# HIGH FRICTION SURFACING FAILURE MECHANISMS

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## ABSTRACT

In recent years the New Zealand Roading Authorities have identified sites on their roads that have high crash rates and a higher demand for surface friction. High Friction Surfacings (HFS) are a cost effective solution that have been proven to reduce crash rates in similar situations around the world.

HFS have proven to be very effective on almost all sites where they have been applied. However there are issues with the life of the treatments; they are not lasting the target life used in their Life Cycle Cost Analysis (LCCA) and in some cases, are failing less than a year after application.

This paper investigates the failures of a number of HFS systems that have been applied over the past five years in various situations in New Zealand with the aim to identify the mechanisms or combination of mechanisms that have contributed to the failures.

In the majority of cases, the premature failure is caused by cohesive failure within the top 20mm of the underlying asphalt.

## HISTORY OF HIGH FRICTION SURFACES

In the early 1960s the United Kingdom (UK) was experiencing large increases in traffic and corresponding increases in vehicle crashes and fatalities on its roads. This led to a focus on vehicle skidding as one of the main causes of these crashes, especially at roundabouts, sharp bends pedestrian crossings and intersections, which had higher crash rates than the rest of the network. The sites with high crash rates became known as black spots. At this time the UK's Transport and Road Research Laboratory (TRRL) was investigating various aggregate sources with various types of binders to produce surfaces with extremely high friction. TRRL also investigated the identified black spots and discovered that the aggregates used on these sites tended to be polished and the surfaces were losing skid resistance over time.

By the mid 1960s the Greater London Council (GLC) was investigating ways to restore surface friction to these black spots. The GLC concluded that the most effective high friction surface treatment was the application of 3mm Calcined Bauxite (CB) chips on a bitumen-extended epoxy-resin binder. Two companies working with GLC and TRRL developed two high friction surfacing (HFS) systems.

These new systems showed a reduction of skidding crashes of 60 to 70% and a reduction of all crashes of 50%. The application of HFS became commonplace in the UK by the early 1980s.

One of the first HFS sites in New Zealand was constructed on Ferry Road for the Christchurch City Council in the early 1990s. One of the most successful HFS sites in New Zealand was constructed in 1997 on State Highway 2 at the Petone Overbridge.

## INTRODUCTION

New Zealand has been using High Friction Surfacing (HFS) to reduce accidents on sites with high crash rates since the early 1990s. Most HFS surfacings include the application of a synthetic binder (normally epoxy or polyurethane) which is then covered with CB. CB is a synthetic aggregate which has proven to have a high resistance to polishing. Unfortunately while these surfaces have performed very well in reducing crashes on most of the sites where they have been applied, there have been many sites where the HFS has failed prematurely. As the HFS is very expensive when compared to other treatments on a square metre basis, it has to reach its design life to be considered a cost effective solution. Life Cycle Cost Analyses

(LCCA) are calculated to justify the expenditure, and the benefits of the reduction in crashes and fatalities and social costs being shown to far outweigh the costs of installation, as long as the surfacing lasted 7 years or more. Unfortunately the high numbers of premature failures have lowered the client's confidence in the HFS lasting the required 7 years.

A review of the performance of much of the HFS recently laid around New Zealand suggests that the most common failure mode on the sites that fail prematurely is cohesive failure within the top 15-20mm of the surface of the underlying asphaltic concrete. Previously the more common modes of failure were delamination and chip loss.

There at least four main theories regarding the mechanism of the cohesive failure within the top 20mm of the mix under the HFS. This paper will illustrate these theories and discuss the likelihood of each and offer some possible solutions that could reduce the risk of failure due to the specific cause.

Most HFS is applied on high demand sites (and usually high profile sites) and because the installation cost of the surfacing is high the practitioner normally needs high traffic numbers to help justify the expenditure. High demand means that the site may have high crash rates, high traffic counts, heavy braking, acceleration, tyre scrub, steep gradients, tight radius bends or a combination of some or all of these issues. A global search for HFS failure mechanisms showed that of all of the failure modes occurring with HFS overseas, cohesive failures are far less frequent and a comparison between the complete surfacing design in New Zealand and Overseas will be made.

# HFS FAILURES

Three predominant modes of failure of HFS surfacing systems have been identified since it was developed in the 1960s:

1. Delamination failures – The HFS including binder and cover aggregate falls off cleanly. These failures are caused by adhesion issues between the HFS binder and the underlying surface.
2. CB Chip Loss – The CB chip falls off the surface with or without the HFS binder attached. The failures are caused by either adhesion issues between the CB and the HFS binder or the HFS binder is failing.
3. Asphalt or Substrate Cohesion Failure. – The HFS peels off with the surface of the substrate attached. These failures are caused by cohesion issues within the asphalt substrate.

Until recently, delamination failures have been the most common mode of failure closely followed by CB chip loss. These failure modes could normally be traced back to issues with the application methodology used by the contractor. Improvements in the application methodologies used by contractors in New Zealand in recent years have improved the adhesive performance of the HFS reducing the incidents of delamination and chip loss. However, the HFS ultimately relies on the internal strength and durability of the surface upon which it is laid and, now that the HFS is normally well bonded to the substrate, it is the asphalt substrate that is failing through cohesive failure.

# WHAT CAUSES THE HFS FAILURES?

## Shear Stress at Calcined Bauxite – Binder Interface

HFSs are normally applied on sites with high friction demand. Most sites are approaches to high trafficked roundabouts, intersections or pedestrian crossings, other sites include short radius bends, bends with poor geometrics etc all with significant shear stress on the surface. The high traffic counts on most of these sites mean that not only is there a high shear stress on the site but a heavy loading demand as well.

The high shear stresses on the surface are transmitted from the tyre onto the CB chip which is small (either 1-3mm or 3-5mm) and very durable. The small chip size ensures many sharp edges which produce the high surface friction and allows very little slippage of the tyre across the surface. As the tyre stresses the surface the point loading at CB – binder interface is very high. The adhesive bond between the CB and the binder has to be strong to retain the chip. The purpose of the binder is also to bond the calcined bauxite onto the existing surface.

A large range of binders are used in the construction of HFS, these include: Epoxy, Polyurethane, Methyl Methacrylate, Thermoplastic, Polyester to name but a few. The different chemistries of the various binders' means that their physical properties and behaviour in service vary. However the investigation showed that as long as the application methodology followed best practice all of the binders adhered to the chip and the existing surface. There was no pattern that suggested that any of the failure modes was more prevalent with any specific binder.

Common faults in construction methodology which cause adhesive failures between the CB and binder are:

- Dirty chip, the binder adheres to the dirt and not the CB.
- Wet or damp chip, the moisture prevents the binder from adhering to the CB.
- The CB and binder are chemically incompatible; the binder does not adhere to the chip.
- The binder sets before CB is applied.

If the CB adheres well to the binder then the shear stress applied to the surface is transferred to the binder which has to be strong enough to hold the CB in place without failing.

Common faults in construction methodology which cause cohesive failure in the binder are:

- Binder mixture is incorrect and does not cure.
- HFS is trafficked too early before the binder has cured properly. (Figure 1)
- Temperatures too cold and binder does not cure properly.
- Binder application rate is uneven and in areas where it is too low the bond contact area between the aggregate and the binder is insufficient to retain the CB. (Figure 2)

***Figure 1: Traffic too early.***

***Figure 2: Poor binder application causing chip loss.***

## Shear stress at HFS – substrate interface

If the application methodology has ensured a solid bond between the chip and the binder then all of the stresses applied at the surface are transmitted onto the interface between the binder and the substrate. The National Centre for Asphalt Technology (NCAT) Newsletter, Fall (Autumn) 2010, reports that while investigating shear stress distribution throughout the pavement structure researchers found *"… that the critical shear stress at the interface underneath the surface layer is primarily affected by the thickness and stiffness of the surface layer, as well as the variation in stiffness caused by seasonal temperature variations. …Surface layer thicknesses from 0.5 to 2.0 inches were analyzed, with thinner surface layers exhibiting higher interface shear stresses."*

While a thin layer of HFS was not analysed, a range of layer thicknesses down to a 12.5mm thick asphalt layer were analysed. The thinnest layer exhibited the highest interface shear stresses.

If the shear forces on a very thin surface layer cause critical shear stress at the interface between it and the layer below, and the HFS layer is very thin, it will transmit almost 100% of the shear forces applied. The shear stresses produced by vehicle tyres when braking, accelerating, and turning will be significantly higher than those found at the base of other surfacings because the HFS has a high friction surface and there is very little slippage on its surface. The extremely high shear stresses at the interface will cause delamination failures wherever the adhesion of the binder onto the surface of the substrate is compromised and failures within the substrate if the shear stress applied exceeds the internal friction of the substrate layer.

## Delamination

Delamination occurs when the binder does not adhere to the substrate and the complete HFS system comes off in one layer with little or no substrate attached.

In the late 1990s and early 2000s in New Zealand the most common reason identified for the delamination failure was surface contamination, as it was believed that road grime comprising oil drips, diesel spills, and road detritus etc. had prevented the binder from adhering sufficiently to the underlying surface.

Another common cause of delamination is surface moisture; some binders react with the moisture on the existing surface and fail to cure adequately, and in addition the moisture can form a barrier that prevents the binder from adhering to the substrate. Possible sources of the moisture on the surface are: rainfall, moisture from cleaning, moisture from the existing pavement and dewfall. The requirement to apply HFS on high demand sites at night to reduce disruption to the road users increases the risk of rain and dewfall damage on HFS.

Other surface contamination issues such as flushing, bleeding, or no surface texture available to ensure mechanical bond are also provided as reasons for delamination failures of HFS.

Delamination due to surface condition was a common fault at the time and the focus on improving the performance of the HFS led many applicators to change their surface preparation methodology to include water blasting or watercutting the existing surface. The only issue with these processes is that the surface is left wet or damp and another important requirement for good adhesion of the binder to the substrate is that the surface must be dry. Some binders are more forgiving than others e.g. polyurethane binders degrade if water is present during application. Some applicators pre-dry the surface with heat guns or hot air lances before applying the binder. This heat also serves to warm-up the surface aiding and often accelerating the curing of the binder.

Surface contamination is not the only cause of delamination of the HFS and some of the other causes that have been promoted for the different failures they include:

- Moisture infiltrating the bond between the HFS binder and the substrate
- Bitumen on the surface of the asphalt substrate.

On the Wainuiomata Hill site, Hudson (1994) reported that water rising from the subgrade through the permeable asphalt substrate was breaking the bond between the binder and the asphalt surface (see Figure 3). Parfitt (2011) found when inspecting the failures on Wainuiomata Hill that there were also cohesive failures where the moisture caused stripping within the asphalt. He also suggested that the polyurethane binder used was less permeable than other binders in use.

***Figure 3: Delamination on Wainuiomata Hill.***

Coloured surfacings use similar binders without the CB chip so do not produce a high friction surface. These were included in the investigation to illustrate that some of the failure mechanisms are not solely caused by the high shear stress. Figure 4 shows a coloured surfacing delaminating from a bitumen rich chipseal surface on a cycle lane. The surface condition prevented the HFS from chemically and/or mechanically bonding to the aggregate on the existing surface.

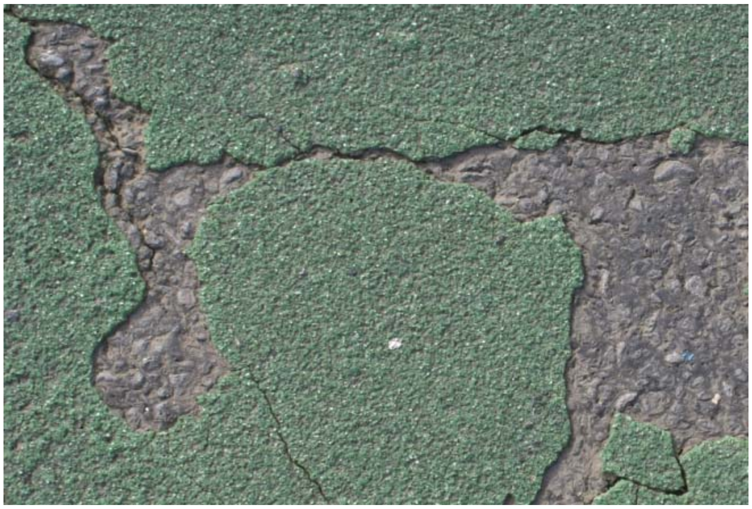

***Figure 4: Coloured surfacing delaminating.***

## Discussion

The problems of delamination have largely been solved by applicators who ensure that the surface is suitable for the application of HFS. Removal of surface contamination by watercutting or waterblasting and ensuring that the surface is dry before the application of all binders is now the industry standard in New Zealand.

Watercutting removes any excess binder, detritus, and contamination as well as removing any soft or loose particles in the surface of the hot mix asphalt (HMA) substrate.

## 1. Cohesive failure in the substrate

Currently the most common mode of failure of HFS surfacings in New Zealand is the cohesive failure in the substrate where the HFS is well bonded to the surface of the asphalt substrate and the HFS with the surface of the asphalt attached to it peels off (see Figure 5).


***Figure 5: 3-5mm Calcined Bauxite with epoxy binder and surface of 14mm HMA***

There are three main possible contributors to the extreme shear stresses that cause this failure they include:

1. Lack of slippage of the tyres when braking, accelerating, cornering etc focussing all of the shear stress on the internal friction bond that holds the coarse aggregate at the asphalt surface that is attached to the HFS in place.
2. The different thermal coefficients of the HFS and the asphalt create significant stress within the surfacing where the asphalt expands and contracts differently from the HFS. The coarse aggregate exposed at the asphalt surface which is bonded to the HFS focuses these stresses on the internal friction bonds that hold the coarse aggregate in the asphalt.
3. The HFS is normally much stiffer than the HMA and every applied load will cause the HMA to deform more than the HFS, this applies significant stress to the internal friction bonds that hold the coarse aggregates in the HMA.

If the applied stress from any or a combination of all of the above is greater than the internal friction within the HMA or other substrate, then the cohesive failure occurs. The main causes of the low internal friction that leads to HFS failure are:

- The binder in the HMA is too soft/weak or has lost its adhesive capability
- The HMA is too fine and the stress is focussed too close to the surface
- Moisture trapped by the HFS in the top of the HMA strips the binder weakening the HMA.

Therefore, the fourth mechanism that may contribute to cohesive failure within the HMA layer is the moisture trapped within the HMA stripping the bitumen from the coarse aggregate. It is common to see clean aggregate surfaces when cohesive failure occurs however it is difficult to identify whether the stripping occurred before or after the cohesive failure, as once the failure occurs it allows moisture under the HFS and the loose aggregate becomes a grinding paste which rapidly wears down the surface of the exposed aggregate in the HMA.

Figure 6 depicts the result of cohesive failure within the HMA, this diagram shows clean aggregate and could represent a failure caused by stripping of binder from the coarse aggregate.

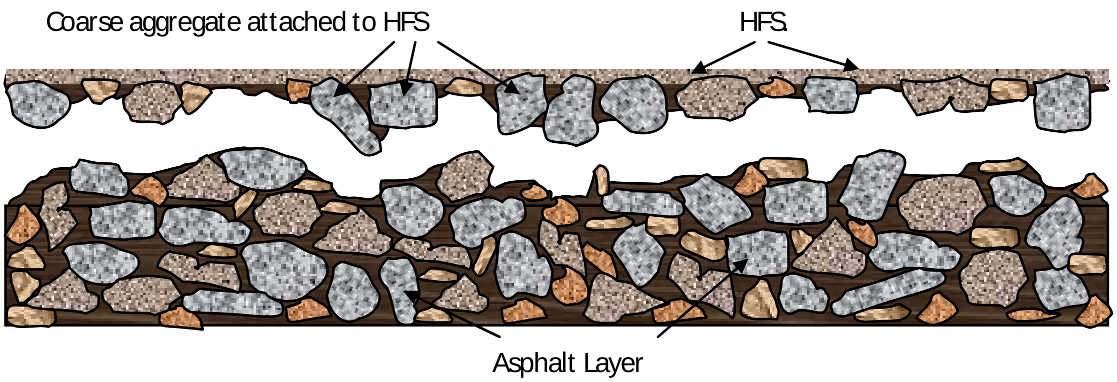


***Figure 6: Diagram depicting cohesive failure.***

## DISCUSSION

The four mechanisms discussed above are all possible contributors to any cohesive failure in a HMA layer. On most sites visited the areas of failure were generally in the areas with the highest traffic demand.

However, on most sites there were failures in areas where the traffic demand would not be considered extreme and in these areas the cause was likely to be one of the other mechanisms. When examining these recently failed sites it was impossible to decide whether the stripping of the binder from the stone in the failure plane happened before, or after, the failure. It was also impossible to decide whether deflections in the pavement or thermal coefficient differentials contributed to the failures. These three mechanisms may be the cause of failure in those areas on site where the shear stress is not considered as extreme.

If it is accepted that one or all of these mechanisms is likely to exist on all HFS sites, then what can be done to reduce the risk of failure?

The problem with lack of internal friction in the asphalt is mostly related to the binder. After hotmix asphalt manufacture and application the hot mix asphalt binder still contains some lighter fractions which must be allowed to evaporate out in the next few months before the application of the HFS. Most cohesion failures are in recently laid asphalt which has not cured and stiffened. Most specifications and HFS system suppliers worldwide suggest a minimum of a month curing time before the application of the HFS. The length of curing time should depend on the properties of the binder when the HFS is applied.

In New Zealand HFS is applied on high demand sites or sites with poor geometrics where applying HFS is more cost effective than realigning the road to improve the geometrics. Unfortunately until recently the surfacing for high demand pavements in New Zealand was 50mm of 14mm HMA on top of a chipseal over unbound pavements.

Internationally deeplift asphalt or structural asphalt pavements are the norm for high demand sites. The top layer of these pavements is generally constructed using larger stone, dense graded asphalt. There is minimal moisture movement, nor deflections in these pavements, removing two possible mechanisms of failure.

In New Zealand the high cost of the HFS and a full depth HMA pavement, the 8% discount rate (which is applied in the economic evaluation required for all projects), and the lack of accounting for disruption to road users in the Project Evaluation Manual (PEM) mean that alternatives such as resurfacing every 2 years with locally sourced high PSV aggregate are the lowest cost solution when compared with a 10 year solution.

Currently the most common treatment is 50mm of 14mm HMA under the HFS. It is estimated that the average depth the coarse aggregate particles exposed at the 14mm HMA surface penetrate is 12mm. These aggregate particles anchor the HFS into the HMA. Larger particles would be embedded deeper into the HMA and provide a stronger anchor for the HFS. The minimum pavement on a high demand site would be a 20mm HMA that would require a depth of at least 60mm.

The difference in stiffness between the HFS and the HMA causes stress within the surface of the HMA when it deflects. If the pavement and the asphalt are stiffer then differential between the HFS and HMA will be less creating less stress.

## SOME POSSIBLE SOLUTIONS

Some possible solutions based on what on what has worked well in practice and what should improve the HFS performance are listed below. Of these only number 5 is still a work in progress.

1. Stiffer binder in asphalt – It may be that the extreme stresses are too much for the ordinary binder and harder, stiffer, stronger binders should be used in mixes underneath HFS. The asphalt must be allowed to cure until the mix is capable of withstanding the extreme stresses transmitted into it by the HFS.
2. Coarser Mix – Currently the most common treatment is 50mm of 14mm HMA under the HFS the 14mm aggregate has an Average Least Dimension (ALD) in the 8-9mm range. Recent trials in Lower Hutt used a Stone matrix Asphalt (SMA) with a Polymer Modified Binder. The trials were successful and outlasted the other materials applied at the site.
3. Reduce Deflections – This failure mode can be minimised by limiting the deflections in the pavement and at the pavement surface before construction of the asphalt layer, increasing the stiffness of the asphalt layer, and reducing the stiffness of the HFS binder.
4. Reduce Stripping – Stripping may contribute to the loss of cohesion in HMA underneath HFS, the risk of stripping can be minimised by the use of additives such as adhesion agents in the hotmix asphalt binder and the HFS binder or binder modification.
5. Softer more flexible HFS binder – The best solution would be to develop a binder that was tough enough to hold the CB in place but which has very similar properties to ordinary hot mix asphalt so that the HFS expands, contracts, bends and breathes with the asphalt. The only requirement of the asphalt would be that it was tough enough to withstand the stress applied by the traffic loading.

## CONCLUSIONS.

1. The New Zealand HFS surfacing industry has identified some early HFS failures mostly related to the inability of the upper 20mm of the asphalt layer to withstand the extreme stress transmitted into the asphalt by the calcined bauxite aggregate topped HFS.

2. A number of specifiers have lost confidence in the product due to the high up front cost and poor performance. A performance based specification for High Friction Surfaces has been developed by industry to put the risk where it lies for all work completed.
3. HFS has been used to reduce the crash risk on high demand sites, but the designs for both the pavement and the asphalt surfacing systems are minimal designs to keep the cost down and the surfacings on these sites are failing prematurely.
4. The minimum asphalt surface underneath HFS should be constructed using at least 60mm of 20mm HMA with Polymer Modified Binder containing adhesion agent.
5. The addition of binder adhesion enhancers should be mandatory to prevent moisture stripping within the asphalt.
6. The asphalt should be left for a minimum of two months in summer to allow the binder to harden before the application of the HFS. While HFS on older asphalt has worked very well it should not be placed on asphalt that is so old and cracked that it fails prematurely before the HFS.
7. Watercutting the asphalt surface to remove contaminants and interstitial fines has reduced the incidence of delamination of HFS surfacings in New Zealand.
8. The use of heat lance or air blower to ensure a dry pavement surface (especially if polyurethane is being used as a binder for the HFS).
9. Most HFS binders have different physical properties than the asphalt surface they are being applied on and this can create extreme stress within the asphalt. A binder should be developed that mimics: the thermal expansion and contraction of the asphalt layer, the stiffness of the asphalt layer and the permeability of the asphalt layer.

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Jeff has been involved in the roading industry since 1977 when he started with Fulton Hogan.

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