



# **GUIDE TO MINIMISING THE RISK OF DELAMINATION IN CONCRETE**



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# INTRODUCTION

Delamination is defined as a zone of weakness or separation along a plane parallel to the concrete surface caused by a either material, processing and/or environmental factors. These surface defects vary in size, depth and timing depending on the cause and other related factors. The prevalence of delamination problems is mostly associated with floor slabs, which has increased in the last twenty years as larger industrial floors have given rise to modern finishing systems [1].

Delamination of concrete has been widely reported overseas with more frequent occurrence coinciding with widespread use of ride-on machines in the early 2000's and a further spike in cases over the last five to ten years [2].

Delamination of finished floor slabs represents a failure of the wearing surface such that the highly finished and hard layer is replaced by a rough and irregular indentation. These defects in the surface are a significant serviceability issue since they disrupt the otherwise hard and smooth surface of finished concrete. Repairs to restore the aesthetics and resistance of the concrete surface have been undertaken successfully but these need to be thoroughly investigated.

To understand the mechanism responsible for concrete delamination, the characteristics of the concrete surface and techniques used to finish floors needs to be explained. This is important since finishing operation during construction of concrete slabs produces significant differences in surface properties of concrete [3].

# CHARACTERISING CONCRETE SURFACE LAYERS

This Guide is written to provide the necessary awareness of risks and mitigations strategies for delamination of concrete, with specific focus on finished floor slabs. Finishing of concrete floors is done to produce an even, hard-wearing surface and consists of the following phases [4]:

- Screeding is the process of levelling concrete to the required flatness and levelness while simultaneously compacting through the depth of slab to remove entrapped air voids
- Floating of concrete is done to remove surface imperfections and provides further compaction without sealing the surface from bleed water rising
- Trowelling of concrete happens at final set when the concrete is starting to stiffen rapidly and the process effectively polishes the surface drawing up cement to improve surface hardness

Finishing of concrete results in different layers being formed close to the wearing surface that are characterised by the following zones [1]:

- Densified surface layer of typically 1-3 mm with increased cement paste and an absence of entrapped or entrained air bubbles
- Distorted layer of up to 10mm with cement paste and some fine aggregate where trowelling has distorted air bubbles into lenses and air contents is below that found in the bulk concrete
- As placed or bulk concrete is the underlying material that is relatively homogeneous and unaffected by the trowelling done on the surface

Timing of these finishing phases is critical to achieve optimum surface properties for achieving excellent performance of floor slabs. The window of finishability is important to allow the contractor sufficient time to finish the whole slab and this is illustrated in Figure 1 for a theoretical case. Exact timing of these operation will depend on the size of the concrete floor being cast, the nature of the concrete mix being used and the ambient temperature on site. The time available for final finishing operation (e.g. power floating and trowelling) can vary quite significantly with the advent of modern chemical admixtures and placing techniques not always helping control this window of finishability [5, 6].

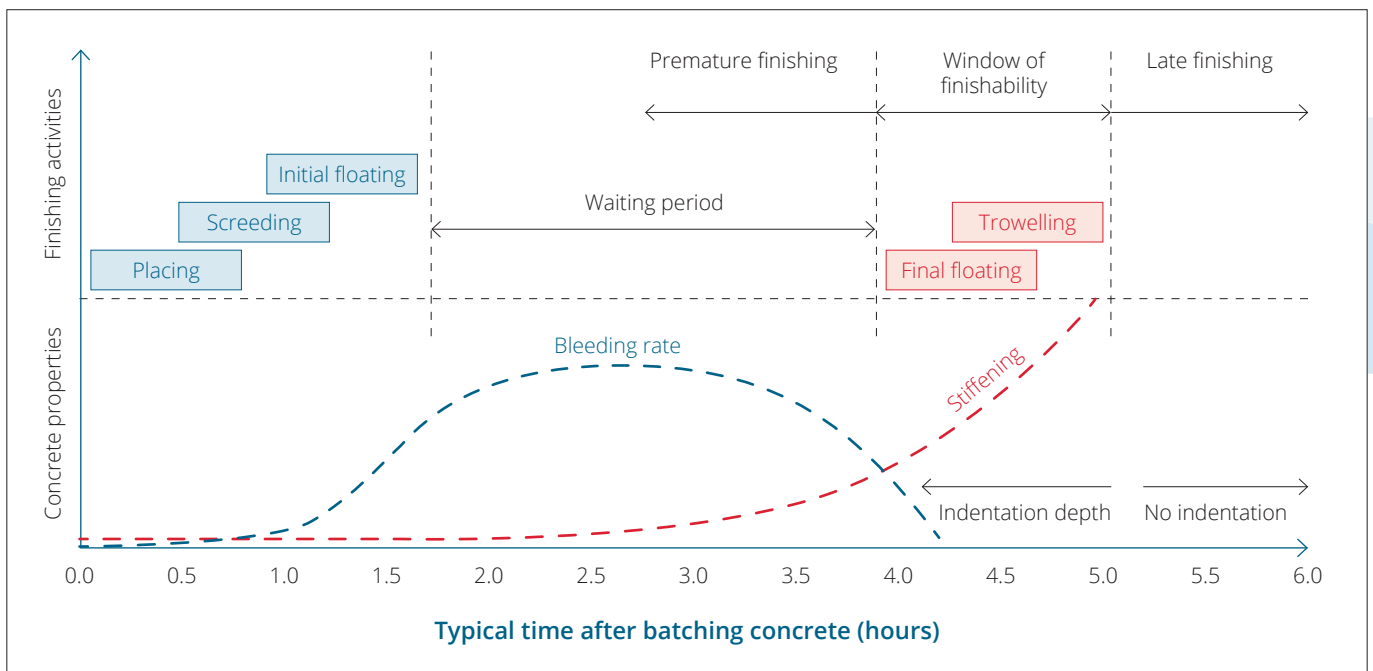


Figure 1: Timing of placing and finishing a typical concrete floor

These near-surface characteristics can be assessed using petrographic techniques where thin-sections from cores are petrographically examined under microscope. This type of examination needs to identify and classify anomalies resulting from air voids or bleed water that are responsible for most cases of delamination of concrete. In theory this appears relatively simple but concrete is a complex, composite material with multiple phases, especially at a micro-level.

# CAUSES OF DELAMINATION OF CONCRETE

Delamination is generally the result of air voids or bleed water trapped under a dense polished concrete surface that creates zones of weakness (see Figure 2). These surface defects can be caused by several different factors and mechanisms including premature finishing, excess air, delayed finishing, surface crusting, unusual bleeding and long-term factors [7, 8].

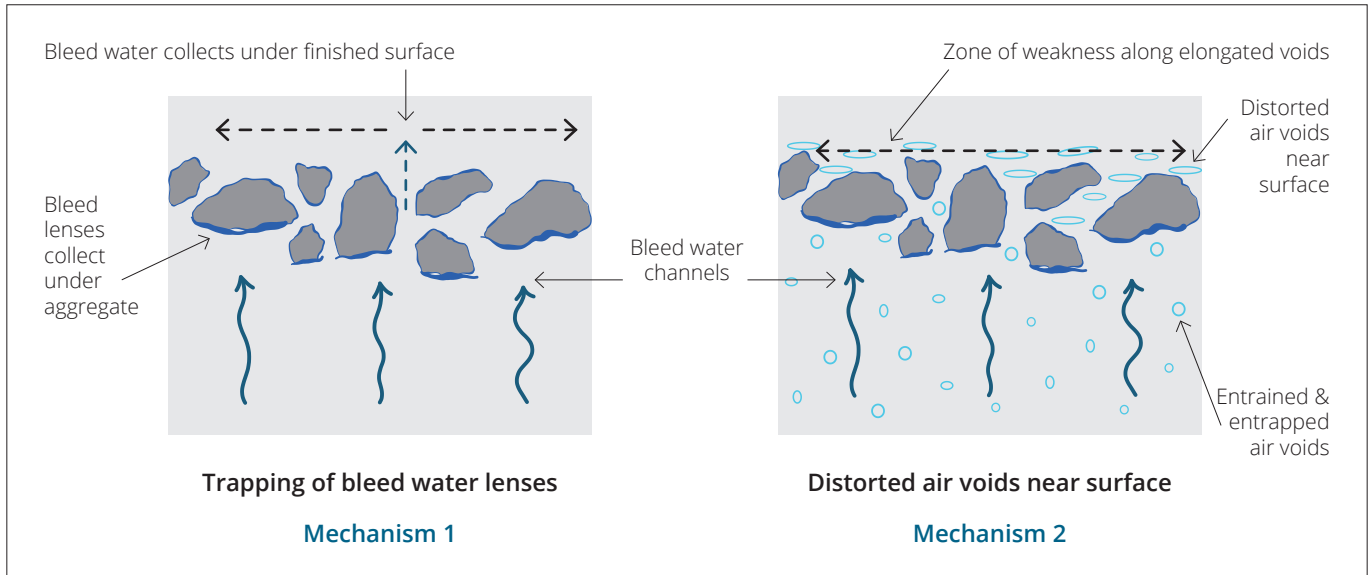


Figure 2: Mechanisms responsible for delamination of concrete

## PREMATURE FINISHING

Densification of the concrete surface before bleeding has ceased may trap water beneath the cement skin and result in relatively shallow delaminations of less than 3 mm [9]. Finishing operations are traditionally started when bleed water sheen is no longer visible on the surface and footprints are less than 5 mm. These two indications are physically related in that bleeding ceases as concrete approaches final set, which leads to a significant increase in stiffening. Misreading the condition of the concrete on site sometimes occurs when the following conditions are present:

- Evaporation of bleed water from the surface of concrete will prematurely dry and stiffen the surface
- Machine finishing means the operator may not have physically assessed the surface stiffness of either the whole slab or slower setting areas that were poured at higher slump or in shaded areas
- Large areas of finishing where the window of finishability is perceived to be too short may encourage the finishing crew to start prematurely

## EXCESS AIR CONTENT

Trowelling of concrete containing excess air can cause bubbles to accumulate and form lenses that can cause zones of weakness that are typically located at 5-10 mm from the surface [10, 11, 12]. Concrete may contain a range of air bubbles when initially cast on site that include large entrapped air bubbles, medium-sized mix bubbles and micro-sized entrained air bubbles. High intensity compaction of the surface during floating removes larger-sized air bubbles and depresses smaller-sized bubble from the surface skin.

The presence of excess air in concrete may create weak zones as these voids elongate and agglomerate under the high shearing action of finishing operations. It has also been speculated that the presence of these lenses of air may also have some role in the phenomenon of late bleed where a second period of bleeding is seen during finishing. This is thought to be heavy finishing machines applying pressure on the concrete surface and squeezing deformed air pockets, which then flex and release trapped bleed water.

## DELAYED FINISHING

Working the concrete surface beyond final set can cause air and water to be squeezed out of the surface layer to collect deeper in the concrete at a depth of 5-20 mm. Prolonged finishing may also cause delamination by over-layering where mortar is removed from high spots to fill hollows [1, 5]. This practice often occurs in the following conditions:

- Adverse weather conditions such as high temperatures that lead to rapid stiffening and water is sometimes added to the surface to get more paste to achieve the required flatness and finish
- Larger than normal areas to be finished may lead to finishing taking longer than expected and areas may be too stiff to achieve the specified flatness tolerance

## SURFACE CRUSTING/TOP-DOWN STIFFENING

Wind and/or a warm surface can cause the top layer to stiffen rapidly while the interior concrete is still plastic and continues to bleed [7]. This can sometimes also occur when the base is cold and retards setting of the interior concrete will the surface is exposed to warmer conditions. Concrete used for floor slabs is supplied with a wide range of aggregates and strength grades and this leads to significant differences in bleed rate of the material. Concrete mixes should nevertheless be designed to have a steady bleed rate to protect the surface from plastic shrinkage cracking.

## UNUSUAL BLEEDING AND SETTING

Special concrete mixes that contain SCMs such as fly ash may have lower and longer rates of bleeding that need different timing when it comes to finishing. The window of finishability may also be much shorter than normal when using some chemical admixtures that cause rapid stiffening [5]. The mechanics of delamination are essentially the same as that of premature finishing where bleed water is trapped beneath the cement skin at a depth of less than 5 mm. Unusual bleeding may also take the form of late bleeding where there appears to be some interruption in the normal process. Typically bleeding occurs slowly at first then steady for several hours before reducing as the concrete stiffens. Occasionally working of the surface appears to reactivate bleed that is assumed to be trapped beneath the surface and this has been postulated to be due to excess air voids.

## LONGER-TERM FACTORS

Delamination may occur in hardened concrete as a result of internal expansive reaction such as freeze-thaw, alkali silica reaction (ASR) or corrosion of steel reinforcement [1, 13]. These processes can cause delamination in concrete despite the absence of latent defects and are induced by internal pressure from long-term deterioration processes. Depth of delamination is generally deeper than those for early-age damage and may be at the level of reinforcement within the concrete.

These types of delaminations are diagnostic by occurring much later after construction as well as having other physically distinguishing features. Hardened concrete subject to stresses causing delamination with fracture through some aggregate particles rather than around stone particles as happens with most early-age defects. Delaminations may also have signs of reaction product such as silica gel, in the case of ASR, or rust, in the case of corrosion of reinforcement.

Table 1: Causes of delamination of concrete of new floor slabs

Cause	Mechanism	Location	Other factors
Premature finishing	Bleed water trapped	1-3 mm	Large floor areas requiring finishing
Excess air content	Air lenses formed	5-10 mm	Air entrainment or foaming issues
Delayed finishing	Deeper voids	5-20 mm	Adverse weather or logistical issues
Surface crusting	Bleed water trapped	Varies	Adverse weather esp. hot & windy
Unusual bleeding	Air and water	1-5 mm	Entrapped air near the surface

# DIAGNOSIS OF DELAMINATION

Survey and investigation of concrete floors is often done to identify the extent and cause of delamination beneath the surface. These investigations are generally reliable when the extent of the potential damage is needed but establishing the cause is complicated by interaction of material, processing and environmental factors [14]. Figure 3 shows how some delamination areas are obvious on the surface while others are more deep seated and may not be apparent.

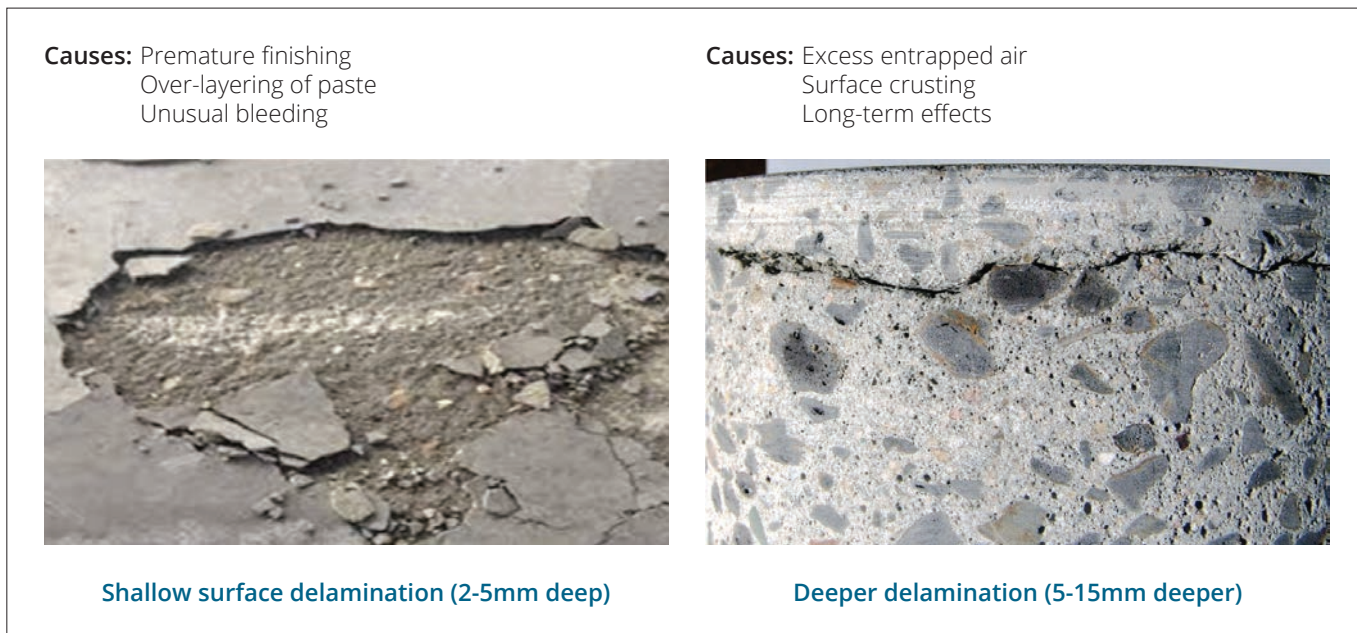


Figure 3: Typical pattern of delamination and likely causes

## DETECTING DELAMINATION

Locating areas of delamination is done using a range of techniques with increasing levels of sophistication and expense that include visual, mechanical and non-destructive scanning. A summary of these techniques is briefly given below with more details available in the following references.

- Visual appearance can be diagnostic with shallow delaminations since these areas will dry more rapidly than the surrounding concrete and when rewet will hold moisture for longer. Craze cracking may also be associated with these localised areas.
- Trapping and chain dragging may also identify hollowness beneath the surface but this is somewhat subjective and occasionally destructive if heavy hammering occurs
- Rebound hardness testing of the surface using a Schmidt hammer may provide useful information when delaminated areas are deeper but this method is too intense when assessing shallow areas of potential delamination
- More sophisticated scanning technology is sometimes used that is done with infrared thermography, impact-echo and ground penetrating radar. Care should be taken when interpreting this data as operators tend to have limited experience with micro-assessment that is required when assessing the surface quality of concrete.
- Destructive testing using cores is sometimes undertaken but while this is invasive it is able to identify the extent of the problem and is generally done for forensic reasons (e.g. to identify the mechanism of delamination and therefore the most likely cause of the problem). Figure 4 shows a concrete core that has been sliced in half and prepared for image analysis

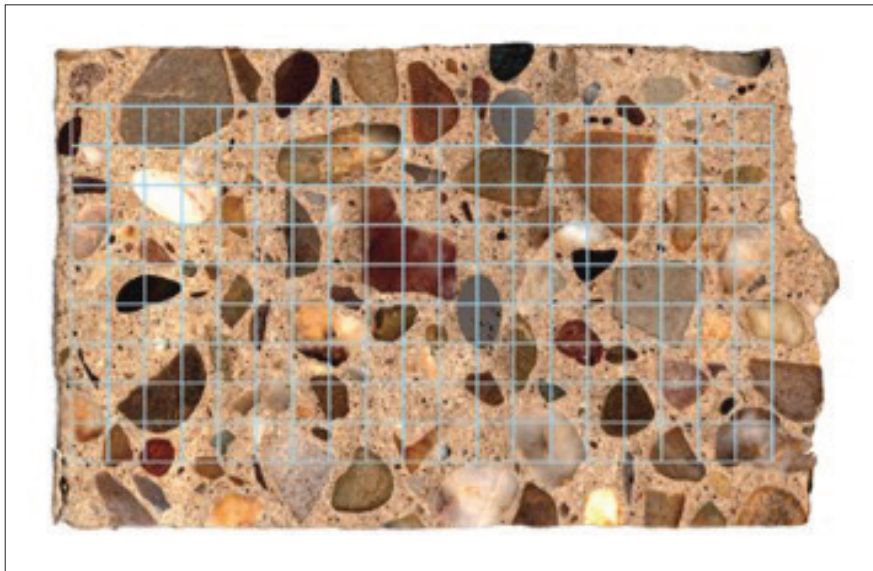


Figure 4: Petrographic preparation of concrete core sample for petrographic examination

## DIAGNOSING THE CAUSE OF DELAMINATION

Diagnosing the cause of delamination can often be reliably done by reviewing the construction, concrete supply and environmental records if these are available. On some projects this information is either incomplete, unreliable or conflicting and further testing is required. Petrographic examination of the concrete should be undertaken using guidelines such as ASTM C856 that characterises the physical, mineralogical and compositional properties in the near surface region [15]. Significant features that relate to early-age damage from surface delamination include the following:

- The depth and size of areas of delamination and associated incipient areas showing a discontinuity in the concrete layers
- Characteristics of the surface layers of concrete in terms of colour, texture, hardness, paste content, aggregate type and presence, surface condition and air voids
- Variation with depth of air content and characterising all voids whether air or derived from bleeding such as lenses under coarse aggregate particles
- Micro-separations such as discontinuous defects in the paste or elongated or distorted air voids or other evidence of shearing damage
- Evidence of excessive bleeding in the form of bleed channels, settlement of aggregate or bleed lenses under flat surfaces
- Thickness of the slab from the core sample, sub-base conditions and any other macro-level observations taken before microscopic survey
- Summary of overall damage of slab including cracking and delaminated area to provide some overall context to the investigation

A summary of diagnostic techniques is shown in Table 2 below. These diagnostic techniques range from non-invasive and cheap to destructive and requiring a significant amount of analysis and interpretation.

Table 2: Diagnosis techniques for quantifying delamination of concrete

Diagnostic phase	Purpose	Techniques	Relative costs
Visual	Size, depth and extent of damage	Visual observation	Low
Non-destructive	Identify incipient areas of delam.	Sounding survey GPR or impact echo	Moderate
Core examination	Mode of failure of delamination	Core extraction and logging of damage	Moderate
Petrography	Detailed mechanics of delamination	Thin sections of critical areas	High

# MITIGATION DELAMINATION RISK

Three main factors need to be controlled to mitigate the risk delamination of concrete; namely controlling environment, material and processing. Specific factors that should be considered before construction are listed below and these may require significant planning and optimisation [16, 17].

## ENVIRONMENTAL CONTROL

Delamination issues are mostly related to in situ concrete where environmental conditions are less controlled than for precast concrete. The surface of concrete may be exposed directly to the environment that increases the risk of problems due to temperature, wind and humidity fluctuations. These dynamic processes will affect concrete properties and complicate finishing operations when these differences require significant adjustments in the timing of operations across a large slab.

Where casting large industrial slabs the vagaries of the environment can be significantly reduced by building the structure first. By having the walls and roof in place before placing concrete for the floor has the advantage of moderating the influence of ambient conditions. Large buildings will however create their own climate due to draughts set up across openings and higher temperatures in some cases.

## CONTROLLING BLEED

Concrete mix designs need to have some robustness to deal with construction practices that are sometimes less than optimum. This particularly applies to bleeding of concrete that should not be reduced below a certain threshold level since this protects the surface and provides an indication of timing of finishing. Modern concrete mix design has increasingly reduced bleeding of concrete as chemical admixture usage has progressively cut the water demand of concrete to limit drying shrinkage and improve strength. Figure 5 shows the major material influences affecting bleeding of concrete.

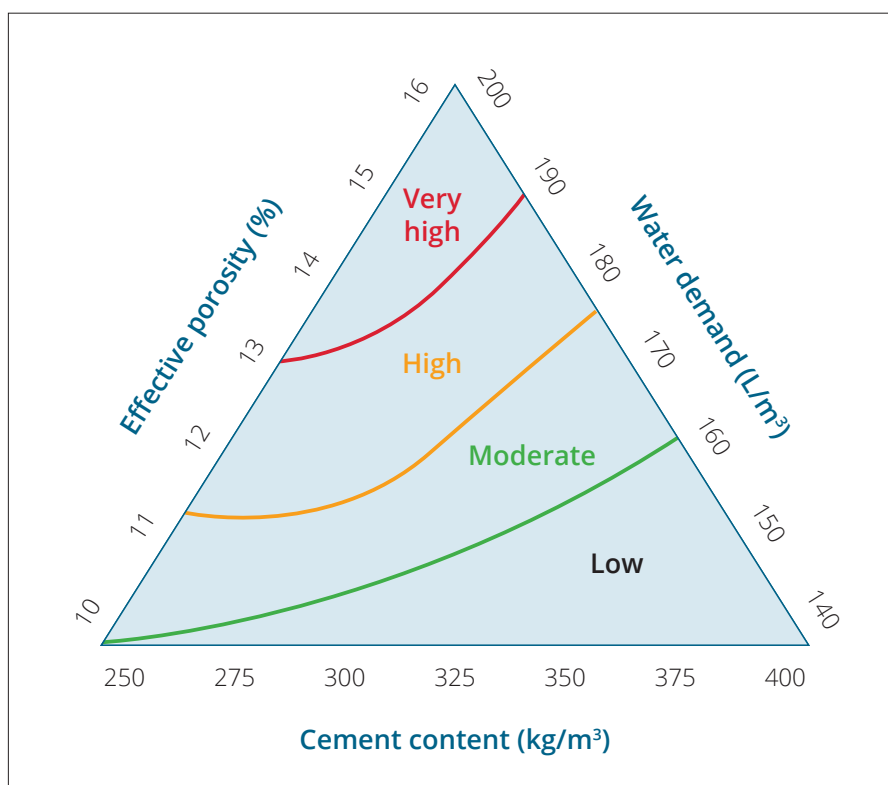


Figure 5: Qualitative bleed estimates based on concrete mix properties

There is no minimum level of bleeding that concrete should have for use in industrial slabs since this will depend on the application and environmental applications. Concrete suppliers should however undertake appropriate trials on concrete mixes to characterise the bleed of concrete mixes used in these applications. While such trials are usually done in accordance with ASTM C232 under laboratory conditions these data provide a useful reference that can be compared when there are concerns. Material factors that may influence bleeding of concrete include air content, grading of sand, silt or clay contamination, colour pigments and cement fineness.

## MONITORING AIR CONTENTS

Monitoring of air content of concrete is important since this can fluctuate due to material, seasonal and application differences. When using air entrained concrete, adjustment is made regularly to ensure air contents remain relatively constant despite changes in temperature and sometimes material properties. Concrete without air entrainment typically has air contents between one and two percent. Industrial floors are usually designed with concrete that does not have air entrainment but it is still important to monitor air contents to ensure defoaming action in modern chemical admixtures is effective.

Control and monitoring of air contents in concrete is traditionally done at the concrete plant after initial batching and mixing. This plant-based testing may need to be supplemented when there are concerns about delamination risk to concrete slabs and a limited amount of site-based testing is recommended. This is particularly important when using new chemical admixtures or materials that may interfere with defoaming agents. Research from Europe has shown how extended mixing and agitation can result in a significant increase in air content for concrete arriving on site (see Figure 6 from RILEM TC-268 SIF report).

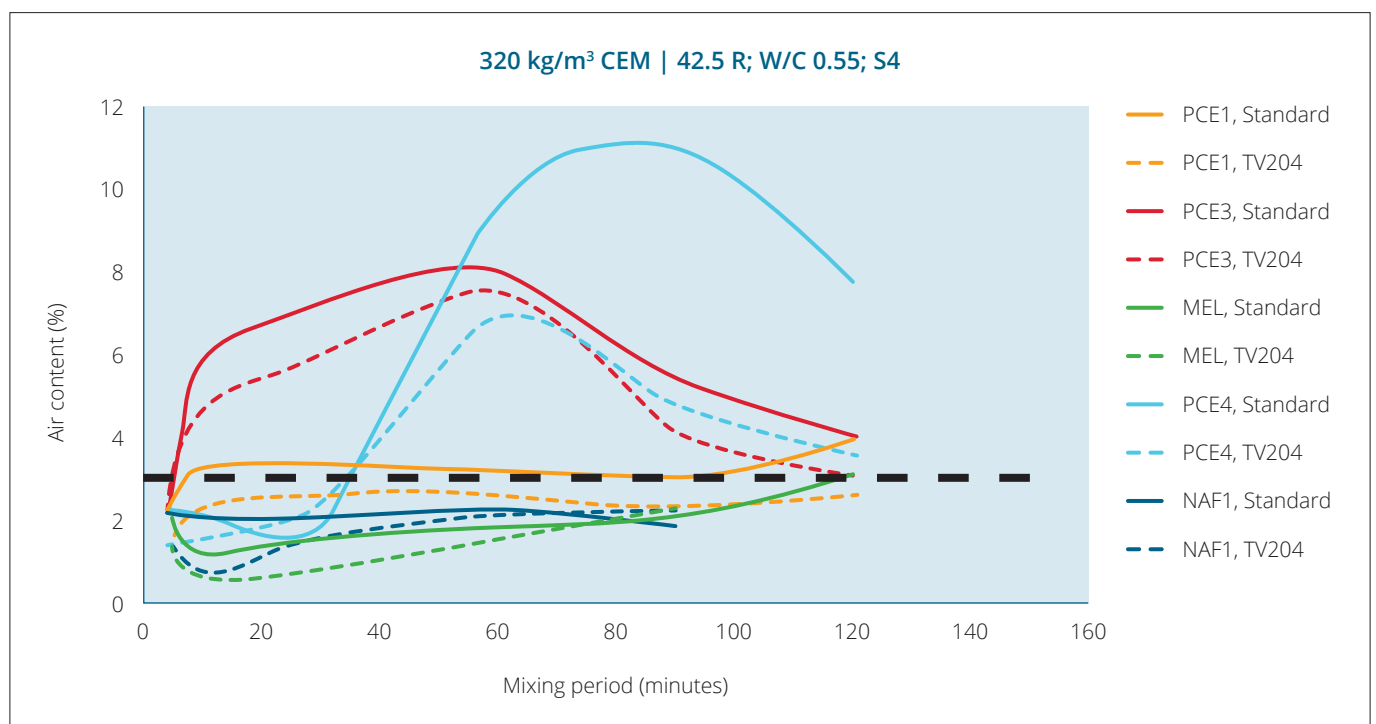


Figure 6: Air contents of non-air entrained concrete with extended mixing [5]

## TIMING OF FINISHING OPERATIONS

Finishing of concrete slabs is traditionally done by specialist contractors who have the expertise to ensure timing and methodology are appropriate. Better documentation of these operations could reduce disputes in cases involving delamination problems. Just as the delivery of concrete is fully documented in terms of material supplied and timing of discharge into the slab, the same could be documented for areas of the slab being finished. Where more sophisticated methods such as semi-adiabatic calorimetry or thermal imaging are used these should be logged together with an activity summary.

## SURFACE TREATMENTS

Application of surface applied treatments are sometimes used to achieve improved hardness of the concrete to resist abrasion and wear. These surface treatments generally consist of dry shake powders that require care to ensure consistent application and timing. These types of application are difficult to control and their contribution to problems such as delamination are difficult to quantify. It is known that these materials can cause differential volume changes near the surface that can exacerbate the risk of delamination.

A summary of recommended measures for mitigating the risk of surface delamination of concrete are shown in Table 3. Some of these measures are relatively easy to quantify and control of these is effective.

Table 3: Mitigation methods to reduce the risk of delamination of concrete

Mitigation measure	Practicality	Difficulty	Effectiveness
Environment	Requires planning of construction	Often done with industrial slabs	Very effective means of control
Bleeding	Correct mix design – trial and testing	Routinely done by concrete suppliers	Effective by materials vary
Air content	Regular monitoring at plant & site	Requires extra testing on site	Effective but needs more monitoring
Finishing operations	Specialist activity by contractors	Requires better recording on site	Critical but difficult to quantify
Surface treatments	Equipment & expertise	Difficult to quantify this activity	Uncertain but not widely used

# RECOMMENDATIONS

Recommendations for mitigating the risk for delamination of concrete include design, monitoring and forensic investigations.

## DESIGN ASPECTS

When considering recommendations to mitigate the risk of delamination it is tempting to simply fall back on a list of prescriptive limits for concrete mixes supplied for floor slabs. This approach assumes that the damage is primarily a material issue. Using a prescriptive specification methodology such as this does not allow flexibility across a wide range of materials and applications. While this approach is questionable, some typical prescriptive limits for concrete are as follows [5]:

- Maximum air content of 3.0 percent in fresh concrete
- Maximum high range water-reducing admixture of 1.0 percent by weight of cement
- Minimum water content of 180 L/m<sup>3</sup> in the concrete mix design
- Maximum cement content of 320 kg/m<sup>3</sup> in the concrete mix design
- Limits of the contribution of fines content contribution from sand
- Other properties such as concrete temperature limits when placing
- No guidance on the consistence level (e.g. slump) is given

These limitations on the concrete mix are implicitly based on ensuring reasonable bleeding of fresh concrete. Unfortunately, these material limits also have a significant effect on other properties such as workability, strength and drying shrinkage. A much more effective approach for specifying concrete used for concrete floors is using performance-based methods such as compressive strength is applied for structural applications. This may be more difficult to specify and measure but has the advantage of being more flexible and is also more related to delamination risk.

## MONITORING PERFORMANCE

What types of performance are therefore relevant to concrete mixes used for industrial floor slabs? The two most obvious performance parameters are bleeding of concrete and setting time and consistence is probably more important than rigid limits [18]. Predictions of these performance-based properties can then be made for specific projects and the actual in situ performance can be monitored and compared with predicted values.

This performance-based approach is increasingly being used in the United States where semi-adiabatic calorimetry is used during construction of industrial concrete floors to monitor setting times and ensure the window of finishability is known in real-time [19]. There is also increasing use of sensors cast into slabs that provide real-time monitoring of important properties such as temperature, which is closely linked with cement hydration and therefore setting time.

## FORENSIC INVESTIGATION OF DELAMINATION ISSUES

When designing and constructing large industrial slabs there is always the risk of surface delamination. It is important that the extent and severity of any areas of suspected delamination are thoroughly investigated and an objective framework is used when interpreting relevant data. A hierarchy of investigative techniques is commonly used when investigating deterioration of concrete, which is shown in Table 4. The full suite of tests would not be appropriate in many cases but understanding what can be determined and inferred from these forensic investigations is important.

Table 4: Summary of techniques for surface delamination reporting [19, 20, 21, 22, 23 & 24]

Methodology	Technique	Relative cost	Interpretation
On site visual	Logging floor	Cheap to undertake on most floors	Easy only if when delamination shallow
On site NDT	Sounding survey Impact echo/GPR	Cheap Expensive	Requires experience Requires expertise
Core examination	Extracting cores	Cheap but causes damage to slab	Useful but may damage surface
Thin section	Petrographic analysis	Expensive for petrographic report	Requires expertise from petrographer
Image analysis	Petrographic analysis	Moderate for void count and shape	Software for quick analysis of voids
Chemical analysis	Cement content or contaminants	Moderate using testing laboratory	Easy but not always relevant to issue

## REMEDIAL OPTIONS

Repair of concrete floors that exhibit signs of delamination have been successfully repaired in the past but this remedial work depends on several factors, that include:

- Aesthetic requirements of the finished floor surface
- Depth of delamination and extent of the problem
- Confidence that forensic survey has identified all significant areas of delamination

Two types of repair are typically specified to remove delamination or incipient areas of potential delamination. These two approaches are as follows:

- Shallow delamination typically less than 3-4 mm where the cement skin is loose or delaminated and the slab surface requires grinding back to a competent substrate (these delaminations are generally easy to identify and repair process can be monitored and approved with some confidence)
- Deeper delaminated zones typically between 5-15 mm where cracking runs through the concrete matrix, the surface is intact apart from minor cracking and epoxy injection must be undertaken by expert repair contractors (some grinding may still be required after treatment to achieve the required finish)

Most cases involving delamination do not exhibit wholesale damage across the slab surface but involve localised areas of a limited extent. Replacement of concrete slabs with only limited delamination is expensive and often cannot be justified when repair of the surface can be done. Agreement of possible strategies before construction may better inform all construction parties of the risks and options.

# CONCLUSIONS

Damage associated with delaminated areas on concrete slabs does not appear to be reducing despite the advent of modern materials and construction practices. The effect of these surface defects has a major impact on the aesthetics and serviceability of floors and has led to numerous disputes and costly remedial measures. With the increasing use of post-tensioned systems for industrial slabs, delamination remains the last major defect that may occur in practice.

The cause of delamination and best forms of mitigation is not simple otherwise the issue would be largely resolved and written off as being due to either inappropriate concrete mix designs, unreliable concrete supply or poor construction practice. Delamination of concrete is problematic as the mechanism is both complicated (i.e. involves a high level of difficulty) and complex (i.e. involves many components). Major factors involved such as concrete, processing and environment have a complicated interaction between components. The overall effect is complex since these material, processing and environmental factors are inter-related with an unknown impact on the risk of delamination.

Major risk factors for delamination are reasonably well understood and there is also agreement on effective mitigation methods. Inflexible and simplistic methods of specifying concrete should be avoided such as using prescriptive limits. A better approach is to rely on performance-based methods and to ensure testing and monitoring is undertaken to control both material supply and construction practice.

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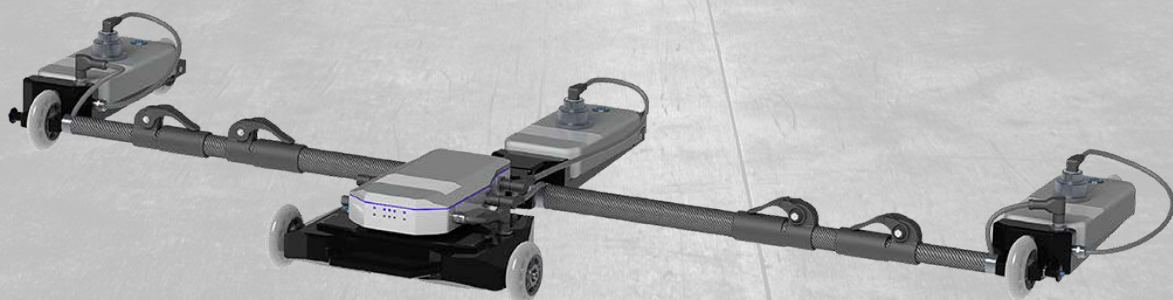
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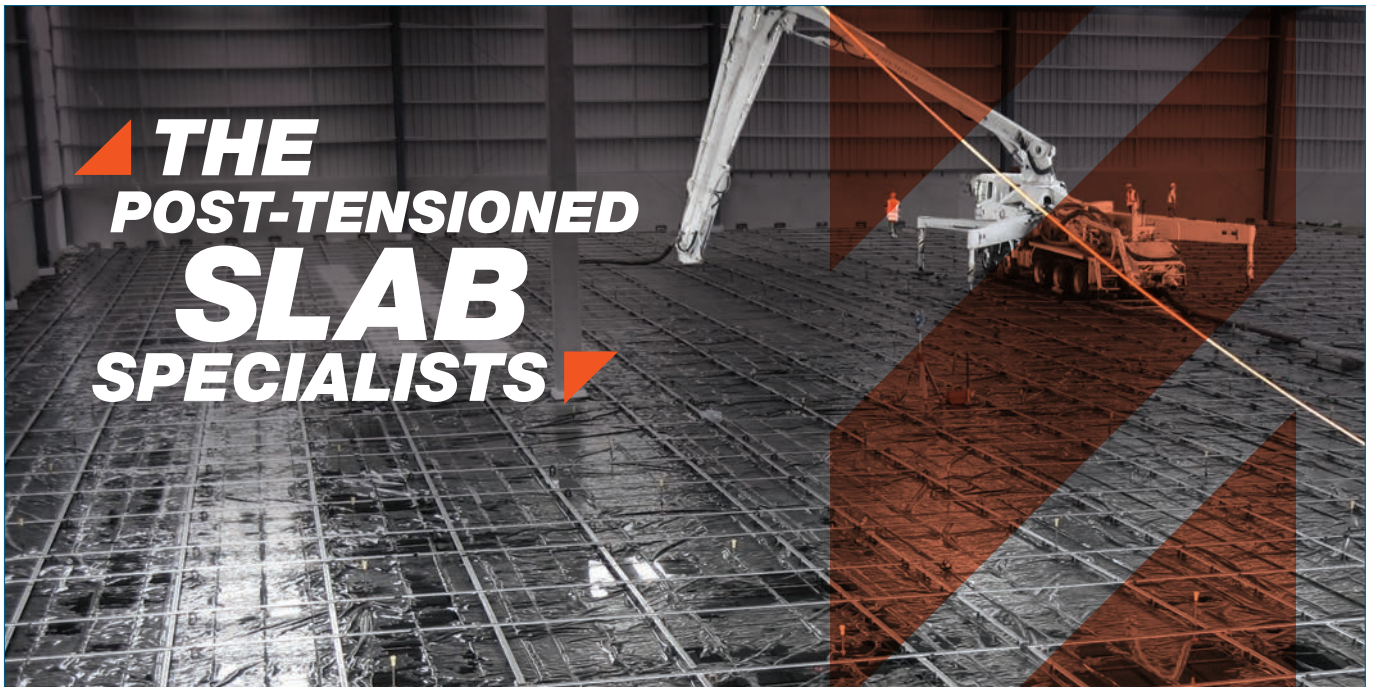


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