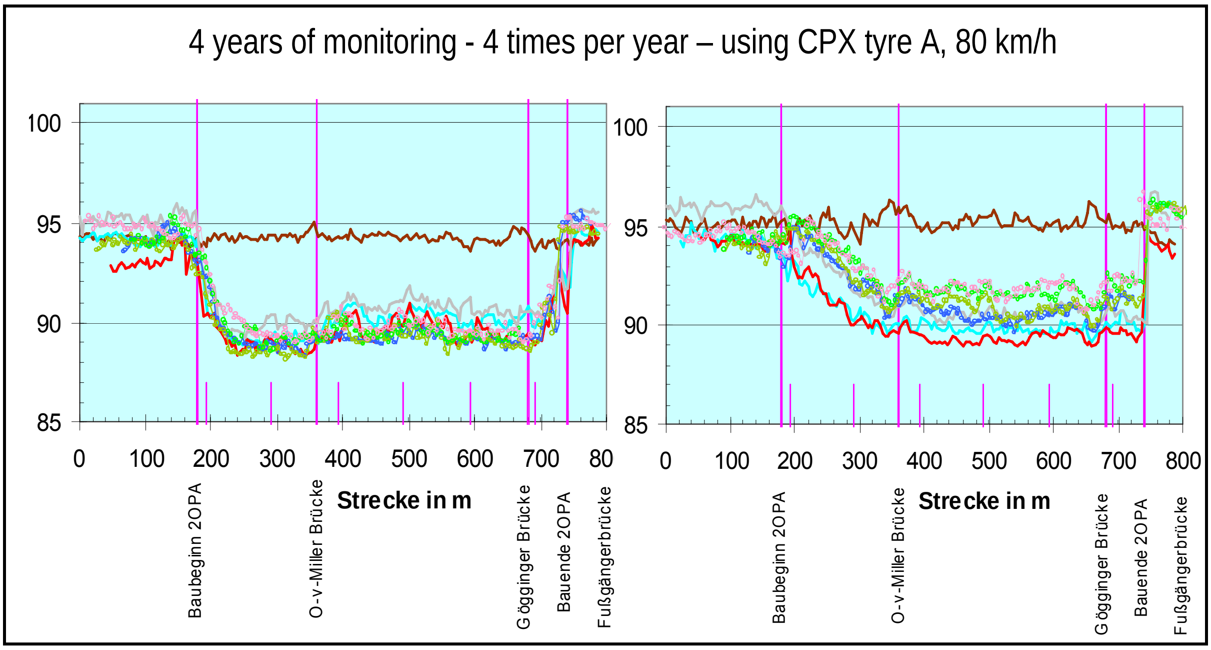

Fig. 15. Example of noise level versus distance measured at several occasions in Germany over a porous asphalt test section with dense asphalt at both ends. The left part shows measurements made during the first two years, the right part during the last two years. The porous surface starts approx at the mark at 180 m. Note the gradual noise reduction from the 180 m mark to approx. the 300 m mark. Figure used by permission [Beckenbauer, 2006]. Similar effects have been found in Sweden.

The CPX method will measure the noise emission along the full test section if the measurement operator so chooses. In this programme, therefore, it is suggested that the following procedure is used:

- Measure with the CPX method over the entire test section and record noise levels each 10 m (when running at 70 km/h, this corresponds to an averaging time of 0.5 s). Make a mark in the recording at the position of the place where spot measurements were made (if they have already been made).

Analyze the noise level versus time (or distance) from a graphic plot; the so-called "time history". Calculate and report four types of values:

- The average (arithmetic mean) of all the noise levels measured over the test length, minus the first 50 m (should be 100 m if total test section distance allows it) from the joint to the adjacent road surface at the beginning of the test section, and minus the last 50 m at the end of the test section. This will represent the average performance of the full test section with the supposedly extra clogged first 50 m and final 50 m eliminated.

- The standard deviation of the individual values taken over 10 m sections (according to the above). This will represent the surface homogeneity or lack of such.
- The noise level representing the spot (+/-10 m from the microphone position) where the spot measurements were made, or will be made. This will be a value describing how well the chosen spot represents the full test section.
- The noise level representing the first 50 m of the test section. This level minus the level according to the first point above will be a value representing the degradation of the surface due to extra dirt transportation from adjacent surfaces.

The above is a compromise. It would be preferred to consider at least 100 m from each end of the test section as potentially degraded due to transported clogging. See Fig. 15. However, the Hong Kong low-speed test sections are not always that long that they allow such long "run-in" sections at both ends of the test section.

9.2.9 Selection of within-site location for measurement

From the discussion above it follows that the selection of location for the spot measurement is crucial. With spot measurement is meant the measurements with the SPB, BALeq or LMLeq methods which are all made with a microphone placed at one single location per test section. Some recommendations for selection of such a spot are presented here:

- If a spot measurement has already been made, use the same spot for also following measurements, in order to be able to see the development over time.
- If a spot measurement has not already been made, first make a CPX measurement and determine from that one where the most representative spots are located. Select such a spot, after considering also the following points.
- Consider first where there are locations along the test section with a minimum of acoustical reflections from large objects. Select a spot where such reflections are minimum or close to a minimum. Note that in severe cases one may put sound absorbing material (such as 100 m thick mineral wool) to cover a reflective object during the time of the measurements. See Fig. 16 for an example.
- Consider also the location from the point of view of grades or bends. Avoid spots where there is a bend (curve) or where the road/street has an uphill or downhill grade.
- Consider also whether there might be disturbances from other or occasional noise sources at a potential location; for example an exit from a parking area, a bus stop or a pub playing loud music. Avoid such locations.
- Consider whether it would be feasible to use a backing board at the spot (if necessary); see Fig.12. If it is feasible, do so.
- Finally, check that the chosen location is free from road surface defects or anything that looks non-representative.

Fig. 16. Example of covering acoustically reflecting material with 100 mm mineral wool mounted in 2.4x1.2 m wooden frames, at the occasion of an SPB measurement (measurements in 2005 by VTI in Sweden). The SPB microphones were located at the far left roadside.

9.2.10 Day and night Leq measurements

At busy streets, in night-time one can expect that the noise sources are quite different from day-time. At day-time, important noise sources are delivery trucks, busses stopping and accelerating, people chatting, shops and local businesses in operation, and congested traffic. At night-time, the noise sources would change dramatically to traffic running mainly in free-flow operation and possibly some partying people; in the worst case perhaps a disco. It is this author's estimation that night-time noise would mainly come from road traffic dominated by cars and running essentially at free-flow, albeit sometimes stopping at red lights or turning.

The latter type of traffic would be the type of traffic for which the low-noise surfaces would potentially be effective. On busy streets in daytime they would not very likely be effective. But if night-time noise is especially disturbing to the residents since they need to sleep, a low-noise surface which is measured to be inefficient at day-time, might well be reasonably efficient at night-time when the noise reduction would be needed most of all.

From the noise monitoring sheets in the data directory for the test sections, it seems that noise monitoring was made during the time period 10:00 - 13:00 only. This would mean that only the most ineffective time period of low-noise surfaces on low-speed busy streets is measured, and the efficiency during night-time, when people should be particularly grateful for noise reduction would be totally neglected.

It is therefore recommended that supplementary night-time measurements are made starting as soon as possible. It is of course much more expensive and inconvenient for the staff involved, but in order to evaluate the programme it is an important issue.

9.2.11 Influence of temperature

It is commonly known that ambient and/or road surface temperature affects the measurement results significantly. If measurements are made on a hot summer day, the air temperature could be above 40 ^{o}C whereas on a winter day it could be 10 ^{o}C. A 30 ^{o}C difference may affect the results by 2-3 dB(A) for light vehicles and when tyre/road noise dominates. For a mix of traffic, and for LNRS surfaces specifically, somewhat lower temperature effects can be expected; perhaps around 1 dB per 30 ^{o}C. Measurements in such a wide range of temperatures are therefore very inaccurate if not corrected for or controlled in some way. Clearly, in the Hong Kong climate, a large part of the variation of noise levels in the low noise resurfacing programme will be caused by temperature differences. In the worst case such variations may be comparable to the variations caused by the surfaces.

It is suggested that measurements are not made if ambient air temperatures are below 15 and above 35 ^{o}C. It is also suggested that both air and surface temperatures are always collected and reported during the noise measurement period. In case of already conducted measurements, if no temperature data are available, it is suggested that such are retrieved by checking temperature history data, which should be available from the Hong Kong Observatory.

9.3 Issues related to the test program

9.3.1 Measurements on high-speed roads

In Hong Kong there are LNRS materials paved both on high-speed and low-speed roads. Although basically the materials are the same they might perform quite differently. There is a lot of experience of LNRS used on high-speed roads gathered over the last 15 years or so; including some measurements of the noise-reducing effects; whereas the experience with LNRS on low-speed roads is being collected in the present program.

There might then seem to be no point in making measurements on high-speed roads in the present programme. This author thinks that, despite the experience already collected on high-speed roads, it is worthwhile to include a certain number of noise measurements in the present program also on these roads. The reason is that the database gathered in a consistent and "standardized" way within this programme will become more useful if the "range" of surfaces and conditions can be extended and not "just" contain low-speed roads and a few medium-speed roads.

It is suggested that 5-10 test sections with LNRS on high-speed roads are added to the low-speed experimental programme as a kind of reference material. These surfaces should ideally be of different age and in different condition. Measurements may not necessarily be new; one may re-use data collected in some earlier programme for this purpose.

9.3.2 Measurements on surfaces other than conventional low-noise surfaces

A low-noise road surface (LNRS) in Hong Kong is usually assumed to be a porous asphalt concrete (PAC) surface, or more specifically a polymer modified friction course (PMFC) which is a particular kind of PAC. However, in the Hong Kong situation where a brushed cement concrete (BRCC) is often the surface type to be replaced by a LNRS material, also other than PMFC surfaces may be effective, and sometimes even more effective than PMFC when considering the whole lifetime and when applied in a low-speed street.

Therefore, it is suggested here that some SMA 0/10 surfaces and some surface dressings are included in the test program. A few SMA surfaces are already considered but it may be useful to extend the number of them somewhat to make sure that different ages and conditions are covered. SMA surfaces may be effective in cases only where they can replace a BRCC pavement.

The author has noted that it is common to apply on BRCC pavements near intersections a special type of surface dressing called "Sho-Bond non-skid paving material"; see Figs. 3-4. The potential noise-reducing properties of such surface dressings on BRCC in Hong Kong seem to have been neglected. The author estimates that such surfacing material might have a noise-reducing potential relative to the BRCC of 2-3 dB(A) if it is laid in the best possible way (which may not be the manual way in which it is normally laid). It is therefore suggested that measurements on a few such surfaces are added to the low noise resurfacing programme evaluations. One should then attempt to find a site with a particularly good Sho-Bond surface, and one of the poor type, to be able to see the range of noise properties of such surfaces.

9.3.3 Non-acoustic measurements

It is useful to have also other than acoustical data from the test sites. The author strongly recommends the collection of the following data on both the reference and LNRS pavements; in particular it is important that this is collected on the reference pavements existing before resurfacing:

- Outflow time, according to the draft European standard prEN 12697-40, see [prEN 12697-40, 2004]. This is a measure of the drainability in vertical direction of a porous surface. Using this will give direct possibilities to study the development of clogging. See Fig. 17.
- Mean Profile Depth (MPD), according to ISO 13473-1. This gives a value representing surface texture which is well correlated with the skid resistance at high speeds, but also used worldwide to characterize road surfaces. See Fig. 18.
- If a profilometer is not available, a simple volumetric patch measurement, according to the European standard EN 13036-1 is suggested, see [EN 13036-1, 2001]. This gives a value representing surface texture which is not as accurate as MPD, but which has been used worldwide to characterize road surfaces (now being phased out and replaced with MPD). See Fig. 19.

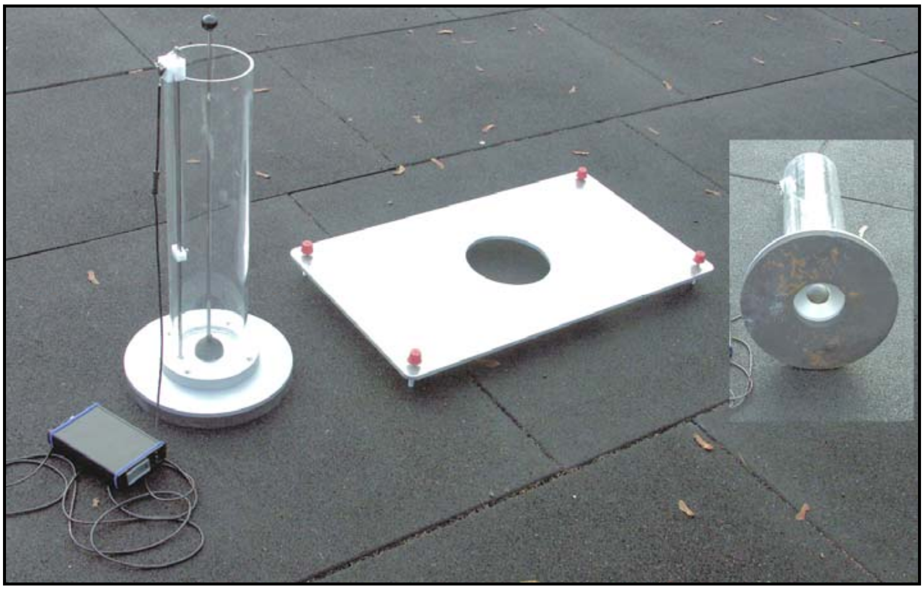

Fig. 17. Equipment for making water outflow measurements. The rubber ring under the meter intended to tighten the space against the road surface is shown at the far right.

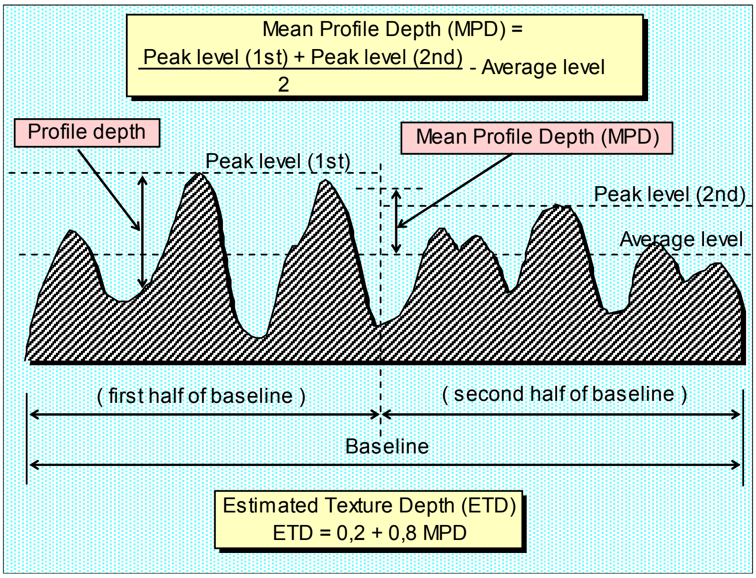

Fig. 18. Determination of Mean Profile Depth (MPD) from a road surface profile curve according to ISO 13473-1.

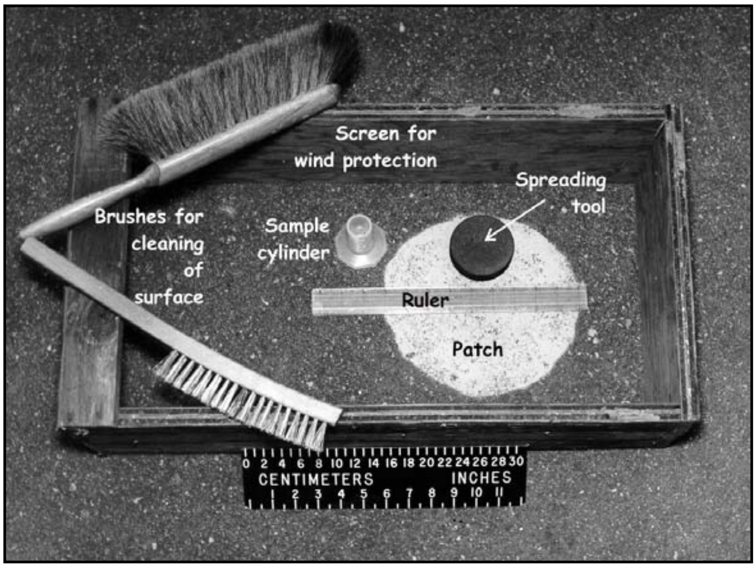

Fig. 19. Equipment for making standardized volumetric patch measurements.

In addition, this author strongly recommends that a few 100 mm or larger bore cores are taken at the LNRS test sections for study in the laboratories to determine air voids content and layer thickness. This should be made not only when the surfaces are new but also later in time, for example each second year. The analyses of air voids content for various ages of the surfaces will be most valuable for determination of the degree of clogging.

Optionally, these bore cores may also be used for measurement of sound absorption by the tube method, in case the commissioned laboratory has such equipment. If this will be made, the author may provide the most recent recommendations and standards, since such methods are presently being standardized within ISO. Such analysis can also be made by overseas laboratories; for example VTI has recently acquired equipment for this purpose. The sound absorption data will give information of (for example) which sound frequencies that are most efficiently reduced by the material, to see if the material is optimized for traffic noise or not.

Optionally, the bore cores may finally be sent to some laboratory where CT scans of them can be made to study in detail the structure of the material, its porosity and clogging (CT = computed tomography, a kind of X-ray analysis). Such services are best made at the Danish Road Laboratory (DRI), see [Bendtsen et al, 2005b], but also Linköping University, neighbour of VTI, can do such analyses in cooperation with VTI.

9.4 Issues related to the data analyses and final assessment of experimental results

9.4.1 Reference surface importance

Crucial to the results will be the noise properties of the reference surface. A reference surface is a road or street surface material against which the low-noise material (LNRS) is compared in order to determine the noise reduction obtained when repaving with the LNRS.

The simplest may be to use as the reference the surface existing before repaving. In the Hong Kong situation BRCC is often the type of surface to be replaced by a LNRS material; thus such a surface would become the reference. In case where a DAC is repaved with a LNRS, the DAC may become the reference. Since the BRCC and the DAC may have very different noise properties, which also may be the case within each surface group, it means that exactly the same LNRS material will give different noise reductions depending on the reference surface. In fact, the "choice" or "existence" of reference surface, and its condition, may affect the noise reduction more than the choice of LNRS material. **The value obtained from a study may more reflect the "noisiness" of the reference surface than the "quietness" of the LNRS. This is often the case in the Hong Kong studies where very different and often undefined reference surfaces are involved.** Noise reduction values will then be meaningless for anything else than comparison to the particular surface on the site before the repaving.

9.4.2 The HARMONOISE virtual reference surface as an alternative facilitating international comparison

This author thinks that one alternative would be to apply the reference surface philosophy developed for the new European traffic noise prediction method HARMONOISE. This is explained and described in a recent paper [Sandberg, 2006]. It means that one would use as a (virtual) reference surface an "average" of a DAC 0/11 and an SMA 0/11. See Fig 20. How such a surface differs from the actual reference surfaces (the ones being repaved) in the Hong Kong experiments, may be determined with a correction procedure described in [Sandberg, 2006] and in Table 1. It happens that the Hong Kong DAC 0/10 and SMA 0/10 are very close to the virtual one and thus corrections will be very small and therefore accurate (+0.5 dB from a DAC 0/10 to the virtual reference). No particular measurements are needed for application of this correction. See chapter 6.2. Thus, by making noise measurements on a Hong Kong DAC 0/10 surface as part of any LNRS test, and adding 0.5 dB to these measurements one would have as the reference surface the virtual reference of HARMONOISE. This would facilitate international comparisons.

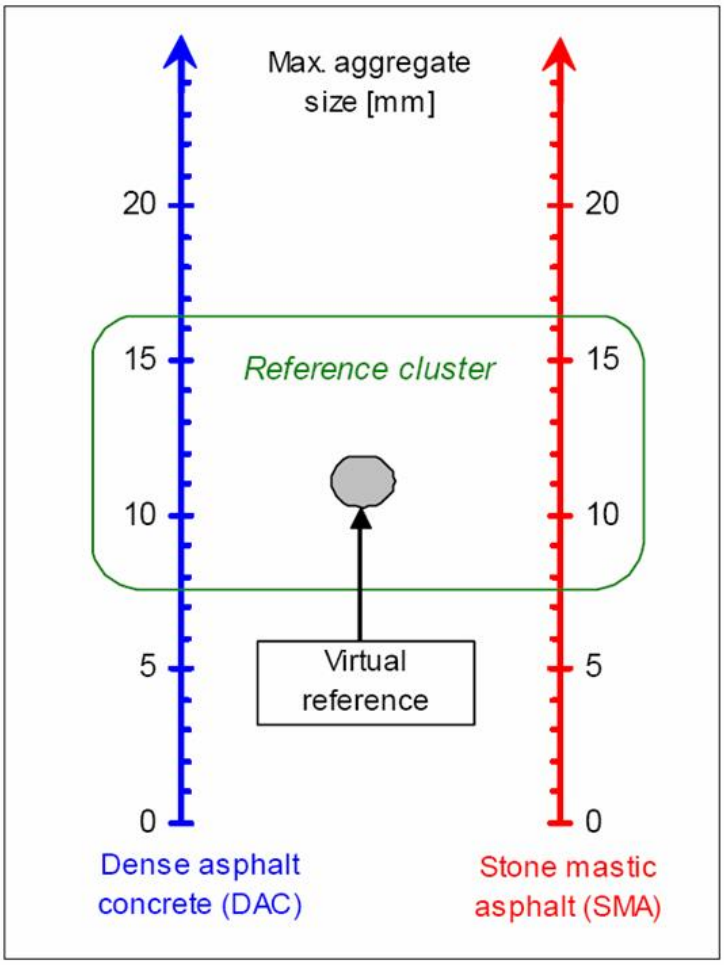

Fig. 20. The concept of the virtual reference surface as being an average of an SMA and a DAC surface with max. 11 mm aggregate size, and the cluster of surfaces being allowed to use as an actual reference, provided a normalization of measured values to the virtual reference is made.

The BRCC surfaces are more difficult to evaluate in this context, for the following reasons:

- These surfaces are generally much "noisier" than DAC 0/11 or SMA 0/11; therefore a rather large correction to normalize to the virtual reference is needed; and larger corrections mean larger uncertainties
- Variability is high between various BRCC surfaces due to the paving and brushing process but also due to the influence of wear

Therefore, it is suggested to compare within the test programme, with the greatest possible accuracy, some BRCC surfaces with a number of either DAC 0/10 or SMA 0/10, or a mix of them. This can be made by means of CPX measurements. For this purpose, CPX measurements on (say) approximately five BRCC and five DAC or SMA 0/10 surfaces should be made. The average of these differences would constitute the correction to be made for the normalization of the BRCC surface to a DAC 0/10 and SMA 0/10 surface, and from the latter to the virtual reference surface a standard correction can be made according to [Sandberg 2006]. It is possible that such measurements will automatically be included in the test programme since they might be part of the test sections under study. If this is not so, it is recommended that such measurements supplement the test programme. They can normally be made within a couple of days.

The difference between the commonly used DAC and SMA surfaces in Hong Kong and the virtual reference surface are as follows, based on [Sandberg, 2006]:

- From DAC 0/10 to DAC 0/11: Add 0.25 dB to the value measured on DAC 0/10
- From SMA 0/10 to SMA 0/11: Add 0.25 dB to the value measured on SMA 0/10
- From DAC 0/11 to the virtual reference: Add 0.3 dB to the value measured on DAC 0/11
- From SMA 0/11 to the virtual reference: Subtract 0.3 dB to the value measured on SMA 0/11
- From DAC 0/10 to the virtual reference: Add 0.55 dB to the value measured on DAC 0/10
- From SMA 0/10 to the virtual reference: Subtract 0.05 dB to the value measured on SMA 0/10; i.e. set the correction to 0 dB.

The two last points are the final corrections to be applied to Hong Kong measurements made on DAC or SMA as pre-resurfacing material, to bring the noise reduction values to the virtual reference. For BRCC surfaces, as described above, additional measurements are needed to determine the correction factor. According to [Roovers & Doorschot, 2005] brushed concrete is around 2-3 dB(A) "noisier" than DAC 08 and DAC 0/11 for car tyre/road noise. This is consistent with the conclusion in an NCHRP study in the USA where it said "In general, when dense-graded asphalt and PCC pavements are compared, the dense-graded is quieter by 2 to 3 dB(A)" [Wayson, 1998].

The consistent use of a well-defined reference would facilitate international comparison and would make comparisons with other surfaces and with future measurements easier and more relevant. Statements of "noise reductions" will no longer depend on the material used before repaving, but will always refer to the virtual reference surface. However, in cases when one would like to talk about noise reductions relative to a BRCC surface instead, one simply adds the correction determined by the simple tests described above.

9.4.3 Practical reference surface procedure within the present programme

The author first thought that the virtual reference of HARMONOISE would be the best procedure for use in the LNRS low-speed trial programme, but after studying the procedures already used in the beginning of the programme and a great number of noise monitoring reports, it has become apparent that it will not work well unless the test programme is completely reworked. Therefore, the author has the following suggestions instead, which are much more practical:

In each trial site, clearly define and document the type of pre-resurfacing pavement. As argued earlier, this is equally important as defining the LNRS! This information shall include the main type (rigid or flexible), for flexible pavement also the max aggregate size; for a rigid pavement the type and direction of texturing shall be reported. The report shall also include a measurement of the texture depth by the volumetric ("sand patch") or the MPD method. It shall also include a close-up photo of the surface. The area to be covered could be approx 200x150 mm and it shall always include a one dollar coin as a reference item in the picture.

Essentially, this will mean that there will be two major types of reference surface: BRCC and DAC 0/20; possibly with a few exceptions. In order to be able to compare results between these two cases, a special study shall be made to compare these two reference cases; i.e. to determine a "correction factor" (a decibel value) that shows the difference between these cases. This study can still be made, and should be made as soon as possible. The author recommends that it be made using both the CPX and the SPB methods. In case of the CPX method, the two reference tyres shown in Fig. 14 should be used.

Once the above comparison has been made, it will be possible to correct all measurements to the case of a DAC 0/20 reference, which will mean that all noise monitoring values will be referenced to a common reference surface. The present situation is that there is no control of the reference surface characteristics.

9.4.3 Temperature corrections

With temperature data available, as suggested in an earlier section of this report, it is suggested to apply corrections to the measured noise levels to a reference temperature of 20 ^{o}C. The best available data for this are presented in [Sandberg, 2004b]. The corrections suggested there are intended for tyre/road noise; there are no consistent data available for power unit noise from vehicles. In this programme, it is suggested to apply this correction to the CPX and SPB results; in the latter case only to the light vehicles. In order to avoid confusion, this correction should be made as one of the last steps in the data analyses, in order that there will be tables both with and without the temperature corrections applied.

9.4.4 Control of uncertainties

The uncertainties in the noise monitoring for the low-noise resurfacing programme are large; the author estimates it to be approximately ± 1 dB expressed as 95 % confidence limits. This is comparable to the noise reductions indicated so far, which are approx. 2 dB(A). The reason for the uncertainties is a large number of error sources adding up to a total. Fortunately, the noise monitoring takes place each 3 month, which means 8 times in two years, and if one looks at the "average" trends of these values, the total uncertainty may become reasonable.

To judge the quality of the data, it is suggested that at one place a special study is made to determine the typical spread between nominally identical measurements. It could be performed by repeating a noise monitoring exercise between 10:00 and 13:00 (the normal time so far) each day for an entire week; i.e. five times. This will give an idea of the spread in noise levels for an individual noise monitoring session with no expected change in the surface during this week. Such an exercise is important to determine the possibility to distinguish between differences in results, and to judge at which locations the PMFC surface worked fine and where it did not work fine.

There is one potential uncertainty which dominates the whole picture. This is the noise monitoring before resurfacing. Just as all other noise monitoring, this "before" monitoring has been appears to have been made for a total duration of only 3 hours. But this event determines the reference value, against all later measurements will be compared. An uncertainty here of (say) ±1 dB will mean that all subsequent noise reduction calculations (made once per 3 months) will suffer from the same uncertainty. This is not acceptable. In order to have an optimum uncertainty balance, the uncertainty of the "before" measurement must not be greater than the uncertainty of the combined noise reduction values over one or two years. To solve this problem it is suggested here that each "before resurfacing" monitoring exercise is repeated at least three times, in order to give a total of four monitoring events to average. In this way, the uncertainty of the "before" measurement, on which all noise reduction values are based, is reduced to half of the present one.

10. REVIEW OF THE LNRS CONSTRUCTION TECHNOLOGY IN HONG KONG

10.1 Review of the "Guidance Notes on Noise Reducing Road Surfacing"

The "Guidance Notes on Noise Reducing Road Surfacing" [HyD GN, 2001] is described briefly in Chapter 8. The author's review has resulted in the following comments related to the Notes.

Nowadays, those who work with pavement engineering should be well aware of the experiments made with low-noise road surfaces in Hong Kong; thus the introductory sections with general noise-related information can be deleted and replaced with a bibliography on the subject, or alternatively be moved to an appendix.

Nevertheless, it would be good to include a table in which expected noise reductions by low-noise surfaces in various situations (speed, traffic composition etc) was listed. One should then distinguish between cases where the initial surface is a brushed cement concrete (BRCC) and where it is an asphalt concrete. Furthermore, one might include also a diagram or some description indicating how much and how fast the noise reduction deteriorates with time.

The specifications of the PMFC have been updated since the document was written in 2001. The latest version, appearing in this report as Table 3, should be included.

It is stated that in low-speed situations, PMFC is not laid on cement concrete. This is definitely wrong; thus this paragraph should be corrected.

It is stated that exposed aggregate cement concrete (EACC) cannot be used in Hong Kong due to the aggregate available in Hong Kong is not sufficiently polish-resistant. This author does not challenge this statement, but suggests including a comment regarding possibilities to import suitable aggregate from the closer parts of Mainland China. The author also suggests including a note about the noise reduction properties of diamond ground cement concrete (see the Benchmark report), which the author considers as the potentially best way of reducing noise emission on BRCC pavements in Hong Kong.

It is also stated that thin surfacings have not been tested in Hong Kong and cannot therefore be used as low-noise materials. It would be good to have some statement related to the prospective use of such surfaces and why they have not yet been tested despite their promising features. It may be noted that thin surfacings have several advantages in typical Hong Kong situations, such as low thickness and thus weight, which is important on bridges, flyovers or where the height of barriers or kerbs may be negatively affected by a thicker surface.

It is stated that SMA surfaces reduce noise by 2-3 dB(A) compared to traditional bituminous surfacing. In general, this is misleading, probably due to incorrect or misleading information in the overseas literature. SMA surfaces are not significantly noise-reducing compared to bituminous surfacings with similar aggregate sizes; rather the contrary. Exceptions, maybe responsible for the misleading statement, may be the "noisy" HRA surfaces used traditionally in the U.K. but now being phased out due to their "noisiness" or the German "Gussasfalt" compared to German SMA surfaces. Nevertheless, in the special Hong Kong case, the statement is has some justification, since the "traditional bituminous surfacing" in Hong Kong is a dense asphalt concrete with 20 mm chippings, with an extremely smooth texture. In comparison to such a surface, an SMA with 6 or 8 mm chippings may in fact be 2-4 dB(A) quieter. A well-designed SMA 0/10 may then be some 2 dB quieter than a very smooth-textured DAC 0/20.

It is recommended to mention that the BRCC may be resurfaced with a dense asphalt concrete (DAC 0/10) or an SMA 0/10 to provide approximately 2 dB of noise reduction on a high-speed road and (at least) 1 dB on a low-speed road; in cases where a PMFC would not qualify or be sufficiently efficient due to expected clogging.

The binder type and amount in PMFC is of crucial importance. A special study was made within the Dutch IPG program concerning the binder which is probably the most comprehensive study on binder properties in porous asphalt that has been published [Nielsen, 2007]. Modifiers such as SBS, EVA and rubber were studied for a total of 13 test sections. Despite the systematic approach the author was unable to publish some advice or firm conclusions regarding the preference of binder modifiers or the amount used. Therefore, this author is also unable to give some advice regarding the binder and its modifier in the Hong Kong PMFC Guidance Notes. However, the author suggests that the road engineers in Hong Kong consider the Japanese binders. The specifications for porous asphalt used by MLIT in urban areas were obtained by Mr Albert Liu during the study visit to Tokyo/Japan 17 May 2007 and this author believes that these might contain the best available binder specifications for the Hong Kong climate.

The policy of PMFC use can be improved; but suggestions for this are presented in a later section of this report. Also the specifications for PMFC can be improved; but suggestions for this are presented in section 10.6 of this report.

Requirements for kerbside drainage are missing. Whenever the wearing course is bordered by kerbstones, a water basin is created in wet weather if the drainage provisions are inadequate, and the PMFC will become saturated with water and increasingly dirt-filled. The kerb-side drainage in the trials in Hong Kong that this author has seen is inadequate. It is recommended to study the Danish, German and Japanese experience on this[11]; see Fig. 21.

10.2 Aggregates, binders and gradings

In Hong Kong, the aggregate is produced by means of sieves 5, 10, 20 or 40 mm; see Fig. 22 which was shot at a visit to Tarmac Asphalt Hong Kong Ltd.

[11] See examples in the Benchmark report

Fig. 21. Kerbside drainage system used in experiments with double-layer porous asphalt in the city of Copenhagen 1999-2006 (photo by the author).

Fig. 22. Aggregate fractions and materials typical of Hong Kong. From the left: 40 mm, 20 mm, 10 mm, and 5 mm and less. The upper row is volcanic, the lower is granite.

The limited number of sizes is probably a small economic advantage, but it limits the freedom in design of an optimum surface. In most countries in Europe, and also to some extent in USA, the number of aggregate fractions produced is at least twice as high; for example in Sweden it is common to supply 2, 4, 6, 8, 11 and 16 mm, sometimes also 14 mm and 20 mm. The different sizes give increased possibilities to proportion a mix in a more optimum way for a particular purpose.

It is suggested that Hong Kong abandons the old limited "system" and starts producing aggregate based on sieves 16, 11, 8, 6, 4 and 2 mm, like in Europe.

If for example thin surfacings are to be produced in Hong Kong such a change in aggregate policy is absolutely necessary.

The aggregate material does not have sufficient PSV values to make it possible to produce Exposed Aggregate Cement Concrete. It may be justified to investigate whether nearby parts of Mainland China could supply such an aggregate. If the transportation distances are not too high, the extra cost might be worthwhile.

The PMFC which is the dominating low-noise surfacing, uses a polymer modified binder (RLA 2097/1 according to the Guidance Notes), and a binder content of 5.5-7.5 %. Recommendation for an improved binder cannot be given by the author at this stage.

The PMFC is considered to be weak in terms of ravelling resistance under conditions of accelerating, decelerating, braking or turning traffic; especially for heavy vehicles. It should be possible after some research to find binders for increased ravelling resistance (note the research in Europe and Japan). In the meantime, one might consider using the Japanese method of adding a small amount of epoxy binder in critical spots to substantially increase durability at intersections and similar critical locations.

For the SMA trials in Hong Kong rather serious flushing has sometimes occurred. It could be worth considering whether the binder might be unsuitable for the SMA:s in the Hong Kong climate? The reason may also be inexperience or inaccuracy of the contractor. Although in Sweden there are now a couple of decades of experience with SMA surfaces, now and then such resurfacing operations still result in inhomogene surfaces with patches of flushing. It is extremely important that the contractor uses the utmost care in his SMA operations.

10.3 Special concerns at critical spots

Critical spots with regard to durability of a PMFC might be the following:

- Intersections with other streets, where vehicles are stopping and accelerating and sometimes also turning
- Bus stops; where buses accelerate and decelerate and also turn a little
- Exit/entrance from/to parking areas, where vehicles are stopping and accelerating and sometimes also turning
- Lanes used for parking; where vehicles start and stop and also turn their wheels

- Parking bays for motorcycles; where the stands for the machines give very high pressures at the point where they touch the pavement; it is similar to knocking with a hammer on the pavement.

There is no particular advice regarding critical spots in the Guidance Notes, apart from bridge and end joints and concrete slab joints. Nevertheless, the spots listed above are presently handled in this way:

Intersections with other streets: Here it is common to use a DAC instead of the PMFC
Bus stops: Here it is common to use a special durable semi-flexible surface designed for bus stops, but in many streets there are no special strengthening measures
Exit/entrance from/to parking areas: Special measures are not usually applied
Lanes used for parking: Special measures are never (?) applied
Parking bays for motorcycles: Special measures are never (?) applied

The problems can be alleviated in the following ways. The current policy of using dense asphalt at intersections may be replaced by the Japanese way of adding epoxy (see above). The epoxy will make the surface less pervious, so most of the noise reduction is lost, but the advantage is that it is not necessary to change paving material when crossing an intersection. The same thing should also be tried at bus stops and at exits and entrances to parking lots.

Where there are parking bays for motorcycles, could one perhaps put up special permanent motorcycle stands (in concrete?) into which the motorcycles can be fixed in order that the regular motorcycle stand is not needed? Such pre-mounted stands may be less expensive than repaving or repairing the surface. Or consider the epoxy method here again.

10.4 Paving technology

The author knows too little about the paving technology in Hong Kong, and about paving technology in general, in order to be able to comment on this topic. However, if double-layer porous asphalt will be used in Hong Kong in the future, the hot-in-hot paving technology shall be used, see [Sandberg & Masuyama, 2005].

Hong Kong might also want to consider the technology developed in Japan to recycle old dense asphalt into a porous asphalt layer. This will be described in the Benchmark report.

10.5 Maintenance

It is important that maintenance work will not be too burdensome. Maintenance work would cause disturbance to other road users and, if carried out during night-time, would cause sleep disturbance. Maintenance issues of special concern to PMFC would be:

- Spot repairs (such as damages due to ravelling)
- Rejuvenation
- Cleaning of the porous structure

Spot repairs: The author has no comment regarding this topic other than that he has seen very nicely done spot repairs of PAC surfaces in Tokyo.

Rejuvenation: It is suggested that critical spots of a PMFC are rejuvenated periodically (say, in year 2 and 4 after resurfacing) in order to extend the technical lifetime. This will reduce the noise reduction but it will prevent the exposure to air in the open structure to affect the material too much. It should be economically justified. Rejuvenation is treated in [Sanders, 2005]. There is a world-class expert on rejuvenation technology and materials in Sweden.

Cleaning: This will be treated in the Benchmark report. See also [Sandberg & Masuyama, 2005]. However, it can be mentioned already now that so far no really effective cleaning methods have been demonstrated. The Japanese method of cleaning one time per month is the most promising, but it is probably not cost-effective for low-speed roads in Hong Kong and monthly cleaning operations would cause disturbance on these local roads and streets. Nevertheless, it is suggested that a pilot study on this topic is considered in Hong Kong based on the study tour to Japan.

10.6 Possibilities to improve the construction technology

10.6.1 Material with improved noise reduction without jeopardizing durability

The diagram shown in Fig. 23 was presented earlier in the report. It is reproduced here too since it is essential to the following discussion.

First it shall be reminded that the essential parameters to control for an efficient noise reduction are maximum aggregate size (to create a smooth surface for the tyres to run on), air voids content (to provide good drainage of air and water and to provide sound absorption), and thickness (to provide sound absorption at frequencies low enough to fit the traffic noise spectra and to provide a good reservoir for accumulation of dirt).

To improve the noise reduction potential, the first thing that one can do is to eliminate the oversized aggregate; i.e. the fraction between 10 and 14 mm. The disadvantage would be essentially economical since it is not so easy to get rid of the oversized material.

The second thing would be to reduce maximum aggregate size from 10 mm to 8 mm (again with no oversized material). The two measures so far would increase noise reduction by about 1 dB(A), and this is likely to remain over the full lifetime of the surface. The disadvantages with the change from 10 to 8 mm might be:

- As written above, the grading system in Hong Kong must then change, since at present an 8 mm aggregate is not produced. This should not really be a big problem more than before the change has been fully carried out. The aggregate cost might increase marginally.

- Possibly, an 8 mm aggregate instead of 10 mm might affect the risk of ravelling, but if so it would be only marginally.

The third thing would be to increase the thickness from the present standard 30 mm to 50 mm. The ongoing tests on Chui Tin Street suggest that this increases noise reduction by about 0.6 dB(A), while Fig. 10 predicts 1 dB(A) (for only light traffic). The disadvantage will be economical: more material is consumed, which makes the resurfacing more expensive. In special cases, such as on bridges, the increased thickness and weight might be a problem. Kerbstones might need to be exchanged, anyway.

The fourth way will be to increase the voids content. This may be achieved by approaching the steeper shape of the Swedish mix in Fig. 23; maybe adopting it but moving it to the left to get an 8 mm max. aggregate size instead of 11 mm. The Swedish mix is stated in the manual to give 17-21 % of air voids, but experts at VTI agree that it seems to be an underestimation. One might try further to reduce somewhat the content between 2 and 5 mm in order to increase the voids further, perhaps to 25 %. However, there is always the risk of increased ravelling due to the increased voids, so the effect should be checked by laboratory tests. One might also try to find improved binders. The positive side is that increased voids mean somewhat lower aggregate consumption and lower weight.

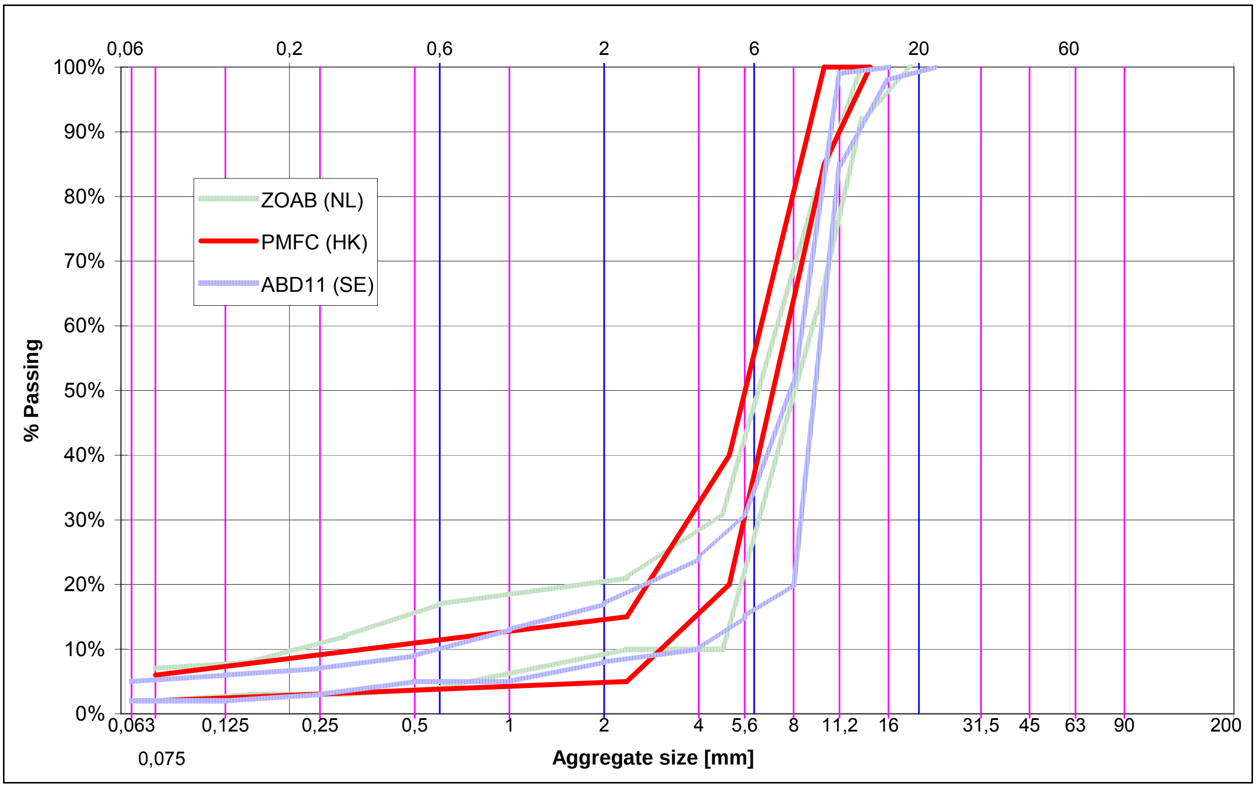

Fig. 23. Grading of the conventional PMFC (Table 3); here compared to the corresponding "standard" PAC surfaces in the Netherlands ("ZOAB") and Sweden ("ABD11"). ZOAB means very open asphalt concrete and ABD11 means drainage asphalt concrete 11 mm.

The mixes shown in Fig. 23 are by no means state-of-the art mixes; they are "standard" mixes in their countries. State-of-the-art mixes, tried in Europe, combine the suggested improvements mentioned above.

To go even further one may use double-layer mixes, achieving thicknesses of 70-80 mm, such as was used in the Danish city experiment.

Finally, one may try to blend a significant amount of rubber granules 1-3 mm into the binder; such as is made in the Arizona ARFC mix. They use a rubber contribution of 2 % by weight of the total mix. As was written earlier, this might offer an extra 1-2 dB(A) of noise reduction. See further the subchapter about the EcoPark below.

10.6.2 Improved drainage of surrounding structures

The study visits in December 2006 (see Chapter 11) highlighted the problems with poor drainage of structures surrounding the PMFC. It was observed that the PMFC sections on low-speed roads were partly or totally saturated (filled and flooded) with water already during a moderate rainfall. This creates a number of problems:

- Water spray is not reduced in comparison to conventional paving materials.
- All noise reduction is eliminated until the surface has been reasonably dried up.
- The water standing still on the surface, often creating a pool covering most of the carriageway, will help spread dirt from the road edges to the main part of the surface, thus spreading clogging over a larger surface
- Dirt polluting the water flowing from the pedestrian areas (from shops, etc) and from exits of parking lots and yards will be spread out over the PMFC instead of draining away directly at the kerbside.

In general, to avoid the negative effects above, it is important that water and dirt in the water is transported away from the PMFC as quickly as possible. The present drainage on the low-speed roads and streets is far from satisfactory. The fast clogging on such roads is probably partly due to this. It may be 10 m or more between gullies and there is generally no other means of transporting water and dirt away from the kerbside. A better construction would be that shown in Fig. 21, which will be described in detail in the Benchmark report.

Therefore, this author thinks that it is a necessity to substantially improve water drainage at the kerbside, maybe also at a few places under the PMFC layer if the area covered is large (such as at intersections).

Another thing to consider is to increase the lateral slope (crossfall) of low-speed roads from the present minimum of 2.5 % [HyD GN, 2001] to 3 %, perhaps with a design target of 4 %. Over a carriageway width of 5 m, 4 % makes 200 mm. This would not be desirable on a high-speed road, but it may be acceptable on a low-speed road. Anyway, the author's subjective impression is that the minimum crossfall of 2.5 % is not really met at many of the streets visited. It is suggested here that this parameter is actually **checked** in 2008 on each test section.

10.6.3 Miscellaneous topics

The addition of a small amount of epoxy at critical spots such as at intersections, mentioned in 10.3 above, would be a way of improving the construction towards decreased ravelling and increased durability.

10.6.4 Improvements for cement concrete surfaces

In cases where a cement concrete surface is preferred, either in new construction or as a re-conditioned old surface, the following low-noise alternatives are suggested:

- For a new construction; use an EACC pavement with max. 8 mm chippings
- In case of an old existing surface in reasonable condition: Use diamond grinding to make the surface even and to give it a longitudinal "quiet" texture with good wet skid resistance
- In case the old surface is even, smooth-textured and in good condition; use the Sho-Bond surface dressing as a temporary surface to reduce noise and increase skid resistance

11. REVIEW OF THE HONG KONG LOW-NOISE RESURFACING PROGRAMME FOR LOW-SPEED ROADS

11.1 Previous experience with LNRS on high-speed roads

The first trial with low-noise surfacing in Hong Kong took place in 1987, when a 50 mm thick 10 mm nominal aggregate size PMFC with 18-25 % air voids was laid on a portion of the Island Eastern Corridor flyover [Ng & Tse, 2005]. This road had a speed limit of 70 km/h, and the test section was about 300 m long. The flyover initially had a brushed concrete surface carrying some 55,000 vehicles daily with a percentage of heavy vehicles of about 25 %.

The PMFC tried in that experiment was 50 mm thick as compared to 30 mm for the present "standard" PMFC and might have had a little higher air voids content. Noise emission was monitored with what is called the BALeq method in Chapter 9.2.

Fig. 24 shows the deterioration of the noise reduction effect of the PMFC against time [Ng & Tse, 2005]. About 5 dB(A) of noise reduction was recorded initially which then deteriorated to about 1 dB(A) at an age of 5 years, which could be seen as the end of the "acoustical lifetime". Also the maintenance records for this and other trials indicate that service life of this type of surface on high speed roads is around 5 years.

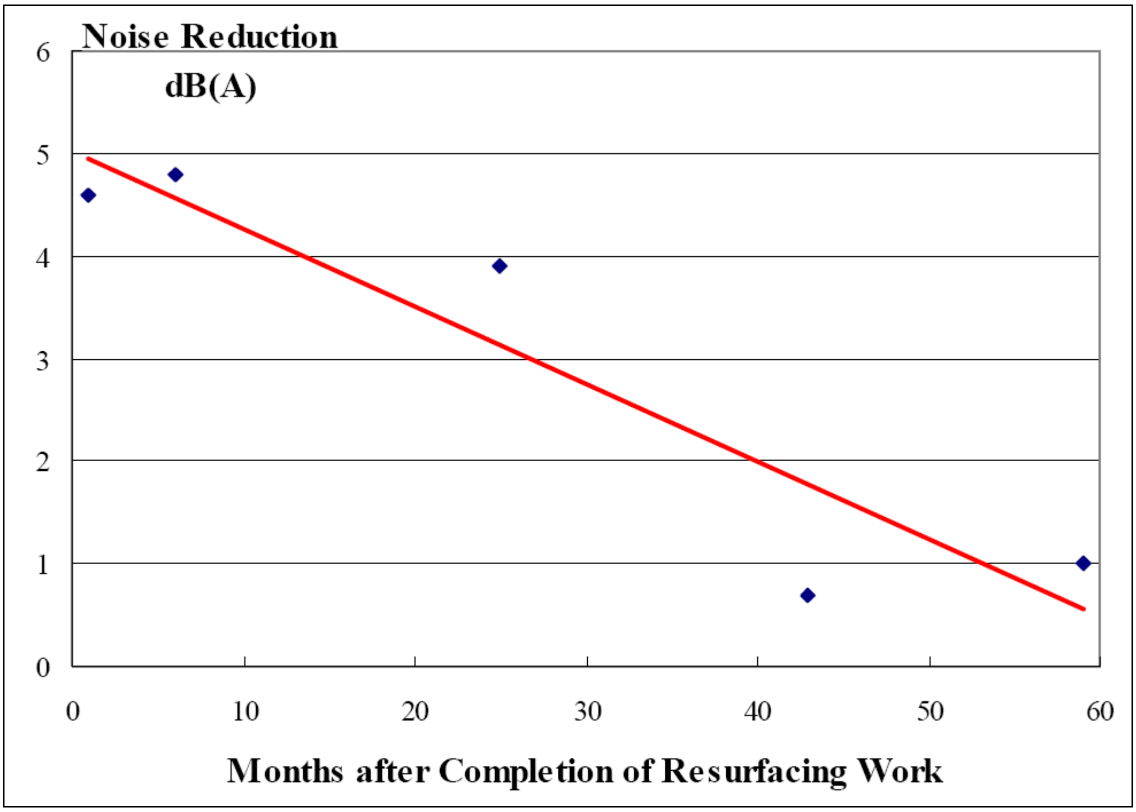

Fig. 24. The change against time of the noise reduction effect of the PMFC in the 1987-1992 trial on high-speed road. Figure copied from [Ng & Tse, 2005].

The following may be noted from this experience:

Service life of a PMFC is about 5 years on high-speed roads. On low-speed roads one may probably expect a lower service life.

The noise reduction of 5 dB(A) initially is not very high if one considers that it is compared to the original brushed cement concrete. Had the original surface been a DAC 0/11, the noise reduction would more likely had been about 3 dB(A). The rather small noise reduction recorded may be an effect of three things: At the speed of 70 km/h (1) and a heavy vehicle proportion as high as 25 % (2) and with the relatively noisier heavy vehicles of that time (3), the contribution of heavy vehicle power unit noise would probably had been over 50 % after the resurfacing and thus would limit the noise reduction obtainable by tyre/road measures.

Noise reduction deterioration was about 0.8 dB(A) per year, which is comparable to the noise reduction deterioration rates recorded elsewhere on early versions of porous asphalt; for example the 1 dB(A) per year that the Japanese were counting of some years ago for the Japanese single-layer porous asphalt with 13 mm aggregate paved on the expressways. This is also similar to Swedish experience on high-speed roads. In middle Europe, recent data from research programmes indicate deterioration rates of approx. 0.3 dB(A) on high-speed roads.

After the trial described above, more tests were made on high-speed roads (generally 70 km/h) in a programme completed in 1999 with 11 km of highways resurfaced; benefiting about 16,000 homes [Ng & Tse, 2005]. The experience from these only confirmed the results of the first trial.

It was concluded that to realise the full noise reduction benefits from resurfacing work, the roads under consideration must meet with the following criteria [Env HK, 2000]:

1. The road should be relatively level (otherwise power unit noise will dominate)
2. The road should originally be paved with brushed concrete or other similar non-open textured surface (producing a high level of tyre/road noise)
3. The road must carry smooth high speed traffic (where tyre/road noise will be a problem) with a low percentage of heavy vehicles
4. The traffic noise from the road is a dominant noise source (reducing which will become tangible)

11.2 Previous experience with LNRS on low-speed roads

11.2.1 Summary and analysis of the trial study 1995-1997

The present low-noise resurfacing programme for low-speed roads is based on the experience of an earlier test programme "Trial study on the use of friction course as a noise mitigation measure on low speed roads" [HyD 022, 1998].

To review the mentioned study is not within the objectives of this project. However, the experiences and results of that study are so interesting and valuable to compare with the present programme that a summary of its findings are included here.

The study learned from the high-speed road studies and used basically a similar material (PMFC) but in four variants:

Material A: PMFC, 30 mm thick with 10 mm aggregate

Material B: PMFC, 30 mm thick with 14 mm aggregate

Material C: PMFC, 50 mm thick with 20 mm aggregate

Material D: PMFC, 30 mm thick with 10 mm aggregate, on top of PMFC, 50 mm thick with 20 mm aggregate, thus creating a double-layer porous asphalt

In the report it is stated about the road surface used before the resurfacing: "The original topmost surfacing materials of the five trial sites were ordinary wearing course...". The author has tried to get information about what this means, but several indications point at a dense asphalt concrete (DAC). However, there is no clue as to the maximum aggregate size; it would probably be either 10 or 20 mm.

As test roads, the following five trial sites with posted speed limit of 50 km/h were chosen:

Site A: 570 m long straight road, inclined with 4-7 % gradient and a signalized junction. AADT approx. 41 000, proportion of heavies was approx. 40 %. On this test road, all four materials were tested on sub-sections.

Site B: 180 m long straight road, inclined with 5 % gradient, sharp bend and a signalized junction. AADT approx. 35 000. Only material A was tested here.

Site C: 400 m long straight road, level, and a signalized pedestrian crossing. AADT approx. 18 000. On this test road, materials A, B and D were tested on sub-sections.

Site D: 130 m long straight road, level, and a signalized pedestrian crossing. AADT approx. 16 000. On this test road, material C was tested.

Site E: 200 m long straight road, inclined with 8 % gradient, and a signalized pedestrian crossing. AADT approx. 15 000. On this test road material A was tested.

On these test sites, separate for each material, noise monitoring took place before resurfacing, immediately after resurfacing and then each 3rd month (except month 15) up until the study finished after 24 months. The method used was what is called BALeq in Chapter 9 and the noise data were normalized for differences in speed, traffic volume and heavy vehicle proportion according to the British traffic noise model CRTN.

Furthermore, careful and systematic observations were made of the performance with respect to durability.

The measured results in terms of noise reduction are presented in Fig. 25. The reduction is calculated as the difference between the noise level measured before the resurfacing and after the resurfacing. The irregularity of the curves is not likely to reflect corresponding changes in the performance of the surface; rather they would reflect the errors in the measurement. From this graph it looks like the errors are approximately ± 0.5 dB expressed as standard deviation.

On top of this error, seen in the curves in the figure, there is an error also in the measurement made before the resurfacing; i.e. the measurement that determined where the zero level should be located. This error is approximately as large as the error of other individual measurements; i.e. approx. ±0.5 dB. It may be understood as a tolerance around the zero level in the diagram.

All curves have one feature in common, namely that there is a deterioration of the noise reduction with time. Fig. 26 shows the average noise reduction of all 11 curves[12]. This comes out as a quite smooth curve, since then the errors of the individual sites and materials have been more or less averaged out. It is believed that the reason for this behaviour is one or both of the following:

- The porosity becomes clogged with dirt as time passes by
- The surface texture becomes rougher due to ravelling or damages

It appears that the changes mainly occur in the first 9 months and that the situation stabilizes after that. This is most likely clogging, implying that clogging occurs rapidly and that already after 9 months it has filled the voids with dirt. The result is that the surface behaves like a conventional dense asphalt surface after this, albeit not with the same durability.

There is an alternative explanation for the deterioration of the noise reduction. This is that, for all asphalt mixes, it has been noticed that a newly laid surface is "quieter" than a surface which has been in operation for one or two years. Fig. 8 is an illustration of this effect[13]. It happens that the noise reduction at time zero is approximately the same in both Fig. 8 and Fig. 26. The difference is the rate of change with time, which is much shorter in Fig. 26 than in Fig 8. It is speculated that this could be a special feature related to the very hot and humid climate in Hong Kong as compared to northern and middle Europe where the data for Fig. 8 was collected. The heat might speed up the ageing process, as is common in many other areas of technology.

The reasons for the "stabilization" of the noise reduction at approximately 1 dB might be the following:

- There is a remaining porosity which reduces noise a little compared to the original surfaces
- The texture of the "steady-state" condition (after 9 months) is already "acoustically" dense, but it is also better optimized for low noise than the texture of the original surfaces.

The author considers a mix of both alternatives as the most plausible explanation. The original surfaces may have had a maximum aggregate size of 20 mm or 10 mm or have been a mix of both cases[14]. If the maximum aggregate size was primarily 20 mm, this automatically would give a penalty of around 1 dB(A) compared to a 10 mm case, and to the 10 mm PMFC[15] which were primarily used in the study after resurfacing. Thus, it is possible, if not even probable, that the remaining noise reduction after 9 months is due to the smaller aggregate size and more uniform texture of the new surfaces compared to the old ones.

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[12] Both Fig. 25 and Fig, 26 have been produced by the author based on the tables in [HyD 022, 1998]

[13] Note that Fig. 8 has not been influenced by any measurements in Hong Kong

[14] The author has requested such information from EPD/HyD but not received it

[15] According to Fig. 7 the penalty should be 2.5 dB(A), but since the model for Fig. 7 is only for car tyre/road noise, and traffic here is a mix of light and heavy vehicles, with probably a dominance of power unit noise rather than tyre/road noise, the 2.5 dB will be reduced to a much lower value, possibly around 1 dB.

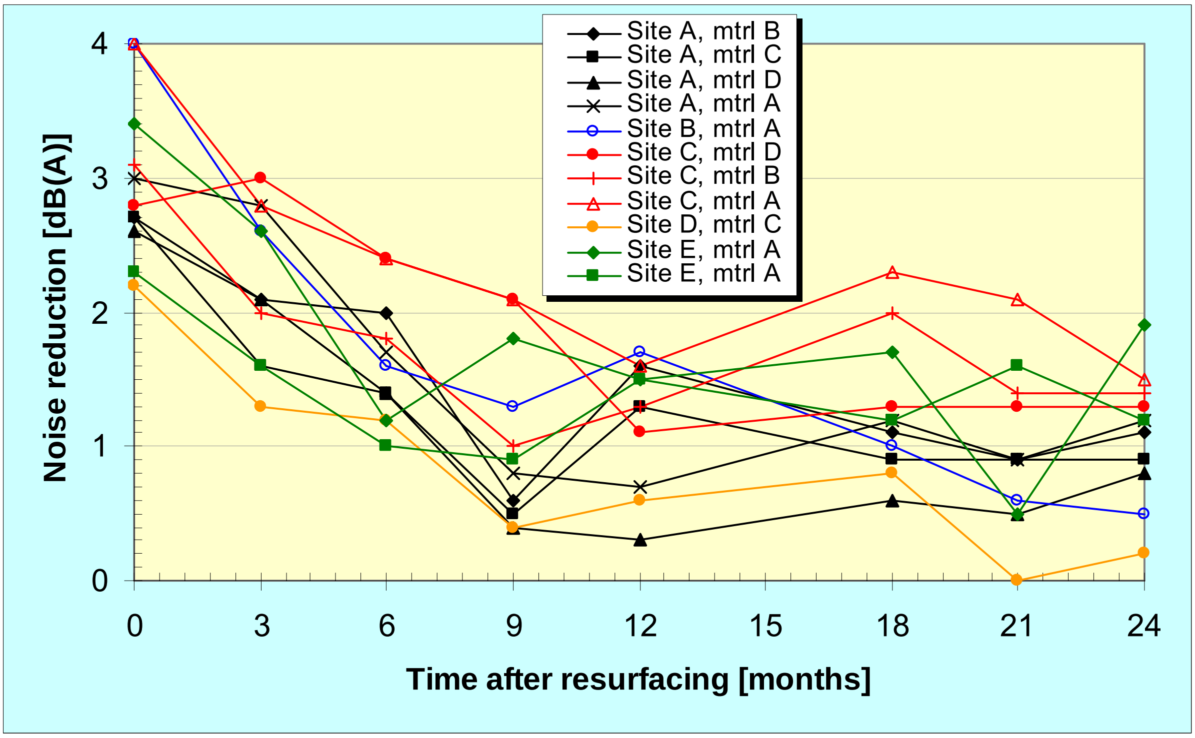

Fig. 25. Results of the noise monitoring measurements for the 5 sites and 4 materials, plotted as the noise reduction as a function of time after resurfacing. The zero level has been put at the level measured on the original road surface, before resurfacing took place.

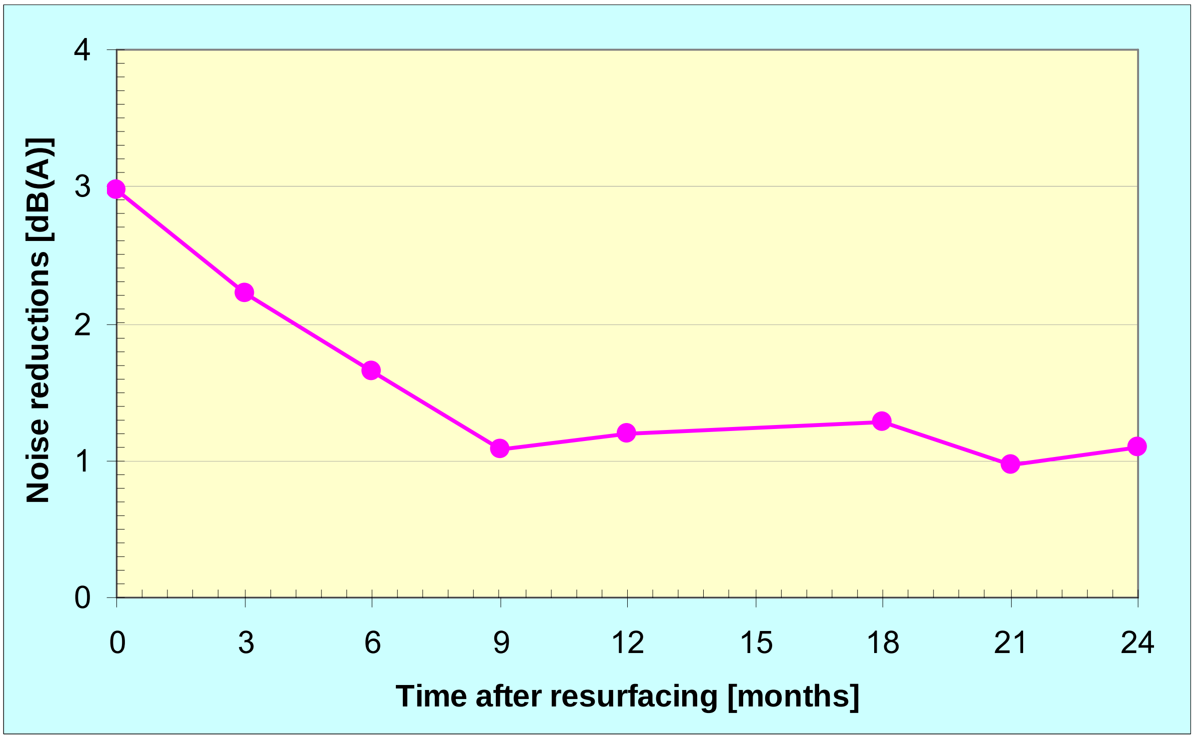

Fig. 26. Results of the noise monitoring measurements, averaged for all 11 combinations of sites and materials tested, and plotted as noise reduction as a function of time after resurfacing. The zero level has been put at the level measured on the original road surface.

Therefore, in principle, almost the same noise reduction as observed in Fig. 26 might perhaps have been achieved with a conventional dense asphalt or SMA with 8 or 10 mm maximum aggregate size if resurfacing with such a surface is made over an existing DAC 0/20. The porosity contribution to noise reduction might have been very small.

At hindsight, it would have been desirable that one of the tried mixes would have been an SMA or a DAC with max. 10 mm or 8 mm aggregate to test the truth of the discussion above.

So far about noise characteristics. Of course, durability characteristics are equally or more important. The systematic observations included the following notes (everything refers to durability issues):

- The degree of pavement deterioration of the trial sites was in descending order (from the worst to the best): Site B, Site A, Site E, Site C and Site D
- Deterioration on level roads (Sites C and D) was found to be moderate
- Deterioration on inclined roads (Sites A, B and E) was found to be far more serious
- Therefore, PMFC materials are not suitable on inclined roads
- It was also noted that the PMFC did not last for the entire studied period at the sharp bend
- High AADT may be a catalyst to speed up the deterioration of PMFC materials

The study also included a cost comparison between conventional wearing course and PMFC (materials A and D). The result was that the annual recurrent cost was:

- For a conventional wearing course: \$16 per m^2
- For Material A (PMFC, 10 mm aggregate, 30 mm thick): \$57 per m^2
- For Material D (double-layer PMFC, 10 mm aggregate on top, 80 mm thick): \$96 per m^2

These costs were based on the assumption of 6 years of lifetime for the conventional wearing course and 3 years for the PMFC materials, also assuming that the PMFC materials always need a new DAC under it.

It was concluded that:

- Materials A and D (topmost layer 10 mm aggregate) could further be considered for adoption on level and straight roads, but not material B
- As no visible defects of material D (double-layer, 80 mm thick, with 10 mm aggregate on top) was noted within the two year study period, it seems that this material is relatively durable when applied on straight and level roads, even under stop-and-go conditions such as at street lights
- There was no reason to disapprove the durability of Material A when applied to a straight and level road with free flow traffic
- Material A had a higher initial noise reduction than material D but its noise reduction effect diminished faster; the two materials would have similar performance in the long term
- It is necessary to relay the underlying layer before applying PMFC, since the PMFC does not have the structural strength of dense asphalt
- PMFC on low speed roads may need replacement after 3 years

An overall conclusion was that friction course should not be regarded as a normal means for noise mitigation on low speed roads. Under exceptional circumstances when noise reduction at local roads must be achieved by applying friction course (as determined by EPD and HyD on a case by case basis), Materials A or D may be considered, provided that the criteria stipulated at the end of Chapter 8.2 are satisfied.

11.2.2 Author's comment to the trial study 1995-1997

The trial study [HyD 022, 1998] fails to inform about the type of surfaces which were measured as the reference in the study. These are equally important as the trial surfaces. A comparison between two surfaces is almost meaningless if only one of them is defined. Because of this the conclusions are not as safe as they could be.

The measured noise reductions may be the result of unique but limited advantages of the PMFC. However, it seems likely that almost the same noise reductions might have been attained with conventional dense asphalt surfaces, provided the max aggregate size would not be larger than 8 mm (preferably) or perhaps even 10 mm. Such surfaces would have meant no extra costs and no sacrifice in durability; yet may have provided almost the same noise reduction. The author thinks that the extra contribution of the porosity to the noise reduction might have been approx. 1-2 dB and that this effect occurs only during the first months.

The (commendable) cost study might have overestimated the cost of PMFC since it assumes that PMFC has no structural strength on its own, but needs a full-thickness conventional wearing course under it to carry the vehicle loads. This is only true to a small extent; porous pavement layers do add extra structural load-carrying capacity to the road; albeit perhaps a little less than a dense layer. For example, porous asphalt concrete is laid in Europe without such a wearing-course layer added. Careful milling of the worn wearing course or perhaps a thin layer to eliminate any surface unevenness on the base may be sufficient.

In the road surfacing handbook of the Swedish Road Administration, it is written that one of the advantages with this surface (the Swedish ABD11, see Fig. 23) is that it has a good structural stability. During the study tour in the Netherlands in 2007 it was confirmed that the Dutch consider the contribution to structural strength of porous asphalt as essentially similar to that of a normal asphalt layer. See also this citation from a brand new report from Switzerland about porous asphalt in Switzerland and in Japan [Puolikakis et al, 2006]:

> **Structural Contribution**
>
> Depending on the mix design for each country, the subject of the structural contribution of porous asphalt to heavy traffic roads is debatable. An investigation by Potter and Halliday in Britain showed that 40 mm thickness of porous wearing course was found to be equivalent in contribution to the structural strength of a 20 mm HRA [17]. Swiss Standard for the DRA suggests that 1 cm thickness of the traditional Swiss base course mix (HMT) is equal to 1.25 cm of the DRA, and that the structural contribution of the DRA is equal to 65% strength of other surface mixes, including Gussasphalt and the SMA [4]. In Japan, porous asphalt is considerd structurally equivalent to other bituminous layers in the mix design. The Japanese experience shows no significant difference in terms of the durability of asphalt pavements (crack resistance against traffic loading) when 4cm porous asphalt was compared with a conventional section with 4cm dense asphalt surface [16].
>
> From : http://www.empa.ch/plugin/template/empa/*/54476/---/l=2

Thus, one should not calculate such a high extra cost for the base layer, if any at all. On the other hand, the cost calculation in [HyD 022, 1998] has missed the extra cost of a kerbside drainage system (see 10.6.2), and possibly should have considered a 50 mm thickness of the PMFC instead of 30 mm (see 10.6.1).

The increased costs of PMFC surfaces, about 4 times as much as for conventional asphalt for single-layer PMFC and 6 times for double-layer PMFC, would probably not justify the limited noise reductions attained, the latter of which were about 2 dB(A) as an average. The cost of 200 m of the single-layer PMFC on a 10 m wide street would be approximately HK$ 114 000 per year based on the calculated cost in the Annex of [HyD 022, 1998]. This is a lot for only 2 dB(A) of noise reduction. However, before such a conclusion becomes final one should study the possibility of noise reduction having been underestimated, in view of night time disturbance, as outlined in Chapter 9.2.10. Please note that the PMFC also has other advantages, which have not been counted and which might compensate for some of the high construction costs, see further Chapters 11.9-11.10.

With the present very high cost estimations of PMFC on low speed roads, it may in some cases be less expensive to compensate the residents by a subsidy, such as is the case in the U.K. for new highway projects, or to improve the sound insulation, if appropriate.

11.2.3 Trial study with respect to SMA surfaces

The Highways Department have considered the applicability of other possible noise reducing road surfacing materials than PMFC, most importantly SMA materials.

A trial was carried out in Hong Kong on two local road sections, one at Lung Cheung Road and the other at Siu Lek Yuen Road. A noise reduction of 1-3 dB(A) was recorded immediately after the laying. The reduction dropped significantly, with one of the road sections losing all noise reduction but 0.4 dB(A) at about 12 months after the laying [Ng & Tse, 2005]. Meanwhile, road defects, e.g. pothole and flushing, were observed about 14 to 16 months after laying [HyD GN, 2001]. Further trials have to be made before using SMA as a noise reducing road surfacing material in Hong Kong [Ng & Tse, 2005].

The author would like to comment that if the surface on the two sites before resurfacing was BRCC or a 20 mm DAC, the repaving with SMA 0/10 would give approx. the mentioned 1-3 dB(A) noise reductions. The diminishing noise reduction with time is a natural consequence of the ageing of the surface during the first two years; see Fig. 8, something which could happen faster in Hong Kong due to the hot weather.

11.3 The extent of the present low-noise resurfacing programme for low-speed roads

The Hong Kong government has launched a programme to resurface 72 local low speed roads with polymer modified friction course in order to reduce the road traffic noise experienced by the nearby residents. The programme started in 2002 and is expected to be completed in 2010.

By that time about 40,000 dwellings would have benefited from the programme. The 72 sites which have been identified as suitable for resurfacing are listed in Table 6.

Normal resurfacing frequency for Hong Kong streets of this type is 6 years. In this programme, it is expected that resurfacing will have to be made after 3 or 4 years, sometimes even after 2 years, due to the lower lifetime of PMFC.

The programme includes some studies of the performance of the test surfaces. Noise monitoring takes place before resurfacing, immediately after resurfacing and then each 3rd month up until this part of the study finished after 24 months. The method used is what is called BALeq in Chapter 9 and the noise data are normalized for differences in speed, traffic volume and heavy vehicle proportion according to the British traffic noise prediction model CRTN.

Furthermore, careful and systematic observations are made regularly of the performance with respect to durability. The durability observations will continue for some time after 24 months.

Part of the programme has already been completed; i.e. the surfaces have been monitored for 24 months which is the end of the noise monitoring period. The number of road sections where this had already occurred was 6 in early 2007. In early 2007, none of these sites had needed resurfacing.

In September 2006, 29 of the road sections had been resurfaced with PMFC. In early 2007 this had been increased to 45 road sections. With two exceptions, the type of PMFC that has been used is a 30 mm thick layer with maximum aggregate size of 10 mm and a target voids content of 19-20 %. Preblended PMFC has been used only on Chui Tin Street.

11.4 Test sites visited by the author and observations on these

The author has visited Hong Kong and as part of the activities visited test sections at three occasions:

- February 2005 (when the main objective of the visit was lecturing)
- October 2006
- December 2006
- December 2007

The road sections visited are listed in Table 7, with a selection of comments included. Overall, the author has visited 35 test sites of which approx 20 are included in the LNRS test programme. Some high-speed roads were among these in order to get a better perspective on the issue.

Table 6. The 72 road sections that have been identified as suitable for resurfacing within the 2002-2010 programme for improving local low speed roads by resurfacing with PMFC. Table adapted for this format from Annex 3 of [EPD Plan, 2006].

Road No. and name		From	To	Implementation timetable
Phase I (24 sections)				
1.	Pik Wan Road	Tak Shing House	Tak Shui House	Works completed.
2.	Cox's Road	Austin Road	Jordan Road	Works completed
3.	Fa Yuen Street	Prince Edward Road West	Boundary Street	Works completed.
4.	Hing Wah Street	Cheung Sha Wan Rd	Un Chau Street	Works completed.
5.	Kimberley Road	Nathan Road	Observatory Road	Works completed.
6.	Mong Kok Road	Shanghai Street	Tong Mi Road	Works completed.
7.	Nam Cheong Street	Cheung Sha Wan Road	Lai Chi Kok Road	Commencement delayed due to other works in the area. Works tentatively to compl. by 2007/08.
8.	Oak Street	Cherry Street	Ivy Street	Works completed.
9.	Portland Street	Argyle Street	Waterloo Road	Commencement delayed due to other works in the area. Works tentatively to compl. by 2007/08.
10	Public Square Street	Ferry Street	Canton Road	Works completed.
11	Reclamation Street	Public Square Street	Argyle Street	Commencement delayed due to other works in the area. Works tentatively to compl. by 2007/08.
12	Sai Yee Street	Prince Edward Road West	Boundary Street	Works completed.
13	Un Chau Street	Hing Wah Street	Tonkin Street	Works completed.
14	Waterloo Road	Ferry Street	Shanghai Street	Works has commenced and tentatively to complete in 2006.
15	Yen Chow Street	Hai Tan St	Lai Chi Kok Rd	Commencement delayed due to other works in the area. Works tentatively to compl. by 2005/06.
16	Lai Chi Kok Road	Tonkin Street	Hing Wah Street	Technical feasibility under review.
17	Tonkin Street	Cheung Sha Wan Rd	Un Chau Street	Works completed.
18	Shanghai Street	Public Square Street	Kansu Street	Technical feasibility under review.
19	Un Chau Street	Tonkin Street	Yen Chow Street	Works completed.
20	Shanghai Street	Argyle Street	Dundas Street	Works completed.
21	Embankment Road	Prince Edward Road West	Boundary Street	Works completed.
22	Shek Kip Mei St	Tai Po Road	Woh Chai Street	Works completed.
23	Tai Hang Tung Road	Tong Yam Street	Tat Chee Avenue	Works has commenced but due to other works in the area completion has deferred to 2007/08.
24	Yim Po Fong Street	Shantung Street	Waterloo Road	Works completed.
Phase II (22 sections)				
25	Aberdeen Main Road	Aberdeen Praya Road	Aberdeen Reservoir Rd	Technical feasibility under review.
26	Connaught Road West	Des Voeux Road West	Water Street	Technical feasibility under review.
27	Electric Road	Gordon Road	Wing Hing Street (Tsing Fung Street)	Commencement delayed due to other works in the area. Works tentatively to compl. by 2007/08.
28	Java Road	Tong Shui Road	Tin Chiu Street	
29	King's Road	Healthy Street West	Java Road	Works tentatively to complete by 2006/07.
30	Kingston Street	Paterson Street	Gloucester Road	Works completed.
31	Lockhart Road	Arsenal Street	Percival Street	Commencement delayed due to other works in the area. Works tentatively to compl. by 2008/09.
32	Queen's Road West	Des Voeux Road West	Hill Road	Commencement delayed due to other works in the area. Works tentatively to compl. by 2006/07.
33	Whitty Street	Des Voeux Road West	Queen's Road West	Works completed.
34	Johnston Road	Luard Road	Fleming Road	Works completed.
35	Wong Nai Chung Road	Sing Woo Road	Broadwood Road	Commencement delayed due to other works in the area. Works tentatively to compl. by 2007/08
36	Queen's Road West	Western Street	Water Street	
37	Wong Nai Chung Road	Sports Road	Broadwood Road	
38	Hennessy Road	Fleming Road	Stewart Road	Works completed.
39	Queen's Road East	Queensway	Kennedy Road	Commenc. delayed due to other works in the area Works tent. to commence and compl. early 2006.

40	Chi Kiang Street	To Kwa Wan Road	Ma Tau Wai Road	Commencem. delayed due to other works in the area. Works tent. to compl. by 2006/07.
41	Ma Tau Kok Road	Kowloon City Road	Ma Tau Chung Road	Works has commenced and tentatively to complete in 2006/07.
42	Wuhu Street	Gillies Ave. South	Chatham Road North	Technical feasibility under review.
43	To Kwa Wan Road	Kwei Chow Street	Chi Kiang Street	To tie in with adjoining road works to be carried out by KCRC. Works tentatively to complete 2010
44	To Kwa Wan Road	Mok Cheong Street	Ma Tau Kok Road	
45	Lomond Road	Argyle Street	Prince Edward Road	Works completed.
46	Nga Tsin Wai Road	Tak Ku Ling Road	Junction Road	Technical feasibility under review.
Phase III (New Territories East - 12 sections)				
47	Jockey Club Road	Po Shek Wu Rd	Man Kam To Road	Technical feasibility under review.
48	Jockey Club Road	Lung Sum Avenue	San Fung Avenue	Works tentatively to complete by 2006/07.
49	Ma Sik Road	Jockey Club Road	Tin Ping Road	Works tentatively to complete by 2006/07.
50	Tai Po Tai Wo Road	On Cheung Road	Nam Wan Road	Works completed.
51	Tai Po Tai Wo Road	Ting Kok Road	Ting Tai Road	Works completed.
52	Nam Wan Road	Nga Wan Road	Pan Chung Road	Works tentatively to complete in early 2006.
53	Shatin Rural Committee Road	Tai Po Road – Shatin Section	Yuen Wo Road	Technical feasibility under review.
54	Sha Tin Wai Road	Ngan Shing Street	Ngau Pei Sha Street	Commencem. delayed due to other works in the area. Works tentatively to complete by 2008/09.
55	Sha Tin Wai Road	Sha Tin Road	Ngan Shing Street	
56	Tai Chung Kiu Road	Sha Kok Street	Sha Tin Wai Road	Works tentatively to complete by 2006/07.
57	Chiu Shun Road	Po Ning Road	Ngan O Road	Works completed.
58	Chui Tin Street	Che Kung Miu Road	Cul-de-sac	Works completed.
Phase III (New Territories West - 14 sections)				
59	Castle Peak Road	Tuen Mun Heung Sze Wui Road	Hing Ping Road	Works has commenced and tentatively to complete in 2006/07.
60	Castle Peak Road	Pui To Road	Tuen Mun Heung Sze Wui Road	
61	Tuen Mun Heung Sze Wui Road	Tuen Hing Road	Siu Lun Street	Works tentatively to complete by 2006/07.
62	Tuen Mun Heung Sze Wui Road	Siu Lun Street	Hoi Chu Road	Works tentatively to complete by 2007/08.
63	Wu Shan Road	Lung Mun Road	Wu King Road	Works has commenced and tentatively to complete in early 2006.
64	Long Ping Road	Fung Chi Road	Long Ping Road INT.	Works has commenced and tentatively to complete in 2006/07.
65	Yuen Long Main Road	Tai Tong Road	Fung Cheung Road	Technical feasibility under review.
66	Yuen Long On Ning Rd.	Tai Kiu Road	Wang Chau Road	Works tentatively to complete by 2006/07.
67	Ma Miu Road	Yuen Long On Ning Rd	Ma Wang Road	Works tentatively to complete by 2006/07.
68	Castle Peak Road	Ping Ha Road	Tin Ha Road	Works tentatively to complete by 2007/08.
69	Chung On Street	Sha Tsui Road	Yeung Uk Road	Technical feasibility under review.
70	Yeung Uk Road	Tai Ho Road	Chung On Street	Works tentatively to complete by 2006/07.
71	Kwai Foo Road	Kwai Chung Road	Hing Fong Road	Works tentatively to complete by 2006/07.
72	Kwai Yik Road	Kwai Chung Road	Hing Fong Road	Works tentatively to complete by 2006/07.

Some general observations are listed here:

- Structural instabilities related to load capacity that were worse than on a conventional pavement were not noticed
- The PMFC surfaces were very rarely cracked, not even on BRCC base layers.
- Clogging was often clearly visible along kerbstones
- There were in most cases too long distances between gullies, sometimes 50 m, and no other drainage provisions; which will seriously affect the development of clogging and means that there is no noise advantage in wet weather
- Manholes sometimes were located in wheel tracks, and sometimes caused rattling of the lids and of equipment on passing trucks

- PMFC was rarely paved over an intersection. Intersections had a DAC or an old BRCC
- Damages were invariably seen at parking bays for motorcycles, caused by the tear of the stands of the motorcycles. This seemed to occur rather soon after resurfacing.
- Ravelling was often seen at or near bus stops or where busses used to turn
- When testing water drainage by pouring water from a bottle, it was generally found that vertical drainage was poor or non-existing
- The preblended PMFC is only used on Chui Tin Street (No. 58).

Some acoustic observations are reported here

- On dry PMFC, passing cars sound "quieter" than on conventional surface; the sound is "typical" of low-noise road surfaces
- For heavy vehicles, there is no difference in noise compared to a conventional surface. The tyre/road interaction is no major noise contributor at these conditions
- On PMFC in rainy weather but when the surface is not saturated with water, there is a substantial difference in noise of passing vehicles (except the largest ones) on the PMFC versus the dense asphalt (lower high-frequency noise on the PMFC)
- On PMFC in rainy weather but when the surface is fully saturated with water, there is no difference in noise of passing vehicles on the PMFC versus the dense asphalt

Some notes on the EcoPark experiment with asphalt rubber are worth mentioning. The asphalt rubber surfaces looked good to this author (although what the difference should be between them is unknown), having texture depths of 0.6-0.7 mm, but the reference surface looked like an industrial hall floor; with a texture depth of approximately 0.2 mm such a surface would never be allowed on any road in Europe or the U.S. due to its lack of macrotexture. However, it is stated as "typical" in Hong Kong. The measurements (1st and 2nd interim reports) had been made available to this author and they indicated approx. 1 dB(A) noise reduction for one of the asphalt rubber sections and 0 dB(A) for the other one [Road Research Group, 2007]. However, the noise measurements are of questionable value, for two reasons:

(1) the reference surface is a surface that seems to have an extremely smooth macrotexture that should not be accepted on a real road
(2) the test tyres used are not reported (differences between smooth-textured surfaces largely depend on the tyres used).

Consequently, it is too early to say that the asphalt rubber surfaces in the EcoPark are not efficient. More studies should be made and one should mainly try the open-graded and not the gap-graded variant. However, both full-scale and laboratory studies in Sweden in 2007-2008 have indicated that for the gap-graded variant of the asphalt rubber surfaces have no significant noise advantage, but this is in comparison to the probably quieter references used in the Swedish experiments (a report is being produced).

The following gallery in Fig. 27-54 intends to highlight interesting issues. Most of them show problems of various kinds. This must <u>not</u> be interpreted as if there are mostly problems in connection to these sites.

Table 7. Road sections visited by the author. If not otherwise noted, the posted speed limit was 50 km/h. PMFC 10/30 means: 30 mm thick polymer modified friction course with 10 mm maximum aggregate size. The surface age is the age at the time of inspection; not the present age.

Road	**Surface type & age**	**Observations**
	February 2005	
Princess Margareth's Road	PMFC	Just passing through. High speed road. Relatively old PMFC in condition soon needing resurfacing
Lion Rock Tunnel Road	PMFC	Just passing through. High speed road. 2-3 lanes per direction. Medium condition of PMFC.
Tolo Highway	PMFC ? months	Just passing through. High speed road. 4 lanes per direction. New PMFC in perfect condition.
Un Chau Street in Cheung Sha Wan	PMFC 10/30 0 month	Resurfacing being made during the visit, largely finished. Noticed long distance between gullies.
Hing Wah Street in Cheung Sha Wan	PMFC 10/30 ? months	Fairly good condition, except ravelling at intersection and in parking lane. Clogged parking lane. PMFC surface ruined by motorcycle stands on parking lane. Oil spillage in parking lane
Lomond Road in Kowloon	PMFC 10/30 >3 months	Good condition, except some spots with ravelling at intersection
Yuen Shin Road in Tai Po	PMFC 10/30 12 months	Speed limit 70 km/h. Surface in good condition, not clogged. DAC on run-on slab for bridge (only).
	October 2006	
Hennessy Road	PMFC ? months	In central business district of Hong Kong. Damages around a manhole, and clogging at kerb, but otherwise good condition.
Johnston Road	PMFC ? months	In central business district of Hong Kong. A couple of square metres repaired with DAC but otherwise in good condition.
Ma Tau Kok Street	PMFC 10/30 10 months	Good texture, but clogged, mostly by dirt from the sidewalks. Much background noise, especially by busses
Junction Road Between Prince Edward Road West and Boundary Street	SMA 20 mm But looks like 10 mm	Looks approx. as SMA in Sweden, but was inhomogene, with flushing in the left part of the lane. Before resurfacing, the surface was DAC. SMA not paved over intersection having BRCC
Shanghai Street	PMFC 10/30 15? months	Practically no drainage at the kerb on this appr. 15 months old PMFC on Shanghai Street. Some ravelling in rightmost lane, plus serious clogging. Serious damage from motorcycle stands
Public Square Street	PMFC 10/30 3 years	Roadworks due to other reasons, they will have to repave with new PMFC. Serious damage in parking lane. Totally clogged.
Lai Chi Kok Road (at large shopping mall)	(PMFC 10/30) Planned, not yet laid	Local street parallel to major 70 km/h road. Existing surf = BRCC on both local and major roads. Resurfacing planned on local road only (political reasons) but it would be much better to do it on the major road
Chui Tin Street	PMFC 10/30 9 months	Excellent condition but not much traffic. Clear noise diff heard when cars passed joint to dense surface
Chui Tin Street	PMFC 10/50 9 months	Excellent condition but not much traffic. As the previous one but thicker. 20 % air voids.
Chui Tin Street	PMFC 20/50 9 months	Excellent condition but not much traffic. Located partly in moderate bend. Proportion of 10-20 mm chippings is low
Tai Po Tai Wo Road	PMFC 10/30 12 months	Speed limit 70 km/h. Surface in good condition. No gullies at the kerbside. Instability on bus stop with dense surface.
Chiu Shun Road	PMFC 10/30 9 months	Bus stop bays paved with extra durable and expensive “Thin Bond Concrete”

Tuen Mun Road	PMFC 10/30 4-9 months	Speed limit was 70 km/h. Extremely high heavy vehicle content. Fast lane SB and slow lane NB 4 months old, perfect condition. Slow lane SB 4 months old, ravelling clearly visible. Noisy manhole rattles for every heavy vehicle passage
Deep Bay Link	PMFC 10/30 1 month	Speed limit 90 km/h, 4 lanes in each direction. Totally new construction on motorway, not yet open to traffic due to political reasons. Perfect condition.
December 2006		
Ma Tau Kok Road	PMFC 10/30 12 months	Observations in rainy weather. There was no really open (porous) section left on this site; appeared marginally different to dense asphalt. “Was it ever open?” There was some ravelling at some intersections, plus in a bus stop lane.
Cox's Road	PMFC 10/30 20 months	Observations in rainy weather: The test section showed quite extensive variations in surface properties, with several patches water-covered and looking impervious. Clogging combined with saturation would be the main reasons for the water standing against the kerbstones, but for the rest of the surface clogging was not obvious. Neither did compaction by traffic look like a probable cause. Instead, the conclusion was that some patches of the surface had been constructed with much too low voids. This would not be noticeable in dry weather.
Pik Wan Road	SMA 10 mm	Steep grade (4-5 %?), bus stop in uphill direction. The surface was in good condition. Good example of place where an SMA would be better than a PMFC
Tseung Kwan O Road	PMFC 10/30 1-2 months, parts much older	Speed limit 80 or 70 km/h (varied). New PMFC laid at significant grade, surface in good condition. Severe ravelling visible in older surfaces in some wheel tracks. Maybe rejuvenation would have helped to prolong the structural lifetime?
Lomond Road	PMFC 10/30 24+ months	Good condition but reduced porosity, appeared to be quite impervious
Shek Kip Mei Street	PMFC 10/30 18 months	Before resurfacing the surface was 50 % BRCC, 50 % DAC. Partly inhomogene due to excessive binder at patches or due to depressions in the surface creating saturated parts of the surface. Severe damage was observed at motorcycle stand.
Un Chau Street	PMFC 10/30 15 months	Partly homogene/inhomogene. No noise reduction in the wet weather. Surface saturated with water all time, no porosity seen. The cause of the inhomogeneity: Either (1) higher and lower patches, where the lower ones are saturated with water but the higher ones look dry, or (2) inhomogene construction. The first option most likely here. This is good example of a street where one should not select a PMFC; would be better cost/benefit ratio to select an SMA. Reasons: (1) Very high volume of heavy vehicles, (2) local businesses operate almost on the street itself, (3) intermittent traffic, (4) low average speed.
Tuen Mun Road	PMFC 10/30 6-11 months	Observ. in dry weather on footbridge near Chi Lok Fa Yuen: The fast lane southbound (towards Kowloon), 6 months: Ravelling clearly visible in the overtaking lane. Southbound slow lane, 11 months: The northbound (towards Yuen Long) slow lane, 6 months: Perfect condition. Approx. 50 m between gullies = much too far. Manholes in wheel track

December 2007		
Eco Park site in Tuen Mun Area 38	DAC 0/20 and Asphalt rubber based on DAC 0/20	One section with DAC 0/20 which was extremely smooth (would not be useful on a real road) and two sections with asphalt rubber (AR) surface (gapgraded). The AR sections had "normal" textures. These looked good. See further the text.
Castle Peak Road	PMFC 10/30 on old DAC 0/20. In one direction it was 3 months, in the other it was 12+ months. 50 km/h site.	Looked good structurally, no ravelling could be seen. But drainage (tested by pouring out water from a bottle) was moderate on the young surface and no drainage at all in the wheel tracks of the older surface, and some poor drainage between the wheel tracks. There were two gulleys close to each other then a long way to the next two gulleys. No kerbside drainage apart from these gulleys.
Wu Shan Road	One year old PMFC 10/30 (≥17% voids) on old DAC 0/20.	Low traffic, 50 km/h, approx. 500 m long section. One of the 4 lanes: In practice totally dense, although it was a PMFC, the three other lanes were OK, although there was no sign of drainage in any of them either. Nevertheless, the sound was quiet. No ravelling could be seen.
Fanling Highway	Trial sections, 200 m of PMFC on 100 km/h road with 3 lanes per direction, high-volume road	Northern half of the road had only 30 mm friction course (no polymer modif.), as had southern half as a base layer. The left half was laid 3 months ago, the right half 1.5 months ago. From the north there was first on old friction course (no polym. mod.), then there was a new PMFC 10/30, and finally PMFC 20/50 mm. Drainage was tested by pouring water from bottle: although looking good, there was no drainage in wheel tracks. Along the road there was a drainage channel with a grid over it, but it was separated by an edge of dense asphalt or concrete from the PMFC, except for approx 20 cm per each 10 m distance. Structural durability looked very good.
Ma Miu Road	PMFC 10/30 over 200 m, 3 months old	Very congested 50 km/h street, heavies > 25 %, aver. speed 20-30 km/h. Despite only 3 months old, the surface already looked clogged. No drainage could be seen when pouring water on it.
Long Ping Road	PMFC 10/30, 120 m long, 50 km/h	1.5 year old PMFC, ravelling cold be seen where busses turned into side street. There was no drainage.

Fig. 27. Conventional DAC at left and clogged PMFC at right, both probably having 10 mm max. aggregate size but with some oversized chippings. Northwestern corner of Victoria Park.

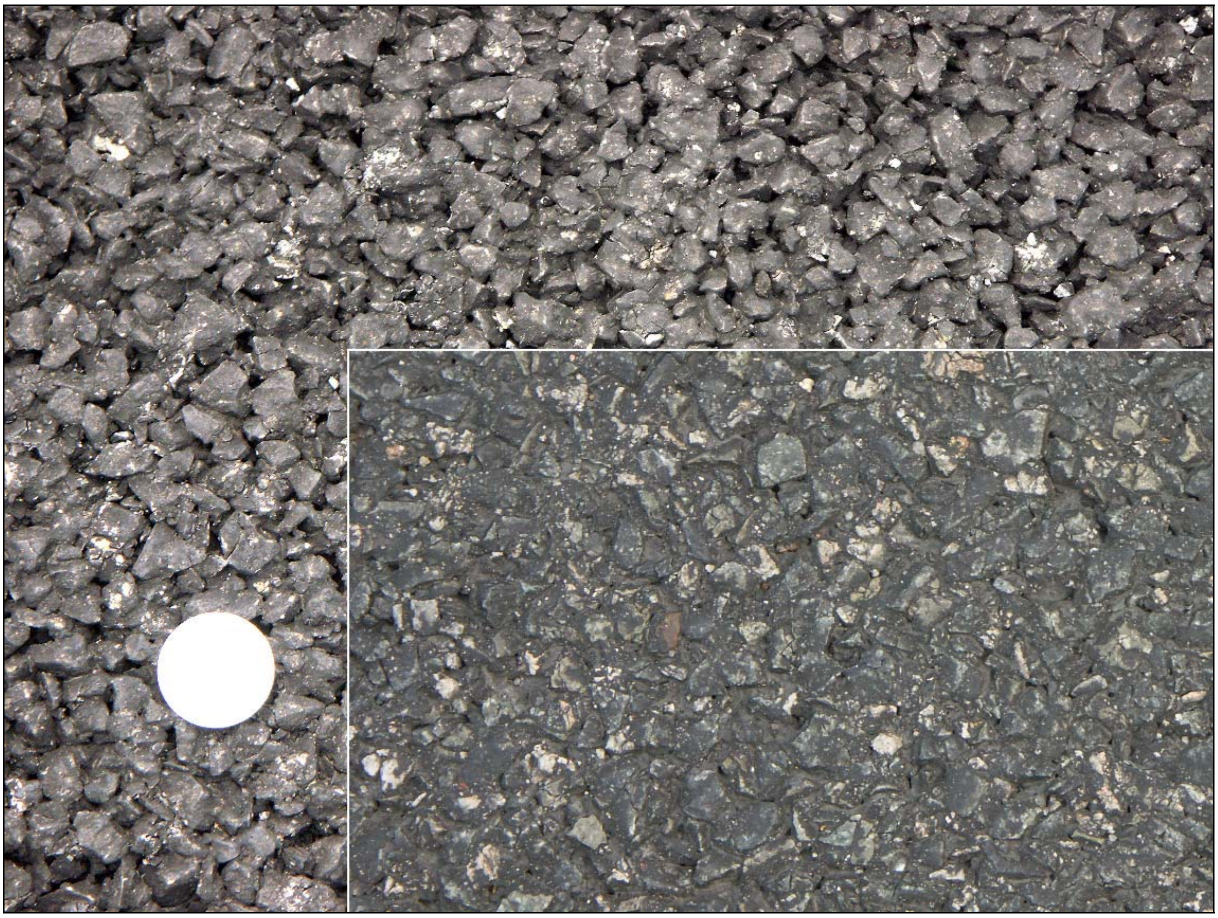

Fig. 28. Newly laid and unused PMFC on Deep Bay Link, with very open structure and an insert with a 9-month old partly clogged PMFC (Chiu Shun Road). The coin is HK$ 1.

Fig. 29. PMFC on extremely demanding location (Princess Margareth's Road), approaching end of lifetime.

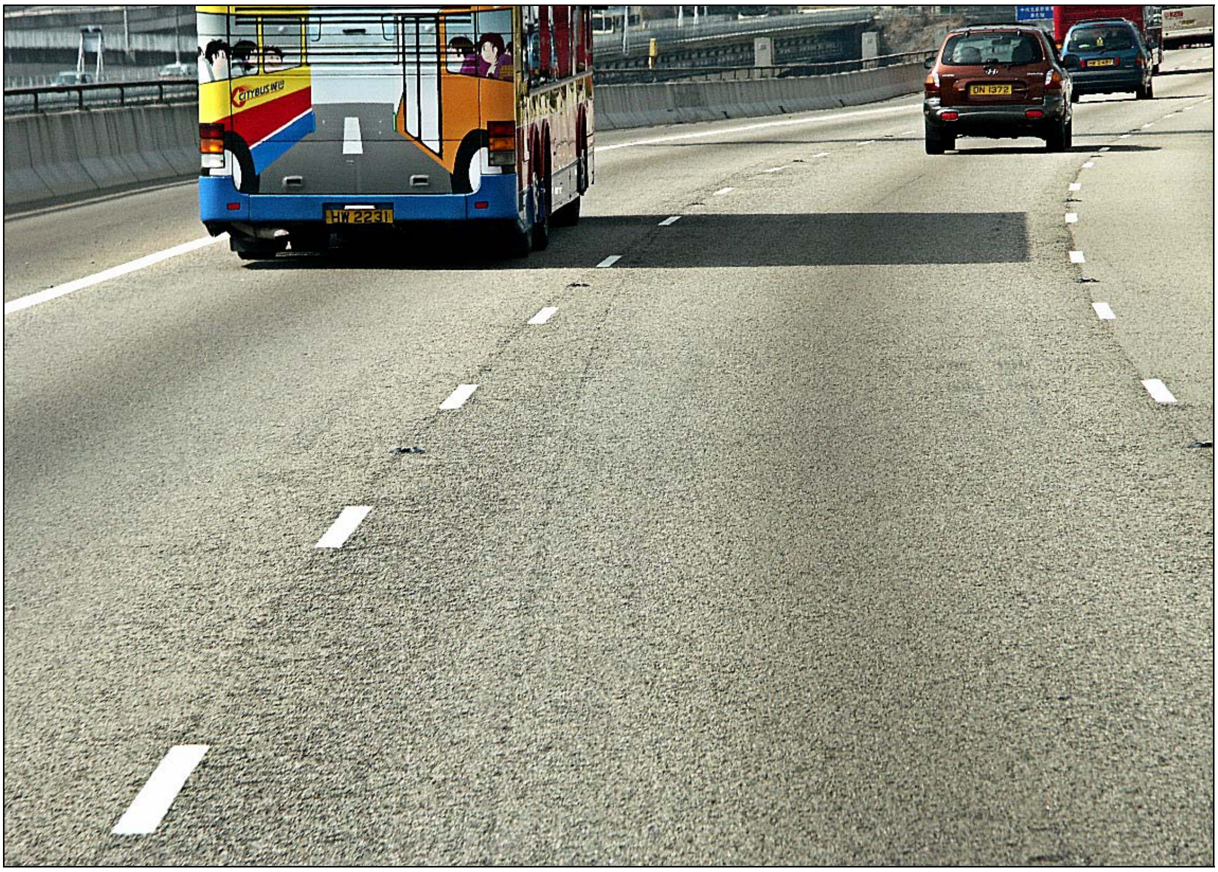

Fig. 30. Ravelling of PMFC in slight bend on high-speed road

Fig. 31. Newly laid PMFC on Tolo Highway, in perfect condition.

Fig. 32. Resurfacing with PMFC just finished on Un Chau Street. Note the location of gullies at the kerbside, with pair of gullies together but long distance between the pairs.

Fig. 33. Ravelling at intersection on Hing Wah Street, with one small spot being repaired.

Fig. 34. Serious ravelling and clogging (lower left) in parking lane on Hing Wah Street.

Fig. 35. Chiu Shun Road with 9 months old PMFC in perfect condition, and bus bay having stronger "Thin Bond Concrete" surfacing.

Fig. 36. Separation problem on Chiu Shun Road, due to binder having collected at the very bottom of a truck load during transportation from the asphalt plant.

Fig. 37. PMFC on Chui Tin Street with max 20 mm aggregate, and with photo of 10 mm aggregate version inserted to scale. Coin is HK$ 1. Surfaces 9 months old, perfect condition.

Fig. 38. SMA surface on Junction Road, flushing in left wheel track.

Fig. 39. Resurfacing with PMFC planned for the rightmost local street (close to mall at right) but should instead be made on the BRRC surface on the main road (Lai Chi Kok Road)

Fig. 40. Ma Tau Kok Street, paved with PMFC, is extremely busy at midday.

Fig. 41. Totally clogged PMFC on Ma Tau Kok Street, 0.5 m from the kerb. Coin is HK$ 1.

Fig. 42. Bus stop on Ma Tau Kok Street has been resurfaced due to damages by busses; despite the main area being resurfaced with PMFC only 10 months earlier.

Fig. 43. Example of reasonably well working intersection with PMFC. Ma Tau Kok Street with 10 months old PMFC.

Fig. 44. Public Square Street with 3 years old PMFC, being seriously damaged in parking lane; perhaps aggravated by oil spillage. Roadwork in the other direction is not caused by PMFC problems.

Fig. 45. Totally clogged PMFC, 3 years old, on Public Square Street. It looks like a surface dressing.

Fig. 46. Practically no drainage at the kerb on this approx. 15 months old PMFC on Shanghai Street. Some ravelling in rightmost lane, plus serious clogging along the entire kerb.

Fig. 47. Approx. 15 months old PMFC totally damaged (topmost chippings stripped off) by motorcycle stands on Shanghai Street. Surface also clogged due to poor kerbside drainage.

Fig. 48. Tai Po Tai Wo Road, posted speed limit 70 km/h, with 12 months old PMFC still in very good condition, despite no visible drainage at the kerb. Why manhole in the wheel track?

Fig. 49. Two months old PMFC on uphill section of high-speed road (Tseung Kwan O) with a significant gradient. The section had been repaved because of ravelling of old PMFC.

Fig. 50. Manholes in carriageway on Lomond Road - Four potential noise sources; albeit they are well done.

Fig. 51. Very short and busy road section on Shek Kip Mei Street with PMFC. LNRS would not be effective on such short section and with this type of traffic.

Fig. 52. Differences between dense asphalt and PMFC, also showing inhomogeneities in PMFC (right lane) probably caused during paving.

Fig. 53. Inefficient drainage at the kerb on Un Chau Street, potentially speeding up clogging.

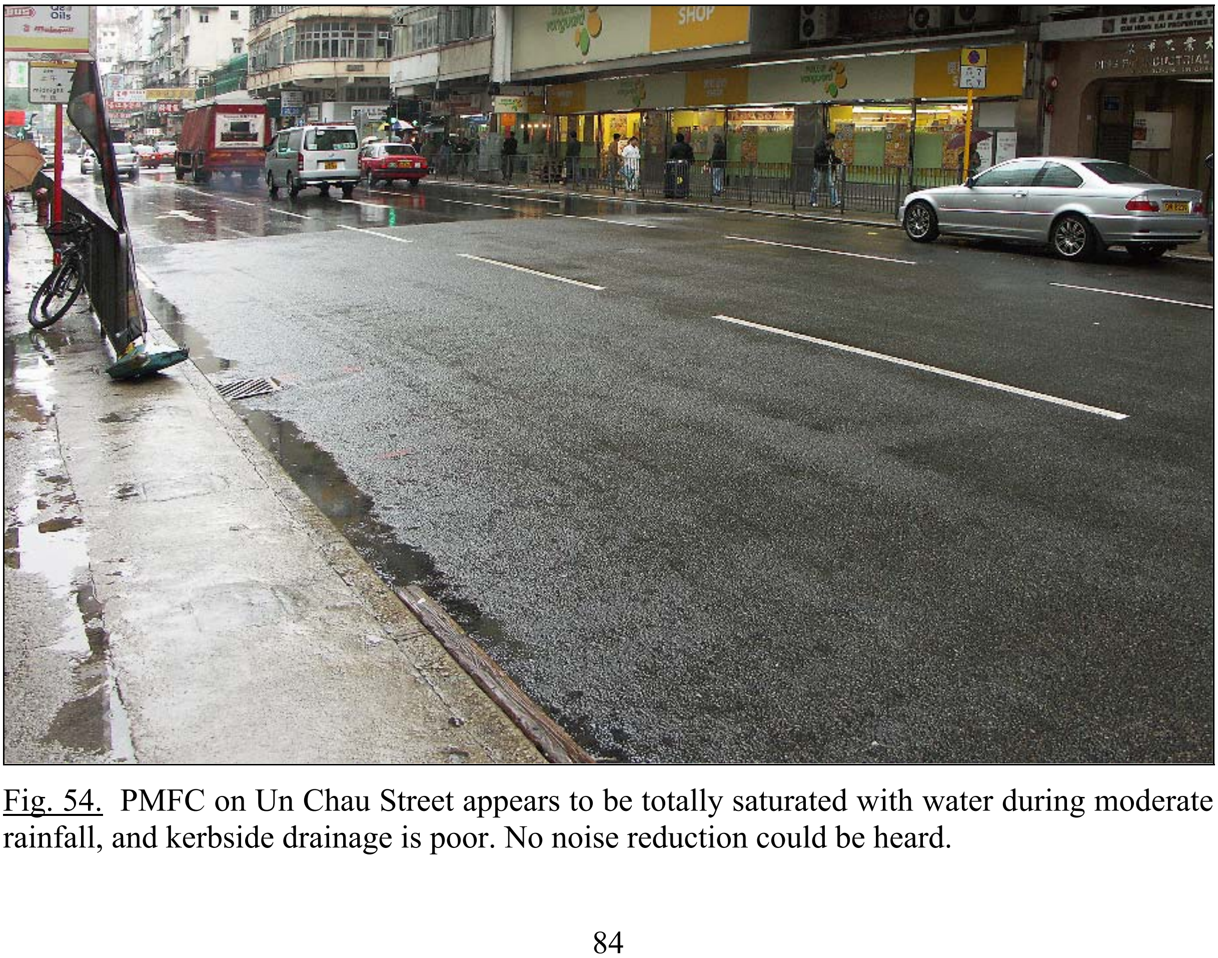

Fig. 54. PMFC on Un Chau Street appears to be totally saturated with water during moderate rainfall, and kerbside drainage is poor. No noise reduction could be heard.

11.5 Review and analysis of test data obtained from Hong Kong

11.5.1 General issues

Test data obtained from Hong Kong so far only include noise monitoring reports. The monitoring reports contain results of measurements in A-weighted level of L10, L90 and Leq over 6 half-hour periods. The 6 periods are also averaged. Traffic data (% of heavies, number of vehicles and speeds) are also reported and these values are used to normalize the "after resurfacing" noise levels to those measured before resurfacing. The model used for the normalization is the British CRTN. After this procedure, the averages are compared and the difference between the "before" and "after resurfacing" measurements is calculated and called "noise reduction". The noise monitoring reports usually contain also air temperatures during the measurements.

Measurements were generally made on weekdays between 10:00 and 13:00, in dry weather. It has been noticed that in several cases there are dramatic differences in vehicle composition and/or vehicle speed between the measurements before and after the resurfacing (such as 55 vs 35 km/h, 30 vs 55 % heavies). This puts high demands on the correction procedure for speed and heavy vehicle proportions in the used CRTN procedure; which most probably has led to substantial errors in the corrected measurement results.

The above procedure is fine in principle. However, it would be better to use a more modern noise model than the CRTN. The CRTN is based on obsolete vehicle noise data and thus the correction for % of heavies and speed would not be up-to-date. The potential error will even change with time, as quieter new vehicles are replacing older and noisier ones in the traffic.

An example where the correction procedure seems to have failed substantially is Shanghai Street. On this street the heavy vehicle proportion before resurfacing was 57-60 %, and vehicle speeds 41-51 km/h, while after resurfacing it was 32 % and 33-36 km/h, respectively. This has resulted in corrections about 3 dB and indications of noise *increases* after resurfacing by about 1 dB instead of the expected noise *decreases* after resurfacing. In any case, this illustrates why this author recommended that before-resurfacing-measurements would include not only one measurement but at least three ones, since any error in this measurement will progress through the entire data set.

11.5.2 Results of the noise monitoring

The noise reduction values measured so far have been compiled and processed by the author in various ways. The noise reduction data for each of the sites are first presented in Table 8 and Fig. 55. Note the very large spread between sites in Fig. 55. This is partly a reflection of large measurement errors; in particular reflecting the measurement errors in the pre-resurfacing measurement. Note the extremely low position of Shanghai Street, for which a possible explanation is offered in the previous paragraph.

Table 8. Noise reductions measured of the low-noise road surfaces compared to the surface used before resurfacing took place. All noise reductions are L_{10} values in dB(A), normalized with respect to traffic to the "before resurfacing" situation.

Road	Surface before resurfacing	Time in months after resurfacing									Ave-rage
		0	3	6	9	12	15	18	21	24	
Hing Wah Street	BRCC	1,9	1	1	1,3	1,2	1,6	0,8	1,4	1,4	**1,29**
Oak Street	BRCC	2,3	2,9	2,2	1,7	2	2,9	2,6	2,1	2,2	**2,32**
Tonkin Street	BRCC	2,3	4,1	3,5	3,8	3,6	3,8	2,8	3	3,3	**3,36**
Embankment Road	DAC?	2,7		1	0,1	0,3	1	0,2	1,7	2,1	**1,14**
Yim Po Fong Street	BRCC	2,7	3,1	3,4	3,8	3,5	3,5	3,9	3,9	3	**3,42**
Kingston Street	BRCC	1,2	0,6	1	0,5	0,4	0,5	0,1	0,4	0,2	**0,54**
Cox Road	BRCC	1,6	3,6	3,6	3,4	3,6	3,9	3,9	4,3	3,7	**3,51**
Shanghai Street***	BRCC	0,9	-1,25	-1,35	-1,05	-1,3	-1,4	-1,4	-1	-1,3	**-1,02**
Shek Kip Mei Street	DAC?**	1,7	2,1	1,8	1,8	2,1	1,3	1,7	2,3	1,8	**1,84**
Tai Po Tai Wo Road (OCR-NWR)	DAC	1,5	1,4	1,6	2	2,5	2,6	2,4	2,3	2,6	**2,10**
Tai Po Tai Wo Road (TKR-TTR)	DAC	1,3	1,7	1,6	1,4	1,1	1,2	1,1	1,5	1	**1,32**
Chiu Shun Road	DAC	1,5	1,6	2,5	1,7	2,2	2,3	2,8	2,3	1,4	**2,03**
Un Chau Street	BRCC	2,1	1,7	1,5	1,9	2	2,3	2,6	2,3	2,2	**2,07**
Castle Peak Road, 70 km/h	DAC	3,8	4,29	4,2	3,9	3,8	4	3,8	3,8		**3,95**
Wu Shan Road	DAC	2,2	2,4	2,5	2,2	2,7	2,2	2,4	1,8		**2,30**
Chui Tin Street* (10mm / 30mm)	DAC 0/20?	2,3	1,7	1,7	1,6	1,5	1,5	1,5	1,3		**1,64**
Chui Tin Street* (10mm / 50mm)	DAC 0/20?	3,3	3	2,9	2,7	2,7	2,6	2,4	2,5		**2,76**
Chui Tin Street* (20mm / 50mm)	DAC 0/20?	2,8	2,6	2,4	2,2	2,2	2	1,9	1,8		**2,24**
Lomond Road	BRCC	3	3	3,6	3,9	2,2	3,6	3,7	3,2	3,7	**3,32**
Whitty Street	BRCC	1	0,7	0,6	0,7	0,8	0,8	0,8	0,6	0,4	**0,71**
Ma Tau Kok Road	BRCC				1,5	1,3	0,5	-1,7	-1,4		**0,25**
Average		**2,11**	**2,12**	**2,06**	**1,95**	**1,92**	**2,03**	**1,82**	**1,91**	**1,85**	**1,95**

** Three materials were laid: PMFC 10 mm max aggregate size and 30 mm thick / PMFC 10 mm max aggregate size and 50 mm thick / PMFC 20 mm max aggregate size and 50 mm thick*
*** Both DAC and BRCC surfaces existed before resurfacing, it looks from a photo as if a DAC was used*
**** It was noticed that measurements before repaving was made with exceptionally high prop. of heavy vehicles, see comment in 11.5.1*

The data for the individual surfaces have been averaged over time; see Fig. 56. When averaging is made in this way, the measurement errors are largely averaged out. It appears that there is a significant but small change in average noise reduction over time; from the regression equation it appears to be approx. 0.3 dB(A) over the time period studied; i.e. this is the loss in noise reduction with time. Note that this looks totally different from the results of the earlier study; see Figs. 25-26, where there was a large noise reduction loss during the first few months, but a stabilization occurred in the second year.

The data in Fig. 57 compares the two studies. It appears that the present study achieved higher time-averaged noise reductions, but for some strange reason there is no tendency for a rapid loss of noise reduction with time during the first few months, which is so typical of PMFC.

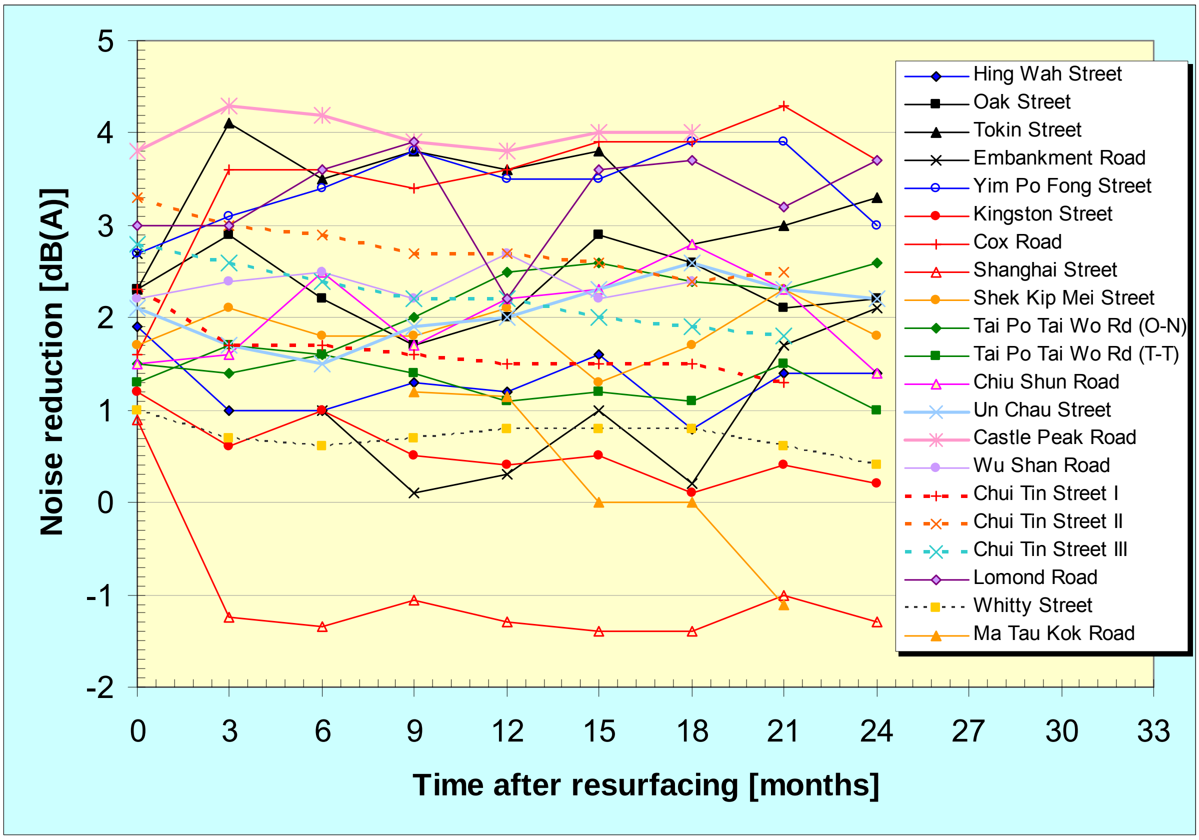

Fig. 55. Change with time of the noise reduction for all 21 surfaces measured. Note the discussion for the lowest curve (Shanghai Street) in 11.5.1.

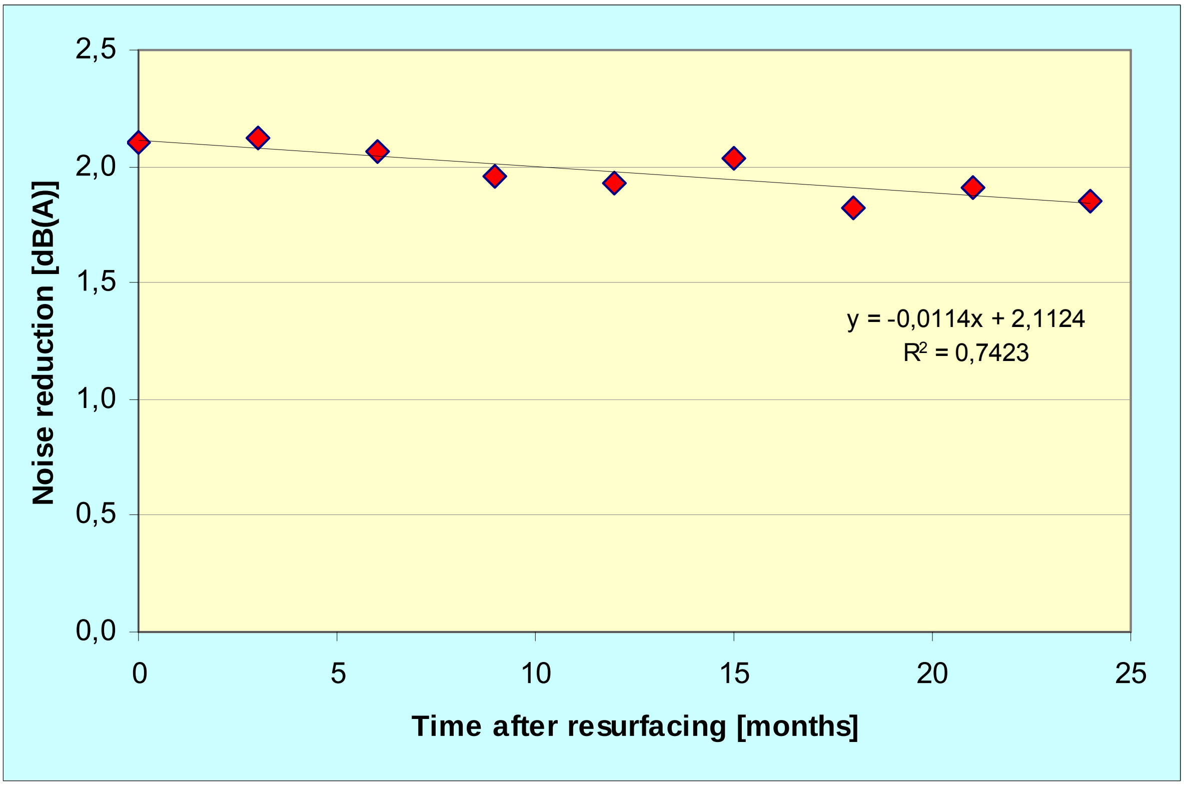

Fig. 56. Change with time of the noise reduction, as an average per time period for all 21 surfaces. The regression line, its equation and R^2 are indicated in the diagram.

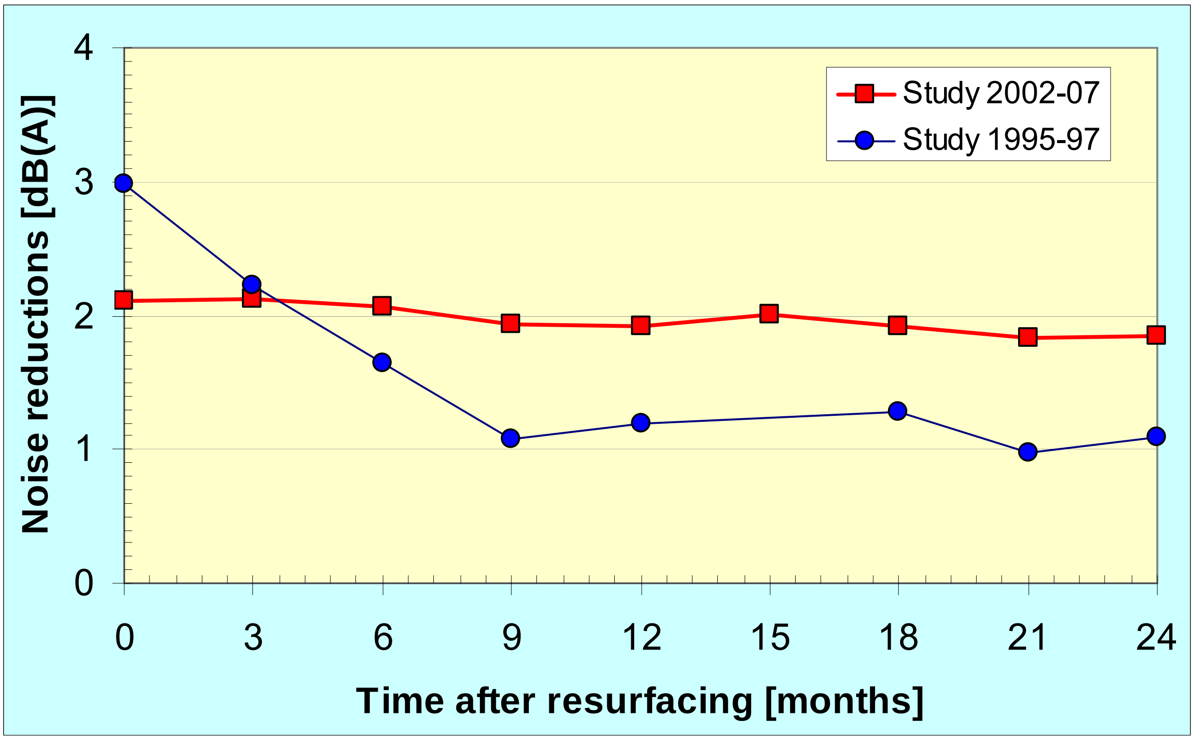

Fig. 57. Change with time of the noise reduction, as an average per time period for all 21 surfaces in the present study (2002-07) compared to a corresponding analysis in the earlier study (1995-97).

Despite the above, there is a clear loss of noise reduction with time for the LNRS laid on Chui Tin Street; see Fig. 58. The loss with time there is approx. 1 dB over the two year period, which is a lower rate than for the study in 1995-97 in which 2 dB were lost over only 9 months. The reasons are probably that Chui Tin Street has a relatively low traffic volume, medium speeds and the heavy vehicle proportion is rather low, which means that the LNRS behaves more like on a high-speed road than on a low-speed road. Note that the thicker version (50 mm) gives a 1.2 dB advantage over the thinner layer (30 mm). Fig. 9 predicts about 1.8 dB of advantage, but that is of course for higher speeds than on Chui Tin Street.

The data have also been averaged for all the periodic measurements per each test site, see the rightmost column in Table 8. Studying these averages, it appears that there is a range from -1 to + 4 dB(A) in noise reduction. This is a very large range when applying in principle the same new surface everywhere, but probably it is so large because the old surfaces differ a lot, in combination with measurement errors in the pre-resurfacing period. The old surfaces are never described other than as "rigid" or "flexible", and even that basic information was obtained only after the author insisted on it. As the author has pointed out before in this report, the old surface probably influences the noise reduction more than the LNRS, so it is more important to describe the characteristics of the old surfaces than the LNRS. But it must be accepted that such essential information unfortunately is missing.

One interesting thing is whether the rigid surfaces (BRCC) are noisier than the flexible ones (DAC); i.e. if the noise reductions measured are higher when paved over the BRCC than when paved over the DAC surfaces. Such an effect can NOT be observed; on the contrary the noise reduction is 0.3 dB higher when paved on the flexible than on the rigid surfaces. This difference is not statistically significant, however. But one may conclude that the old DAC surfaces existing before resurfacing are relatively "noisy" surfaces. Thus, one may expect relatively high noise reductions in all cases.

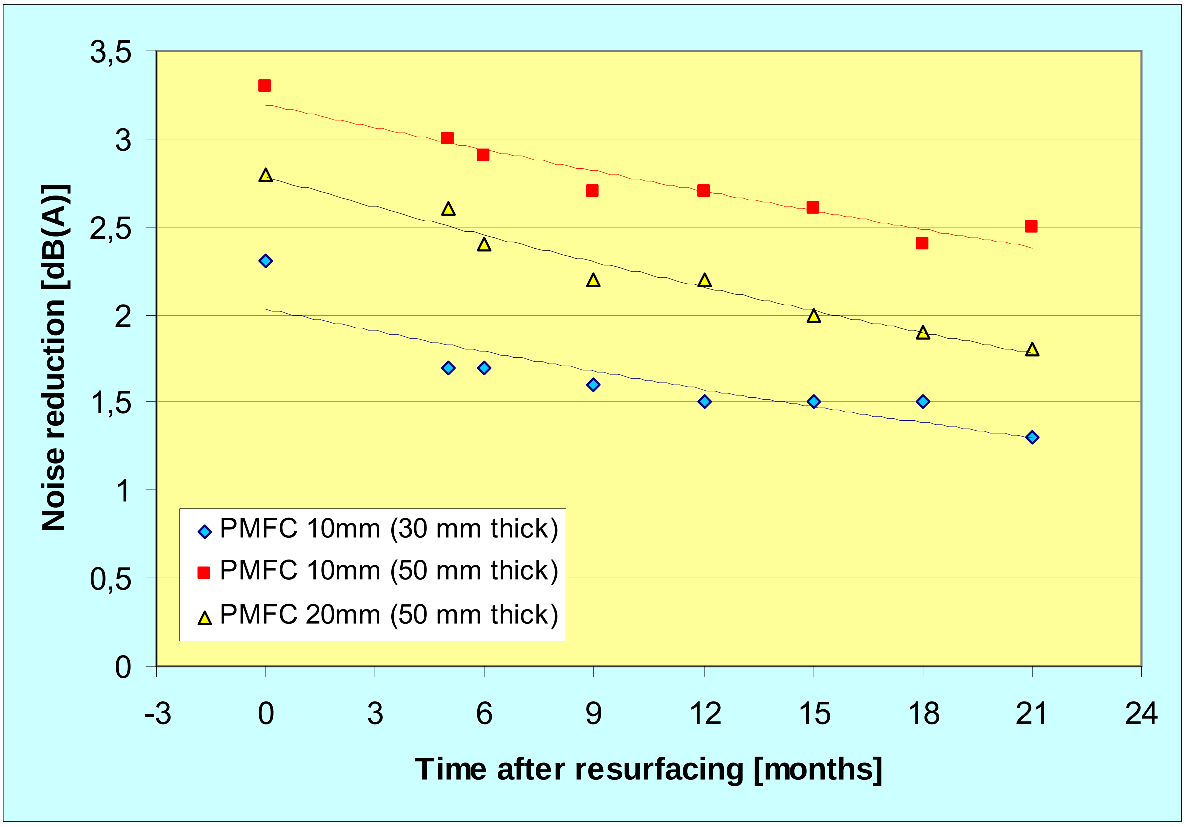

Fig. 58. Change with time of the noise reduction for the three LNRS on Chui Tin Street.

The fact that better noise reduction cannot be seen during the first months of operation, with the exception of Chui Tin Street, is really strange. To try to find a reason for this, the author has compiled air temperature data in a similar table as Table 8. It turned out that temperature affects noise reduction somewhat, namely by about 0.5 dB over the range encountered (higher temperature gives higher noise reduction), a range which was about 20 degrees, but the effect is rather randomly distributed over the time periods and does not explain the failing time dependence. Consequently, no explanation for the failing time dependence can be offered.

Note that, as for the study 1995-97, it is likely that there is an uncertainty in the measurements of an individual point in Figs. 55 and 58 of approximately ±0.5 dB(A) expressed as a standard deviation, and ±1 dB(A) expressed as 95 % confidence intervals. In addition, the reference level (0 dB) would have a similar uncertainty. The average levels presented in Fig. 56 are the most reliable ones.

A couple of more relationships are worth studying. In Fig. 59, the relationship between noise reduction and proportion of heavy vehicles (HV%) in the traffic is shown. The relationship between noise reduction and average vehicle speed is shown in Fig. 60.

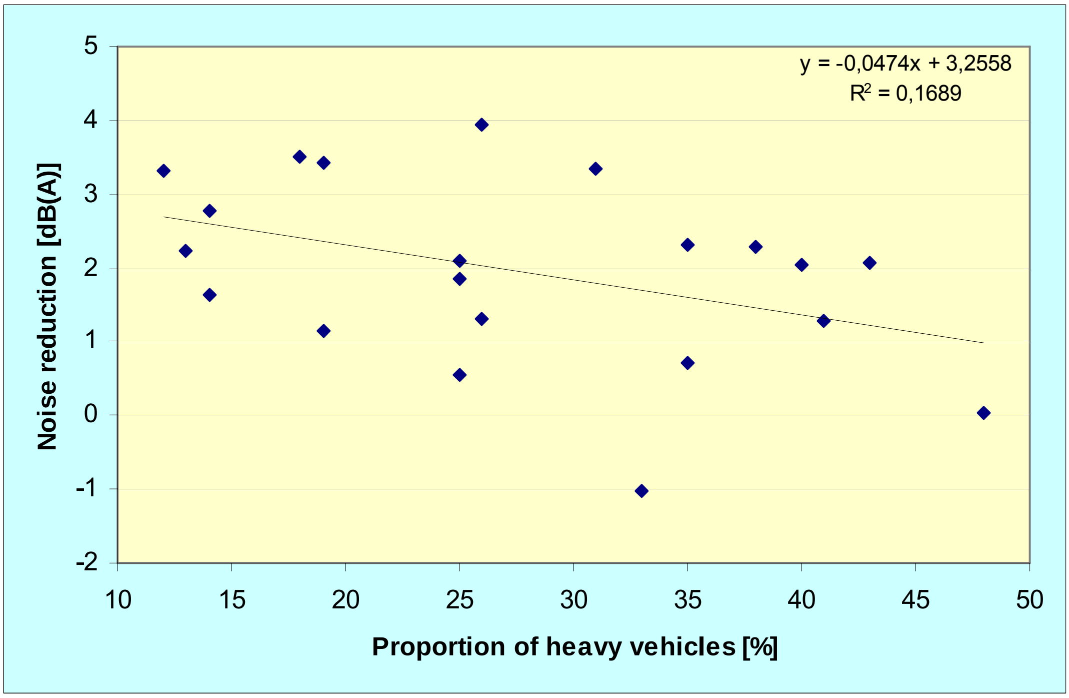

Fig. 59. The relationship between measured average noise reduction for each site and the proportion of heavy vehicles (HV%) in the traffic on the same site (also average). Regression line, equation and explained variance R^2 are also indicated.

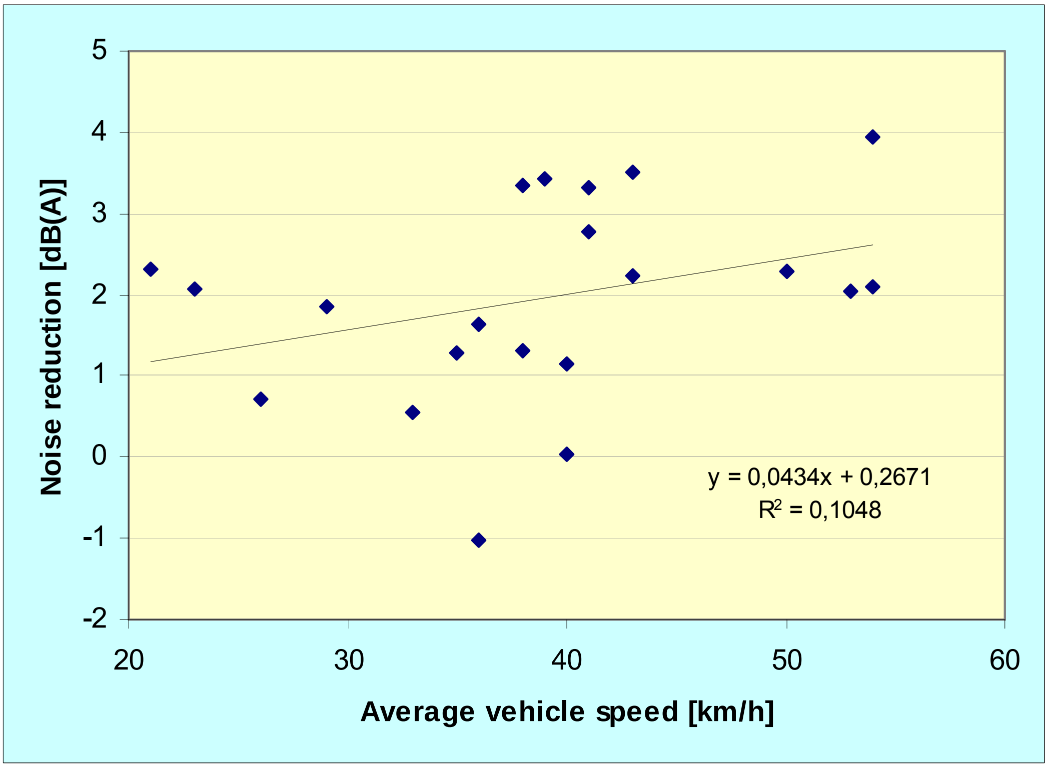

Fig. 60. The relationship between measured average noise reduction for each site and the average speed of the vehicles in the traffic on the same site. Regression line, equation and explained variance R^2 are also indicated.

The HV% explains about 17 % of the total variance (R^2) and the effect over the range of HV% (from about 12 to about 42 %) is 1.8 dB; i.e. at the highest HV% the noise reduction is 1.8 dB lower than at the lowest one. This is rather logical and is caused by the power unit noise of the heavies, which is not much affected by the porosity or the texture of the LNRS.

The vehicle speed explains about 10 % of the total variance (R^2) and the effect over the range of speeds (21-54 km/h) is 1.4 dB; i.e. at the highest speeds the noise reduction is 1.4 dB higher than at the lowest ones. This is also logical and is caused by the power unit noise of the vehicles, which is not much affected by the porosity or the texture of the LNRS, and which is relatively higher at lower speeds than at higher speeds.

If one would look at the combinations of high HV% and low speeds one would find that the noise reduction effect is more than 2 dB lower than at combinations of low HV% and high speeds. The situation of Whitty Street versus Chui Tin Street is an excellent example of this.

Finally, it should be pointed out that the noise reductions achieved in the monitored locations are limited by the following conditions; more or less depending on the conditions:

- There is other noise than noise from the road traffic that influences the noise measurements; for example, on busy business streets there is noise from the merchants' activities, in some cases perhaps also some aircraft noise and some noise from horns
- There is also noise from road traffic coming in from outside of the area which was resurfaced with PMFC
- As described earlier in this report, PMFC tend to become extra clogged near joints with dense surfaces. Since several of the noise monitoring locations are rather close to such joints, the PMFC efficiency would be poor there due to the "end effects".

11.5.3 A better designed test programme

The following observations have been made of how the test programme could have been designed in more efficient way:

- First of all, the existing old surfaces should have been defined by its design parameters and quantified by texture measurements on each test section. The extra costs of this would have been marginal, and well justified.
- Secondly, the number of measurements before resurfacing should have been at least three, instead of just one single measurement, since the measurement errors are too large for only one measurement. Making three instead of one measurement and averaging these would have reduced the error to about half. The extra costs of this would have been well justified.
- Thirdly, the corrections for varying HV% and vehicle speeds should have been made with a more modern noise model than the obsolete CRTN model. This would not have cost anything extra.

- Test sections of PMFC have been laid on too short road lengths; implying that the "end effects" are too significant over most of the test sections; especially, the noise monitoring locations should never be close to such an "end". This is of course difficult to avoid when street sections are not so long. Chui Tin Street is an excellent example of when this is not a problem; Shek Kip Mei Street one of many examples of the contrary.
- Finally, one should have tried not only PMFC in this programme but also 2-3 fine-textured SMA and 2-3 conventional flexible wearing courses. Also, at least one Sho-Bond surface dressing should have been included in the experiment. This would have saved money in the project since all the alternative surfacings are less expensive than the PMFC, and would easily have paid for all the other extra costs suggested above. With the present programme one cannot tell if the PMFC really have been worth the cost (other than in Chui Tin Street). Had one tested SMA:s the result might have become equally positive, at least on some roads; the same with the surface dressing. The justification for using a couple of conventional wearing courses is that this would have tested the "placebo effect"; i.e. one would see if using no low-noise road surface would have had an effect or not. It could well be that simply replacing a DAC in poor condition with a similar one in new condition might have given 1 or 2 dB of noise reduction too?

Provided a diamond grinding machine could have been brought into Hong Kong at a reasonable cost, the author would also have preferred that one of the BRCC test sections had been diamond ground instead of being milled and overlaid with a PMFC.

Additionally, using the CPX trailer for as many measurements as possible (it was not available until the beginning of 2007) would have been desirable, provided one would use the two test tyres supplied from Sweden and that these tyres had been kept in cooled condition between measurements.

The considerations above may hopefully be valuable for the last phases of the low-speed LNRS programme, or for any follow-up studies.

11.5.4 Conclusions

The following conclusions are made from the ongoing low-speed LNRS trial programme:

The average of the noise reduction values measured so far is 2.0 dB(A). This is an average over all the 21 test sections and over all 24 months during which noise monitoring has occurred. The existing old surfaces which were replaced were not defined, but since the analyses include 21 test sections, one may say that the average noise reduction is representative of what one would get for a "typical" mix of conventional Hong Kong wearing courses.

A noise reduction remaining at 2.0 dB(A) after two years of operation is not bad. However, it is a disappointment and surprise that the average reduction was not higher during the first year. The change with time of the noise reduction is only 0.3 dB(A) over these 24 months (0.3 dB lost noise reduction), which is lower than expected and lower than any experiment has indicated earlier.

Chui Tin Street results, however, show the expected loss of noise reduction over time; namely about 1 dB(A) over the studied two years.

The three different PMFC surfaces tested on Chui Tin Street indicate that the increase from 30 to 50 mm thickness of the porous layer gives approx. 1.2 dB(A) of extra noise reduction. It also shows that switching from the normal 10 to 20 mm maximum aggregate means a loss in noise reduction of about 0.5 dB(A).

Shanghai Street shows highly unexpected results, namely that noise was increased after resurfacing. This is probably explained by an extremely large difference between proportions of heavy vehicles and average speeds before and after the resurfacing, the correction for which has created erroneous results.

Visual observations by the author, combined with very limited information from Hong Kong observers, suggest that the general durability of the PMFC surfaces has been acceptable over the studied period. Some localized damages have been observed, but apart from parking areas and bus stop bays, these have not been serious enough to justify abandoning the trials.

The visual observations, however, clearly show that clogging of the porous surfaces occur very soon after laying. After only 6-9 months, in most cases, the areas close to the kerbs are totally clogged, and also in wheel tracks and in the middle of the lanes clogging is so severe that water drainage is seriously deteriorated. This is by no means surprising since the drainage at the roadside is very poor. In principle, with the present design of the kerbs and gulleys, most of the water will be trapped in a kind of basin in which water and dirt will collect. Before water reaches some drain, it has to run for such a long time and so slowly that any dirt in it would most likely have been deposited in the porous structure of the wearing course.

Nevertheless, at moderate rainfalls and before clogging has become too bad, one can see that water is sinking slowly through the porous structure and accumulated in it, in this way delaying the creation of standing water on the surface. This has some positive effects on noise (not measured) and splash and spray, as well as on dirt generation and probably also on wet skid resistance.

Bearing in mind that the change in noise reduction with time is a mere 0.3 dB(A) per two years, while the visual observations make it obvious that clogging is severe already after half a year in many places, it is likely that the noise reduction obtained is only marginally, if anything at all, increased by the porous nature of the surfaces (exceptions occur at sites with medium speeds).

The main reason for the reduction in noise (for most but not all surfaces) might be the exchange of relatively "noisy" and worn conventional Hong Kong wearing courses to an asphalt concrete surface in new condition (PMFC) with a macrotexture and megatexture which is much better optimized for low tyre/road noise than the existing old surfaces.

Ambient air temperature during the measurements affect the results marginally; over a 20 ^{o}C temperature range, the effect seems to be approx 0.5 dB(A) of lower noise with the higher temperatures. This may systematically affect noise monitoring results, but if temperatures vary in a random manner, such effects will cancel out for long-term averages.

The proportion of heavy vehicles (HV%) in the traffic affects the noise reductions significantly. Over the range of HV% about 12-42 %, the effect was found to be approx. 1.8 dB; i.e. at the highest HV% the noise reduction is 1.8 dB lower than at the lowest one.

The vehicle speed has a clear effect on noise reduction. Over the range of speeds in this study (21-54 km/h) the effect was approx. 1.4 dB; i.e. at the highest speeds the noise reduction is 1.4 dB higher than at the lowest ones.

If one would look at the combinations of high HV% and low speeds one would find that the noise reduction effect is more than 2 dB lower than at combinations of low HV% and high speeds.

Therefore, LNRS is the more effective, the higher the speeds are and the lower the HV% is. One should not consider using PMFC at average speeds below about 35 km/h combined with HV% above about 30 %. One may still reduce noise by a couple of dB at such traffic conditions by an exchange of surface, but it is unlikely that PMFC are useful; the author thinks that any texture-optimized dense surface would do as good job as a PMFC, and at a substantially lower cost. Such texture-optimized surfaces include thin layers tested in Europe, SMA 0/10, or even better SMA 0/8, as well as the Sho-Bond surface dressing and a diamond-grinding of an existing cement concrete surface.

If one is going to use a PMFC, it is better to use a 50 mm thick layer than a 30 mm layer, with an aggregate size of maximum 10 mm.

11.6 Some detailed considerations

A major problem of the porous surfaces as they were applied in this programme is the poor drainage of water away from the carriageway in rainy weather. It is not worse than on conventional dense surfaces, but a porous surface relies in this feature being good in order to utilize its main advantage: the porosity. There were in most cases too long distances between gullies, and no other drainage provisions; which will seriously affect the development of clogging and means that there is no noise advantage in wet weather. In rainy weather the porous surfaces got saturated with water; one of the reasons could be that there was no efficient escape at the kerbside. The water in most of the surface had to run not only straight to the kerbside, it had to run also several metres along the road to the nearest gully.

The standing water along the kerb, which sometimes reached a metre or so from the kerb out on the carriageway, was visibly dirty. It is likely that this dirt will clog the surface instead of running off in a gully; and this will mean that the dirt will spread to a wider part of the carriageway. As soon as it has clogged the part of the carriageway near to the kerb, the water from the middle part of the road has no other escape than to run on top of the surface, and the dirt in this water, being heavier than the water, will sink and be trapped by the block near the kerb and will make clogging progress towards the middle of the road.

Consequently, it is necessary to use a much more efficient kerbside drainage system, if a PMFC surface is to be used. One should combine this with a somewhat higher cross-slope of the road; for example 3.5 % instead of the conventional 2.5 %. The latter will ease and speed-up the water runoff, in this way getting rid of dirt before it collects in the PMFC structure.

The efficiency of the cushion layer between the porous layer and cement concrete and the glass grid over the joints is impressive. No reflective cracking could be seen anywhere on the sites visited.

Manholes were sometimes located in wheel tracks, and sometimes caused rattling of the lids and of passing trucks. This should never occur on a street where the large investment in a LNRS has been made.

The parameter "noise reduction" is always a comparison between two surfaces. If one of the two surfaces is well defined but the other is not at all defined, the meaning of the "noise reduction" will be "floating". By choosing a very "noisy" surface before the resurfacing was made, one will automatically get a good noise reduction and it will appear that the low noise surface was very effective (but in this particular case only).

It seems that in this programme, attention has not been paid at all to the surface used before resurfacing was made; at least not in the documentation available to the author. When asking about the surface before resurfacing during the site visit, the author has got information about this which suggests that the surface type before resurfacing was either a brushed cement concrete (BRCC) or a dense asphalt concrete (DAC), depending on the street and location along the street. See Fig. 61. In the DAC case, also the macro- and megatexture is important but it is not often known. Whichever it was of these surface alternatives, there might be a difference of up to 3 dB in noise emission on such surfaces according to the author's estimation; implying that the noise reduction of the same low-noise surface might vary by up to this amount just due to what kind of surface it was laid on and will be compared to. This alone may account for most the variation between "low-noise surfaces".

Fig. 61. Brushed cement concrete (BRCC) on Lai Chi Kok Road. Almost any dense bituminous surface with a texture depth of 0.5-1.0 mm will reduce noise in relation to this surface if tyre/road noise is substantial.

11.7 Maintenance issues

On a PMFC surface it is often considered that cleaning of dirt which has caused clogging is essential. This might then become the most common maintenance operation on such surfaces. Maintenance work would cause disturbance to other road users and, if carried out during night-time, would cause sleep disturbance. Therefore, it is important to be sure before cleaning of a porous surface is started that the cleaning will really have a significant effect. The author thinks that in Hong Kong it is important first to improve the kerbside drainage before any cleaning on low-speed roads would be of interest. Even if kerbside drainage were good, cleaning would probably not be economically justified since the porosity plays only a secondary role in the noise reduction in low-speed locations with heavy traffic such as in this programme.

Cleaning may be justified to try on high-speed roads in Hong Kong, but hardly on low-speed roads at the moment.

11.8 The EcoPark experiments

In the EcoPark in Tuen Mun a couple of experimental surfaces containing a substantial amount of crumb rubber have been laid on the road through the area, in accordance with recommendations made by the author at a meeting in October 2006. They are based on the asphalt rubber friction course (ARFC) of the so-called gap-graded kind used in Arizona. However, the results so far of the experiment are disappointing (see 11.4). Recent observations by the author and some others suggest that the very high noise reductions recorded in Arizona are not mainly due to the rubber, but simply due to the use of porous surfaces in combination with comparison with extremely noisy pre-resurfacing pavements.

The author recommends making new experiments, but with the so-called open-graded variant. Research in Sweden (so far) has suggested that for the open-graded variant, the rubber inclusion has a small positive effect on noise reduction. The effect of the rubber may be extra positive on durability; probably the major advantage of the rubber. In Hong Kong, a special potential advantage may be that the cushion layer laid between an old cement concrete surface and a new PMFC, which is so effective for avoiding reflective cracking, may be unnecessary if an asphalt rubber surface is used. This should be tried. In this way one could save some costs.

11.9 The heat island effect

It has been found that a porous road surface will be somewhat cooler in hot days than conventional asphalt surfaces. One of the reasons is the water retention capacity. The hot asphalt is one of the main reasons for creating the so-called Heat Island effect. This is the main reason for introducing such surfaces in central Japanese cities. Hong Kong must have at least as severe Heat Island problems as Tokyo; probably much worse. Thus, it should be economically favourable to pave the areas close to where people work and live with the cooler porous asphalt. This will save energy for AC and will give a more pleasant climate.

Possibly, this could be a main reason for using PMFC in central business areas; namely that the reduced heat in the area may cause an energy saving at the same time as reducing CO_2 emissions to the atmosphere. The author suggests that the effects of this are investigated.

11.10 Water storage capacity

A 50 mm thick porous surface with 20 % voids, has a potential capacity to store 10 litres of water per square metre. A fully saturated porous asphalt of that type would store about 10 m^3 of water per 100 m of street length if the paved surface is 10 m wide.

This means that in climates where short but very heavy rains may be expected, the use of a porous road surface will reduce the capacity needs of the rainwater drainage system. This will mean potentially lower investment needs.

12. RECOMMENDATIONS

12.1 Recommendations to improve the methodology

Note the importance of the reference surface

Please note that the noise reductions obtained in the low noise surface programme might depend more on the type and condition of old surfaces than on the new low-noise road surfaces. Follow the detail recommendations in 9.4.3 regarding definition and characterization of the old surface.

Triple the "before" measurements on the old (reference) surfaces

All noise reductions which are measured/calculated rely on a measurement before the repaving was done; a "before" measurement. The precision in this measurement is therefore of utmost importance, since an error in this will propagate through all consecutive noise reduction calculations made for the new surface compared to the old surface. It is suggested that for new projects, the "before" measurement is made not only one time, but three times, and the results averaged. The deviations between such repeated measurements can and should be used to estimate the precision in the "before" data.

Start using the CPX trailer of the Hong Kong Polytechnic University as soon as possible

The CPX trailer should be used regularly for the evaluation of the low noise road surfaces laid in the low-speed re-surfacing program. The CPX measurements shall not replace the far field measurements at the roadside; they shall be a supplement which will give increased possibilities to compare results over time and between test sections. For example, they should be used to study frequency spectra of the noise on these surfaces.

It is assumed that when using the trailer, it is used with the two potential reference tyres which the author has helped to acquire. It is also assumed that the extremely critical sensitivity of tyres to hot weather exposure is observed; implying that the tyres must be stored in a cold place (below 10 ^{o}C) between measurements in order to avoid the increase of noise levels with time.

Observe the recommendations supplied earlier to improve the CPX trailer of the Polytechnic University

Before the CPX trailer is used for regular measurements, make sure that the recommendations supplied earlier to improve the trailer are considered, see Chapter 9.2.5.

Other recommendations regarding improved measurement and evaluation methods

Switch over to using a modern noise prediction model instead of the U.K. CRTN. The latter is based on old obsolete data.

Measure the noise emission on porous surfaces no earlier than 24 hours after a rainfall has stopped. If measured earlier, humidity remaining in the porous surface will limit the noise reduction.

In the local projects, measure noise emission not only in daytime but also in night-time. Evaluations for night-time might be more positive than for daytime. Night-time noise will affect people's ability to sleep well.

Avoid if possible to measure noise closer to the beginning or end of a PMFC test section than 100 m, in order to avoid underestimations of noise reductions. This applies to all types of noise measurement. Report in the noise monitoring report the (approximate) actual distance from the measuring location to the nearest non-LNRS surface.

Measure/calculate the L_{10} for use in evaluations typical of the low-speed LNRS project (as is already done). Consider this measure as the probably most relevant one in this application.

For the noise measurements, use the backing board principle to minimize the effects of acoustical reflections from behind the microphone; correct to free field conditions by adding 6 dB(A). Make sure that the microphone is mounted flush with the board since the exact position of the microphone in relation to any reflecting surface may influence noise measurements substantially. The use of a backing board and a flush mounting of the microphone will give more uniform and reproducible measurement conditions than the measurements made so far.

12.2 Proposals to improve the policy regarding the use of LNRS

12.2.1 Present policy

The present policy is based on the study made in 1995-1997 and is as follows [HyD 022, 1998]:

The conditions of application of a low-noise road surface (LNRS) are:

Do not use LNRS on inclined roads;
Do not use LNRS where there is a sharp bend in road geometry;
Use LNRS only if annual daily traffic is less than 18,500 (AADT);
Use LNRS only if the percentage of heavy vehicles is less than 35.

In addition, part of the policy is that the surface to be used normally is a polymer modified friction course (PMFC) with 10 mm max. aggregate size and laid 30 mm thick, with a target voids content of 19 % (17-21 %), with a 45 mm thick dense asphalt concrete under it.

12.2.2 Improved policy

Here it is suggested to modify the present policy to the following new policy.

In this policy, two main types of low-noise road surfaces (LNRS) are considered; PMFC and Thin Layers (also named thin surfacings):

PMFC is defined as a polymer modified friction course (PMFC) with 8 or 10 mm maximum aggregate size and laid 30-50 mm thick, with a target voids content of 22 % (20-25 %). When determining the requirements of the underlying base-course, the PMFC is considered as having the structural strength of a dense bituminous surface with 75 % of the PMFC thickness; thus normally not requiring any extra strengthening layer. However, the base-course must be even and smooth enough to provide a smooth runoff and to avoid water from collecting in "pools". An adjusting thin layer might be needed for this purpose, depending on the quality of the milling operation on the existing surface. If the base-course is a cement concrete surface, there shall be the conventional cushion layer and glass grid between the PMFC and the concrete surface. There must be proper drainage facilities along the kerbside, with outlets (drains, gulleys) at least each third metre.

A **Thin Layer** is a bituminous surface of an SMA or similar gap-graded type with a maximum aggregate size of 8 mm, usually 25-30 mm thick. This needs no extra layer under it but can be paved directly on the old surface, unless if the old surface is a concrete surface in which case one shall use the cushion layer and glass grid as before.

Note: After further testing in Hong Kong, there might be other LNRS types defined, such as Sho-Bond surface dressing, diamond ground cement concrete and asphalt rubber open-graded wearing courses. Also, a number of more advanced thin layers, such as proprietary surfaces offered by European companies may be considered.

The conditions of application of the PMFC type of LNRS on **low-speed roads** are:

- Do not use PMFC on inclined roads;
- Do not use PMFC where there is a sharp bend in road geometry
- Do not use PMFC where there is a major intersection;
- (The previous restrictions may be negotiated if an extra strengthening binder can be applied, such as a small amount of epoxy, but this requires further research)
- If only a moderate noise reduction is desired, use the version of PMFC with 10 mm aggregate size and 30 mm thickness
- If the best possible noise reduction is desired, use the version of PMFC with 8 mm aggregate size and 45-50 mm thickness
- Do not use PMFC if the intended uninterrupted length paved with it is less than 150 m; this may be negotiated down to 100 m if the "interruption" is only due to an intersection with a dense material
- If the road is lined with private businesses which may be expected to generate significant amounts of dirt on a regular basis, the walkway should be equipped with some drains close to the edge through which such dirt and dirt-water can be drained away before reaching the carriageway
- Construct the carriageway to give a cross-slope of at least 3 %, preferably 3.5 %

- Use PMFC only if annual daily traffic is less than 20,000 (AADT);
- Use PMFC only if the percentage of heavy vehicles is less than 30.
- Use PMFC only if the average vehicle speed is higher than 35.

The conditions of application of the Thin Layer type of LNRS on **low-speed roads** are:

- Construct the carriageway to give a cross-slope of at least 3 %, preferably 3.5 %
- At the kerbside, make sure that there are gulleys or similar through which dirt-water can run with a distance of maximum 10 m between each gulley
- Use a Thin Layer only if the percentage of heavy vehicles is less than 40.
- Use a Thin Layer only if the average vehicle speed is higher than 25.

No other restrictions apply.

Note: The reason why there are some light requirements regarding drainage and water runoff is that thin layers have a gap-graded construction and if too much dirt accumulates in them they will not be gap-graded any more and will quickly lose their noise reduction properties.

The conditions of application of the PMFC type of LNRS on **high-speed roads** (70 km/h or higher) are:

- Do not use PMFC on heavily inclined roads;
- Do not use PMFC where there is a sharp bend in road geometry
- Do not use PMFC where there is a major intersection where vehicles may have to stop;
- If only moderate noise reduction is desired, use the version of PMFC with 10 mm aggregate size and 30 mm thickness
- If the best possible noise reduction is desired, use the version of PMFC with 8 mm aggregate size and 45-50 mm thickness
- Do not use PMFC if the intended uninterrupted length paved with it is less than 300 m;
- Construct the carriageway to give a cross-slope of at least 3 %

The conditions of application of the Thin Layer type of LNRS on **high-speed roads** are:

- Construct the carriageway to give a cross-slope of at least 3 %
- At the kerbside, if there are restrictions to water runoff, make sure that there are gulleys or similar through which dirt-water can run with a distance of maximum 10 m between each gulley

The potential noise reductions compared to an average of the conventional road surface materials used in Hong Kong are estimated as follows, as an average noise reduction over the first two years (four years on high-speed road):

Type of LNRS	Low-speed roads	High-speed roads
PMFC, 50 mm thick, 8 mm aggregate	2-5 dB(A)	4-7 dB(A)
PMFC, 30 mm thick, 10 mm aggregate	1-3 dB(A)	3-5 dB(A)
Thin Layers, 8 mm aggregate	0-2 dB(A)	1-3 dB(A)

Within the indicated noise reduction ranges, the lower values are for cases where the proportion of heavy vehicles is near the maximum recommended and the average vehicle speed is low. The higher values are for cases where the proportion of heavy vehicles is relatively low (say around 10 %) and the average vehicle speed is relatively high.

For low-speed roads it is estimated that the technical lifetime of the PMFC is around three-four years, whereas it is estimated to be at least five years for thin layers under the normal Hong Kong conditions.

12.3 Develop knowledge to get an overall environmental and cost/benefit view

Initiate work to develop an estimate of the exterior costs of noise nuisance (dollars per dB over some threshold and per exposed person) and other environmental effects in Hong Kong.

Use international knowledge to estimate the rolling resistance of Hong Kong road surfaces, based on texture measurements.

Calculate the costs of such rolling resistance differences between surfaces.

Use international knowledge supplemented with own studies, if needed, to estimate the effects and costs of emission of particulate matter.

Initiate work to estimate the costs and effects on CO_2 emissions of the heat island effect in Hong Kong and how this relates to various road surfaces.

When the above work has been carried through, attempt to use a CBA model such as the one used by the Swedish Road Administration in order to select the type of road surface based on an overall view of environmental effects as compared to production and maintenance costs.

12.4 Measures to mitigate clogging of PMFC

Clogging of polymer modified friction courses (PMFC) is one of the major problems associated with this type of surface. In order to make PMFC efficient other than when new, it is necessary to avoid clogging. The way to avoid clogging is to have excellent drainage from the entire wearing course both over its area and vertically through its depth. Drainage can only be and remain effective if dirt can be:

(1) as effectively as possible prevented from reaching the friction course
(2) transported away from the friction course as soon as possible

There are a number of measures than can be undertaken to reduce the problem:

- Whenever PMFC is used, give the surface a 1 % higher cross-slope than is normal; i.e. usually 3.5 % instead of the normal 2.5 %. This will increase water/dirt runoff speed. In case of wide road shoulders, it is recommended to increase crossfall even more

- Never block the runoff of water/dirt from a PMFC along its lower edge (except for approx one or two dm), make sure the full depth of the wearing course has unobstructed access to the roadside or an underground drainage system (if any)
- In an urban street where there is a walkway for pedestrians lined with kerbstones, put a drainage channel along the kerb into which water and dirt from the PMFC easily can run without obstruction at the edge, as mentioned above. Consider the solutions in Japan and Denmark, but make sure that the slots are somewhat wider than in the Danish case
- In order to prevent water and dirt generated by businesses along the street from running out into the PMFC, put an extra drainage channel along the walkway outer edge. Optimize the slot width and shape in order to prevent ladies heels to get stuck in the slots, yet providing good drainage
- In cases where there are plant areas or loose soil close to the road with a risk of dirt/soil running out onto the road in case of rain storms, use a similar drainage channel to separate the PMFC from the roadside

12.5 Other recommendations for short-term consideration

The performance so far of the low-noise road surfaces

In the low-speed conditions it is not sure that the noise reduction is caused by the porous nature of the low-noise surface (PMFC), except in a few cases (Chui Tin Street is such an obvious case). One might well obtain almost the same or even the same noise reduction by using a well-designed SMA, surface dressing or thin surfacing. These would then have a much better durability, economy and range of application than the PMFC in low-speed applications. This matter should be studied more, as outlined in the following sub-sections.

In any case, to increase the effects of the porosity, the target air voids for PMFC should be increased from the 19 % used today to 22 %. High air voids content is crucial to get high noise reduction, and above all to get a slower clogging. This can be achieved by adjusting the grading curve; in particular when the European sieve sizes have been applied to get a more varied selection of aggregate sizes (see below). The MLIT specifications for porous asphalt obtained during the study visit to Tokyo would probably be useful here.

Measure noise characteristics of friction-increasing surface dressing for cement concrete

The "Sho-Bond" surface dressing which is often used on cement concrete at intersections and grades has a potential to provide a significant noise reduction, based on its favourable texture which is similar to what one may consider as a “texture-optimized surface” (for noise reduction purposes). It will not reduce the low-frequency noise created by the underlying cement concrete which has a substantial unevenness and megatexture, but it should reduce the mid- and high-frequency noise created by (mainly) the air pumping generation mechanism. The author's estimation is that this surface may reduce tyre/road noise (only) by approximately 3 dB(A) compared to the underlying cement concrete, which may be equivalent to a 1-2 dB(A) reduction for overall vehicle noise in most situations where the proportion of heavy vehicles in the traffic is not exceptionally high.

To explore this possibility, it is recommended that first the Polytechnic University's CPX trailer is used to measure the difference in tyre/road noise emission between this surface and the cement concrete surface. One should select a straight section for each surface type for this comparison. If this turns out favourable for the Sho-Bond surface, one should try one or two such surfaces in the LNRS re-surfacing trial programme.

In a longer-term perspective one may want to consider trying also some proprietary materials such as Shellgrip, EP-Grip, TyreGrip, Italgrip, etc. These might be more expensive than the Sho-Bond but they might also provide a better durability and skid resistance.

Try also other LNRS than the PMFC

One should have tried not only PMFC in the low-speed LNRS trial programme but also 2-3 fine-textured SMA and 2-3 conventional flexible wearing courses. Also, one or two Sho-Bond surface dressings should have been included in the experiment, as stated above. This would have saved money in the project since all the alternative surfacings are less expensive than the PMFC. With the present programme one cannot tell if the PMFC really have been worth the cost (other than in Chui Tin Street). Had one tested SMA:s the result might have become equally positive, at least on some roads; the same with the surface dressing. The justification for using a couple of conventional wearing courses is that this would have tested the "placebo effect"; i.e. one would see if using a conventional road surface would have had an effect or not. It could well be that simply replacing a DAC in poor condition with a similar one in new condition might have given 1 or 2 dB of noise reduction too.

Provided a diamond grinding machine could have been brought into Hong Kong at a reasonable cost, the author would also have preferred that one of the BRCC test sections had been diamond ground instead of being milled and overlaid with a PMFC.

The above are recommendations which can instead be tested in the final phases of the LNRS trial programme.

Consider re-evaluating near-future projects intended to lay a PMFC on low-speed roads and streets with local businesses very close to the street

Consider replacing the plans to lay a PMFC, by instead laying an SMA (8 or 10 mm max aggregate) in cases where all four of the following conditions apply:

- Posted speed is 50 km/h or lower
- Average speeds are 35 km/h or lower
- There is a high content of busses and/or trucks in the traffic (30 % or higher)
- There are local shops and other businesses close to the street along most of the test section (with just a sidewalk between shops and street) and when it is likely that these create substantial "dirt" which is often washed out on the street

Note that no restrictions regarding stop-lights, intersections or gradients are necessary for the use of SMA.

It will be less expensive to lay an SMA and the noise reduction will probably be similar to the case when a PMFC is laid. If possible, it would be desirable to use an 8 mm maximum aggregate instead of the normal 10 mm. Note that it is probably necessary to use also in this case the special provisions to reduce the risk of reflections of concrete joints that are normally used under PMFC (cushion layer and "glasgrid"). Please use only an experienced contractor for SMA jobs and instruct the contractor to make every possible effort to avoid the creation of flushing of the surface or excess of binder in some patches or wheel tracks.

Produce new aggregate gradings

The aggregate gradings available in Hong Kong are limited to correspond to the sieve sizes 5, 10 and 20 mm, which means that the maximum aggregate size will normally be 20 mm, but with 10 mm material also being laid sometimes. In most countries in Europe it is common to produce aggregate classes with maximum sizes of 4, 6, 8, 11, 14 and 16 mm (rounded values); i.e. approximately twice the number of classes in Hong Kong. It means that the number of degrees of freedom in the design of an asphalt mix is much higher in Europe than in Hong Kong and the mix may be better optimized for a special purpose.

It is recommended that Hong Kong starts to produce aggregate classes based on 4, 6, 8, 11, 14 and 16 mm sieve sizes (rounded values), in this way giving more freedom in designing a noise-optimized texture.

Consider improving the construction of PMFC

The PMFC used in Hong Kong since a number of years is not an optimum from the noise point of view. Consider the recommendations in Chapter 10.6. For example, the maximum aggregate size should be 8 mm rather than 10 mm and the normal thickness should be 45-50 mm rather than 30 mm. Of particular importance is to improve the kerbside drainage of water, to avoid clogging and to get less water in and on the porous surfaces.

Re-evaluate the cost estimations for PMFC

The cost estimations made in the report of 1998 from HyD should be updated [HyD 022, 1998]. Especially, one shall consider not using the extra wearing course material under a PMFC. This would reduce the need of milling and the underlying structure might be strong enough to carry the loads; of course depending on what the structure is in the underlying layers. Evidence from Europe and elsewhere consistently suggest that the structural strength of PMFC is comparable to that of a dense asphalt concrete, or at least only marginally lower. To use the extra wearing course material under a PMFC, which is used to date, therefore seems to be a waste of resources and money. Nevertheless, to reduce the risk of reflections of concrete joints when the PMFC is used on top of a concrete surface one must use the "normal" cushion layer and "glasgrid".

Reduce the transient noise when vehicles pass bridge joints or railroads

Try the best German bridge/flyover joints, as studied in Cologne during the study tour to Europe. Also try the special low-noise joints used on the motorway connecting central Bangkok with the new International Airport in Bangkok. The purpose is to see if they are better than existing devices in Hong Kong.

In case of complaints about noise from road/railroad crossings, which potentially might be an issue in Tuen Mun, try the STRAIL material as studied in Sweden and Denmark and reported within the SILENCE project.

12.6 Recommendations for further research

Test the diamond grinding technique in Hong Kong

Hire a diamond grinding machine from Europe or USA to come to Hong Kong and do some grinding work on existing cement concrete surfaces in Hong Kong. Follow-up with the normal noise monitoring and other regular measurements to document the performance.

Study the effect of cleaning of clogged porous surfaces

Invite the Japanese company Seikitokyukougou Co. Ltd. to demonstrate their most advanced and recent cleaning equipment in Hong Kong, cleaning a full PMFC test section one time per month and comparing to a similar non-cleaned PMFC section. Measure both permeability and noise emission on the newly laid surface and then after each cleaning occasion. It is recommended to do this both on a high-speed and on a low-speed road.

Carry out new experiments with asphalt rubber friction course (ARFC) in the EcoPark

The experiment with ARFC in the EcoPark should be extended to include the open-graded variant, and the reference surface there should be less smooth than the present one which is smoother than is typical of a regular street surface. The length of the new surfaces should be at least 100 m (each) instead of the present 30 m. Measurements should be made as follows on the ARFC surfaces and an the adjacent conventional dense asphalt pavement:

- Relative hydraulic conductivity (water outflow time) according to European standard EN12697-40
- Macrotexture and megatexture according to ISO 13473-1 and 13473-5
- Noise level, using the CPX method, at 50 km/h and 80 km/h (if 80 is not possible, try to run at 70), using both the ASTM SRTT and the Goodrich MudTerrain tyres. Make a number of runs (and average their results) corresponding to a total measured length of at least 500 m per tyre and speed.
- Make the above measurements approximately at the following times: Within one month of laying, 6 months after laying, 12 months after laying, 2 years after laying, 3 years after laying.

- Make visual observations of the surface condition each month. Use the same rating scheme as used in the low-speed re-surfacing programme.

Note that since it is expected that there will be a lot of heavy construction trucks travelling on the test section, potentially resulting in a dirty surface, it may be desirable to clean (wash and sweep) the test section immediately before the measurements.

Invite contractors to lay thin surfacings on some low-speed roads

It is suggested that some trials with thin surfacings are made in Hong Kong. For this purpose select similar streets with an average vehicle speed of 30-40 km/h and a heavy vehicle proportion of 25-35 %, including at least one major intersection.

Invite a number of contractors to lay their best thin surfacing there (one per street section). It could be announced as some kind of competition. The author suggests inviting the following contractors (the author can supply contact details if desired):

- Heijmans from the Netherlands (they have for example a thin layer studied in the city of Ede during the study tour to Europe)
- Colas from France (they have a very interesting high-rubber-content surface called Colsoft)
- DuraVermeer from the Netherlands
- NCC from Denmark
- Skanska from Sweden
- One contractor from Hong Kong (if available)

Also invite the Danish Road Institute (DRI) to give instructions to (say) NCC to construct on their behalf the best thin surfacing constructed and tested so far at the DRI. Whether the contractors need some economic encouragement or compensation to do this is uncertain; if needed it should be accepted. Give the contractors the instruction that they shall not design their surface to be favourable only at the beginning but to give the best possible noise reduction and durability over a time period of 3 or 4 years; given the traffic and environmental conditions.

12.7 Recommendations for studies of the international development

It is recommended that Hong Kong EPD and HyD shall follow the development on the international scene with respect to the following crucial topics:

- Development of improved binders, especially such which can reduce clogging and/or increase durability. Such research is in progress in Germany and Italy.
- Development regarding expanded clay surfaces (ongoing research in Italy)
- Trials to add a small amount of epoxy to the binder in order to substantially increase its strength against horizontal forces. Such research is underway in New Zealand.

- Follow-up research regarding long-term and durability properties of thin layers; in particular in Denmark, France and the Netherlands
- Development of the poroelastic road surface. A large EU project has recently been proposed to the European Commission.
- Further improvement of the Rollpave surface in the Netherlands aimed at improving the cost-efficiency.
- The general development of porous asphalt surfaces for low-speed applications in Japan, as well as of further studies of the efficiency of cleaning procedures for porous surfaces.

The purpose is of course to apply these new materials and technologies for a more efficient low-noise paving policy when they have been tested sufficiently and found to be useful.

12.8 Make LNRS more efficient by reducing other noise sources

There are a number of policy-related measures that do not directly seem to be related to road surfaces but which can be undertaken in order to make the low-noise road surface policy more effective. To this end, it is possible to make the use of LNRS more efficient by reducing other noise sources which are not efficiently affected by LNRS, by means of the following measures:

Limit the noise emission from the power units of the busses by more stringent regulations. Consider purchasing extra low noise vehicles. Such busses were used in the major cities in Sweden already in the 1970's.

Consider changing as soon as possible from diesel busses to hybrid busses, looking at experience in for example New York City and considering the availability of such vehicles. This could be one the most efficient noise reduction measures ever in Hong Kong and it would simultaneously be very beneficial for reduction of air pollution.

Also for public city busses, require quieter power units. In order to avoid killing this business, consider giving them economic compensation for changing to quieter products.

In order to faster switch to quieter vehicles, consider giving subsidy or bonus to those who change to such vehicles.

Consider the mandatory use in certain streets, perhaps during certain times, of special trucks having an optional quiet driving style program that can be selected by the driver and then does not allow any noisy driving operations. Such trucks have already been produced in Europe. Environmental zones in which only vehicles meeting special "green" requirements are allowed have been established in some European cities, such as Berlin, Cologne and Hanover, effective from 1 January 2008. Hong Kong might want to look at similar principles.

13. CONCLUSIONS

The low-speed low-noise road surface (LNRS) programme in Hong Kong is an important part of the comprehensive plan for traffic noise abatement in Hong Kong. It is unique in the world, albeit similar surfaces are already applied in cities in Japan. However, the Hong Kong situation calls for different solutions. Apart from the Japanese trials, noise-reducing road surfaces in low-speed urban areas have been tested only in limited experiments in Denmark and the Netherlands, and never at such a scale as in Hong Kong. It is one of the most progressive and interesting low-noise surface programmes ever launched in the world.

Due to the uniqueness of the Hong Kong trials, it is not easy to find relevant information and experiences overseas which are directly applicable and useful to Hong Kong, with its hot climate, topography, dense population, high-rise buildings and intensive bus traffic.

This report, and especially its sister report "The Benchmark Report" (under production), attempt to collect, compile and analyze the most relevant information and experiences overseas, which is useful for and applicable to the Hong Kong situation. However, for the evaluation and conclusions, the results and experiences of the trials made and still ongoing in Hong Kong are the most important ones. The author attempts to "mirror" these results and experiences on his own experience and on the international scene, in order to be able to draw safer conclusions and make recommendations based on the best available knowledge.

The low-speed LNRS programme in Hong Kong is a very brave attempt to develop a new measure for abatement of the road traffic noise problem in the urban areas of Hong Kong where traffic on low-speed roads (50 km/h and lower) are causing the noise problems. It is obvious that most of the conventional noise-reducing measures (such as noise barriers) are ineffective in most such cases and to try applying low-noise road surfaces of the PMFC type may at first look like a very good idea. However, with the international experience and to some extent also earlier Hong Kong experience indicating poor performance and large durability problems of PMFC on low-speed streets and stop-and-go traffic, the outcome of such a trial programme is connected with great risks for failure.

However, never conducting high-risk projects due to risk of failures, also means missing the best opportunities of making progress. The Hong Kong authorities have, according to the author, made exactly the principally right thing in order to explore the opportunity to create a new traffic noise reduction measure; namely low-noise road surfaces for low-speed roads.

This programme is still on-going but the evaluation at this time suggests that it has been both successful and not successful; indicating that the risks of failures have been well balanced against the opportunities of progress.

The trials have been essentially successful since they have indicated that LNRS may reduce noise emission by about 2 dB(A) in comparison to the conventional paving materials used and seen as an average over two years, without any major problems with technical durability. In some cases one may even achieve about 4 dB(A) of noise reduction. In a long-term perspective, the noise reduction potential is greater since the development towards quieter power units of vehicles will make the LNRS more effective with time. The lessons from the trials will also make future application of LNRS more effective and less costly. Or one may choose to use a more effective LNRS system at a higher cost, but achieving a better result in terms of decibels per dollar.

There are also unsuccessful parts of the trial programme; for example poor noise reduction (or none at all) for some test sections. The risk of obtaining poor noise reduction increases with the proportion of heavy vehicles in the traffic and inversely with the average vehicle speed. From this one can learn how to apply the LNRS on road sections in the future where they are more effective and avoid using them on sections where they are ineffective.

The main subject of this report is the application of LNRS on low-speed roads. However, an outlook at the situation on high-speed roads is made. It is found that the low noise surfaces have performed well on high-speed roads in Hong Kong. However, it is also noted that it seems possible to improve them in such applications, since the noise reduction which can be credited to the porosity is not as high as have been obtained internationally, when considering that the surfaces they replace mostly are relatively "noisy" ones. The reasons for this is that the PMFC used are not of optimum construction in accordance with international experience. Suggestions are made on how the high-speed low noise road surface policy can be improved.

The methodology in parts of the test programme has some serious flaws, which could have been avoided if the level of knowledge had been higher at the start of the programme. The design of the trial programme could also have been better; mostly by testing not only the PMFC type of LNRS but also including a number of other potential low-noise road surface types, and even including a few conventional wearing courses. But the latter flaws are still possible to correct in the still on-going part of the trial programme.

By learning from the results and experiences so far, the author thinks that the 2 dB(A) of average noise reduction obtained for the first 21 sections analyzed here, can become 3-4 dB(A) of average noise reduction in a future regular application of LNRS on Hong Kong low-speed roads. This would correspond to an effect similar to cutting traffic volume by 50 % and as such be an improvement which is extremely difficult to achieve in other ways. In addition, a wide application of "semi-low-noise road surfaces"; i.e., road surfaces which reduce noise only by 0-2 dB(A), but with only a small cost increase in comparison to the traditional paving policy, one may achieve further improvement of the acoustical quality of life in Hong Kong. The author thinks that the latter is possible in the near future after trying so-called thin layers on a wide scale. Even conventional SMA surfaces which are known to be durable may have such an effect in comparison to the traditional paving materials used in Hong Kong.

When estimating the advantages and disadvantages of the LNRS, one shall not forget other effects than reduced noise. This includes lower rolling resistance (which will occur at least when old concrete pavements are re-surfaced), which will reduce fuel consumption and CO_2 emissions, but it also includes improved skid resistance which may reduce accidents. Two very important advantages of the PMFC type of LNRS is the water storage capacity of such pavements, which reduces the need for high-capacity subsurface drainage systems, and the reduced heat island effect caused by the porous structure and water-retaining capacity of PMFC. When such effects are counted in terms of saved dollars and saved tons of CO_2 emissions, one may find that using PMFC is a win-win situation. Other advantages include less splash and spray and better anti-glare characteristics and in some cases also less emission of particulates; the latter being a serious health effect in many countries.

It is hoped that this report will aid the Hong Kong environment and highway authorities in implementation of a more effective low-noise road surface policy in the future.

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