Curling of concrete ground slabs

OVERVIEW

Curling of concrete ground slabs is a natural phenomenon caused by differential drying shrinkage and is characterised by lifting of the perimeter corners and edges. Serviceability may be compromised due to changes in surface regularity, rocking slabs, relative vertical movement between panels leading to loss of load-transfer by aggregate interlock between adjacent panels, cracking due to loss of support under perimeter edges, sealant failure and edge spalling.

Unfortunately, there is little that can be done to prevent curling, but, with a thorough understanding of how it occurs, it can be minimised by skilful design and material selection, and its symptoms thereafter can be managed as part of an ongoing maintenance regime.

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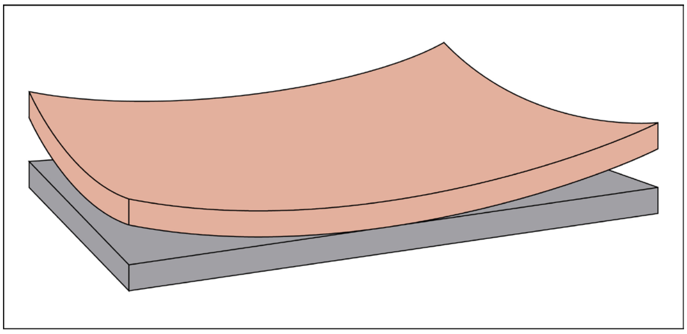

Figure 1: Curling of ground slabs is caused by differential drying of concrete – fastest, and most thoroughly, from the exposed top surface; this causes the slab to warp, or cup, upwards

WHAT IS CURLING AND HOW IS IT DEFINED?

Curling occurs because concrete dries out unevenly. Typically, the upper surface, which is exposed, dries faster and desiccates more thoroughly than the underside, which is not exposed to the air, and so a moisture gradient develops (differential drying of concrete). Because drying shrinkage of hardened concrete is caused primarily by loss of moisture (which occupies volume), the top surface experiences more shrinkage than the concrete lower down. As a result, rectangular panels curl or "cup" upwards – their perimeter lifts, especially the extreme corners, since these are furthest from the centre. Because shrinkage is proportional to loss of moisture from the surface, individual panels cup towards the sky (Figure 1). The problem of curling is well recognised in concrete industrial slabs on the ground (Figure 2).

Damp proof membrane (DPM), or any other impermeable plastic sheeting beneath a slab may aggravate/exacerbate problems associated with curling and irregular crack inducement and opening of saw-cut contraction joints. A saturated subbase at the time of casting can exacerbate curling, as it will prevent any drying from below.

If curling is prevented, for example by heavy loads imposed on a slab, tensile stresses will develop in the upper part of the concrete slab. If this tension exceeds the tensile capacity of the concrete, the slab will crack. Alternatively, where unrestrained edges of concrete panels have curled and lifted clear of the subbase support, subsequent loading of the edges, particularly at corners, may lead to diagonal corner cracking since the unsupported corners effectively become unpropped

Figure 2: An excellent example of extreme curling of concrete panels in the apron at Walvis Bay Airport after a rare high rainfall event; note the extreme lifting of corners and perimeter edges relative to the centre (Photo: Roderick Rankine)

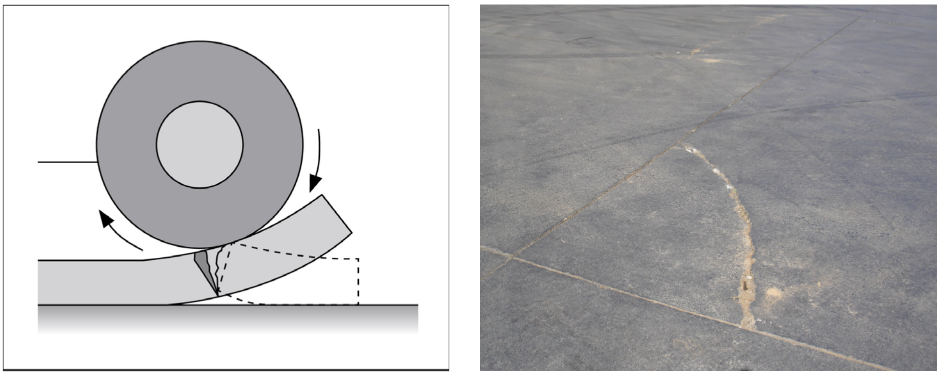

Figure 3: Corner cracking of curled slabs under heavy traffic is a common symptom of curled ground slabs, particularly if load-transfer is absent or compromised; the elevated corner essentially becomes an unpropped unreinforced cantilever

unreinforced cantilevers, particularly if load transfer with adjacent slabs is absent or compromised (Figure 3).

Curled slabs may start rocking in service, particularly if regularly traversed by heavy traffic and/or impact loads. In cases where the subbase has been poorly compacted, the repeated movement at the joints can cause further settlement and an increase in the size of voids in the subbase beneath the joints.

In a healthy floor, aggregate interlock beneath a saw-cut in a contraction joint is a critical load-transfer mechanism whereby a narrow irregular crack (induced by the saw-cut to relieve tensile stresses due to shrinkage within the concrete) transfers load from a panel on one side of the saw-cut to the panel on the opposite side. Because cracks are induced by saw-cuts at an early age, the crack path tends to skirt around strong/stiff aggregate particles rather than run in a vertical plane directly through them. The aggregate particles therefore mesh together, like gears in a gearbox, which provides a convenient mechanism for the transfer of load between opposite panels straddling these joints. The effectiveness of this load transfer depends on a number of factors, including the width of the joint opening. Generally, it is assumed that joints that do not open wider than about 1 mm may be effective in load transfer, but joints that open wider than 1 mm, in areas of heavy traffic or loading, are compromised.

According to work undertaken by Colley and Humphrey (1967), for design purposes, a saw-cut contraction joint that opens 1.5 mm is only capable of transferring 15% of its potential load-transfer capacity. Repeated relative vertical movement, combined with the opening of saw-cut contraction joints, due to drying shrinkage, can gradually grind away at the interlocking aggregates, resulting in loss of load-transfer capacity and an increase in relative vertical differential movement between adjacent panels on opposite sides of saw-cut contraction joints (Figure 4).

In warehouse facilities with very high racking (typically 8 m and higher) and/or very narrow aisles, where tight surface regularity tolerances need to be observed, curling of floor slabs may result in unacceptable undulations in the surface which may compromise the safety of the operation.

The presence of an impermeable plastic membrane beneath the floor slab prevents any loss of moisture from below (either by absorption into the soil layerworks and/or by evaporation), which worsens the problem of curling. Furthermore, plastic sheeting under slabs reduces friction between the soil and the underside of the slab. As a result, the joints that successfully induce cracks (as intended) generally open excessively and adjacent saw-cuts either side of these often do not induce cracks at all – often several joints either side of the functioning joints (with induced cracks) fail to induce cracks and open. Excessive opening of some joints can result in load transfer being lost altogether. Construction joints may be particularly prone to excessive opening, since these offer little initial resistance to drying contraction, unlike saw-cut joints where the concrete beneath the saw-cuts must initially resist some tension to induce them to crack and open.

CAUSES AND SYMPTOMS

Drying shrinkage and choice of materials

Any measures that reduce drying shrinkage will reduce curling. Drying shrinkage is shrinkage associated with the loss of water from the cement gel which occurs in concrete subsequent to it setting. On termination, or absence, of curing, the rate of drying proceeds most rapidly at the beginning of a structure's life and then slows asymptotically, but continues indefinitely. Ongoing shrinkage strains have been measured decades after concrete had been cast. Drying shrinkage may cause extreme internal stresses and forces within the body of concrete.

Longer moist-curing periods have little effect on drying shrinkage and curling, other than delaying the onset. The American Concrete Institute (ACI) (1992) summarises the work by Childs and Kapernick (1958) succinctly by stating, "Extended curing only

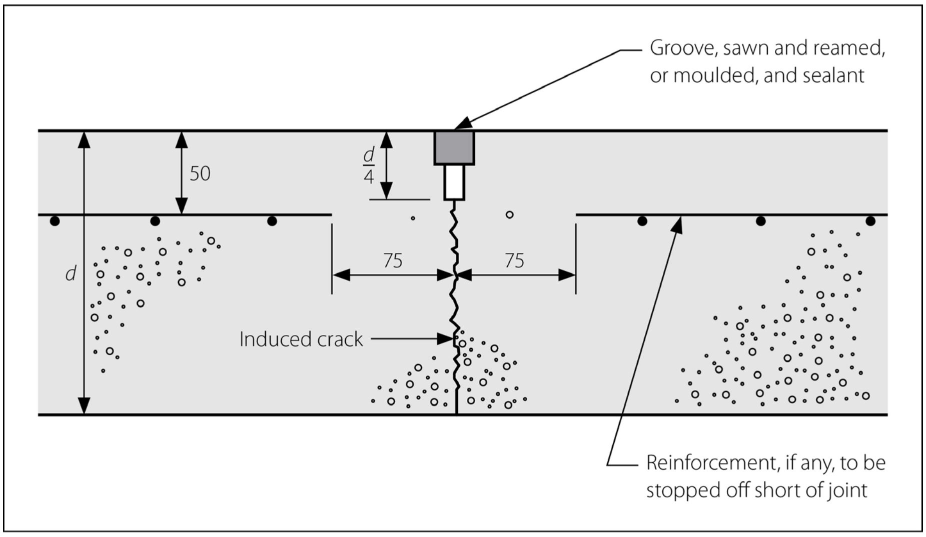

Figure 4: Saw-cut contraction joint with induced crack beneath the saw-cut with a tortuous path that skirts around aggregate particles which facilitates efficient load-transfer, via aggregate interlock, provided the joint does not open excessively

[1] *Large aggregate particles (say 26 mm stone) afford better interlock and better load transfer than small aggregates where the joint opening is significant on account of the greater tortuosity of the crack skirting large around particles.*

delays curling, it does not reduce curling". To a limited extent, both drying shrinkage and curling can be ameliorated by minimizing the amount of mix water and selecting optimal aggregates. Nevertheless, there is always likely to be a tendency for concrete panels to shrink and curl.

Technical Report 34, Concrete Industrial Ground Floors, published by the UK Concrete Society (2013), states the following:

- All concrete shrinks as the water in the concrete evaporates to the atmosphere. The prediction of drying shrinkage is complicated ... Concrete floors usually lose more water from the upper surface, resulting in nonuniform shrinkage and, potentially, curling. Any steps taken to reduce shrinkage will reduce curling.
- Although curing is of great importance in achieving a durable concrete floor, it does not reduce shrinkage. A floor will eventually dry and shrink by an amount that is almost independent of when that drying begins.
- The main factors influencing drying shrinkage are the volume of cement paste and its water content. Cement and water content should be as low as possible, consistent with the specified maximum free-water/cement ratio and the practicalities of placing and finishing. The maximum water/cement ratio should be 0.55. The use of water-reducing admixtures is strongly recommended.
- Although the cement paste is usually the only component of concrete that undergoes significant shrinkage, some aggregates are known to have high levels of drying shrinkage.
- The combined grading of coarse and fine aggregates should be adjusted to minimise water demand. The largest available size of aggregate should be used, consistent with the thickness of the slab.

Unfortunately, besides following the above guidelines, a specialist flooring contractor has virtually no control over the shrinkage and potential curling of concrete ground slabs. Local ready-mix concrete suppliers manufacturing readymixed concrete in accordance with SANS 878:2012 Ready-mixed Concrete do not take responsibility for the shrinkage of concrete supplied by them. Clause 15 of SANS 878:2012, under the heading Durability and Shrinkage, states "In the event of durability or shrinkage requirements, or both, the mix design shall be submitted for approval to the customer before the commencement of the contract. Based on the acceptance of these mixes, the manufacturer shall only be responsible for ensuring that the approved mix proportions and ingredients are maintained within the batch tolerance specified in Clause 7".

Even if the engineer, or purchaser of the concrete, diligently performs tests to measure shrinkage of samples of the supplier's mix, there is likely to be a large discrepancy between the shrinkage values measured under accelerated laboratory conditions and real-world ground slab conditions, since experience has shown that accelerated laboratory shrinkage tests do not accurately mimic real site conditions. Moreover, even the accelerated tests take considerable time to yield results – more time than is often available on current fast-track projects.

For reasons not fully understood, the incidence of excessive curling has become more prevalent in recent decades. There are various theories as to why problems associated with drying shrinkage and curling appear to have increased. These include finer grinding of cement, the increasing use of high-early-strength cements and the use of water-reducing admixtures which may increase shrinkage despite reducing the water content. It should not be assumed that the incorporation of a high-range water-reducing admixture (or superplasticiser) will automatically bring about a corresponding reduction in drying shrinkage. A fact that is not generally appreciated is that the ASTM admixture standard (ASTM C 494/C494M – 17) allows up to 35% more shrinkage in test specimens with admixtures than in control specimens (without admixtures).

Floor slab design and geometry

Within limits, observing empirical dimensional proportions can limit the harmful effects of drying shrinkage and curling. The larger the concrete panel, the greater the risk of curling. The thinner the panel, the more likely it will be to curl.

Standards for constructing such ground slabs (such as SANS 10109-1: 2012) and handbooks on ground floors give empirical rule-of-thumb guidelines to reduce the effects of curling. Since the amount of lifting of perimeter edges of curled slabs is proportional to the distance of the perimeter edges from the centres of panels, larger panels tend to experience worse symptoms of curling. Traditionally, the rule-of-thumb to limit curling and drying shrinkage cracking (in jointed unreinforced floors) has been to ensure that the maximum panel size is limited to the lesser of 30 times the slab thickness or 4.5 m.

Joint intervals greater than 4.5 m also result in both a larger band of perimeter concrete losing contact with the subbase, as well as saw-cut contraction joints opening wider, and losing load-transfer capacity by aggregate interlock, since the width of the joint opening is directly proportional to the panel dimensions and to the drying shrinkage.

As a result of the perceived increase in the incidence and severity of curling, some specialist flooring designers and contractors have adopted a more conservative rule-of-thumb that the panel size should not exceed 25 times the slab thickness or 4.0 m, whichever is less.

A large percentage of reinforcement (say at least 0.25% of the total crosssectional area) in the bottom of a slab will tend to exacerbate the problem of curling by preventing lateral contraction at the bottom. The same reinforcement at the top will help to combat curling. However, the use of reinforcement in ground slabs is problematic, since it must remain in place when trodden upon and it must never run continuously across contraction joints – these requirements may be easy to specify, but they are seldom achieved in practice.

Climate

The problems associated with drying shrinkage and curling are far more pronounced in arid climates (such as Kimberley, Bloemfontein and Gauteng) where ambient atmospheric relative humidity is low compared with that in humid climates (such as Durban). As a rule-of-thumb, for slender concrete elements such as very thin 75 mm ground slabs in a domestic house, the amount of drying shrinkage in an arid inland climate, such as Kimberley (average RH = 46%) in the Northern Cape, is about double that of equivalent concrete in a moist coastal climate such as Port Elizabeth (average RH = 79%) (Alexander & Beushausen 2009).

Layerworks

Curling, although present in most ground slabs, is often accommodated by bedding down of the convex centre of the slab into the subbase. Elevated edges and corners are often able to resist imposed loads and rocking by some load sharing across joints through aggregate interlock and/or dowels (load transfer). However, in some instances where the founding subgrade or subbase has been heavily compacted or cement-stabilised, the layerworks may be so hard and stiff that

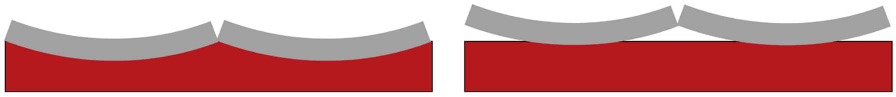

Figure 5: Exaggerated schematic showing the difference between a subbase which is sufficiently soft and compliant so as to allow convex bellies of curled slabs to bed down (left) and a very stiff subbase, such as a cement-treated subbase, which resists bedding down (right)

there is little possibility of accommodating the central convex underside of the concrete as the slab curls, i.e. the curled central convex under-surface is unable to bed down into the subbase so that the outer edges of the slab remain supported by the soil. Instead, individual slabs will tend to rock like a rocking horse on the stiff founding layer (Figure 5).

IS CURLING A PATENT OR LATENT DEFECT OR NEITHER?

As a general rule, if a buyer had the opportunity to inspect an item before purchase/delivery but nevertheless accepted a patently defective item, he or she will have no recourse to the seller. A flaw is a defect only if it is an "abnormal" characteristic, which a reasonable buyer would not expect to find in a reasonable item. According to Wille's Principles of South African Law (Dubois et al 2007), a latent defect is a defect that is not readily discoverable on a proper inspection by an ordinary buyer. The seller is held liable for any latent defect that destroys or substantially impairs its utility or effectiveness. The aedilitian remedies protect the buyer in respect of latent defects only if such defects exist at the time of sale. The onus of proving the latent defect existed at the time of sale is on the buyer.

Drying shrinkage and curling are inherent characteristics of concrete ground slabs, but invariably they are scarcely present, and not recognisable, at the time of acceptance/handover. These are inherent properties of concrete, although their extent may vary depending on factors well beyond the control of the contractor and material supplier. Competent design professionals ought to know about these long-term characteristics and they should warn their clients accordingly. If this is done appropriately, then it is unlikely that a latent defect could be considered in this instance.

All materials have inherent characteristics and unique properties, and many materials are selected for a unique property despite the knowledge that that specific property may change over time, or that the same material may have another undesirable property likely to cause problems elsewhere. For example, neoprene is used for O-rings and oil seals because of its elastomeric nature, heat resistance and oil resistance despite the fact that it becomes brittle with time and will fail and need to be replaced. This change in character is not normally considered to be a latent defect. And transparent polycarbonate is used for roof sheeting because it admits light despite the fact that it degrades under ultra-violet light and may shatter when struck by hailstones.

Engineering is both an art and a science, and the choice of material is invariably a compromise between what is economically viable, buildable, structurally adequate and durable. Substituting one material for another with a specific desirable quality often solves one problem but creates another.

There are currently few viable alternatives to concrete industrial floor slabs. No other material can provide a floor surface that is economical, easily formed, hard, abrasion- and impact-resistant, and durable. Unfortunately, over a long period of time, concrete also shrinks and curls as it dries. At the time of acceptance/handover no appreciable curling will exist and it will not be possible for either the specialist flooring contractor or the client to determine whether a floor will curl excessively. This needs to be understood and accepted by facility owners. Since the symptoms of drying shrinkage and curling are largely beyond the control of the concrete supplier and specialist flooring contractor, it would be both unreasonable and unfair to hold these parties responsible for the remediation of these symptoms – this follows the established principle that someone cannot be held accountable for what is clearly beyond their control. The symptoms of drying shrinkage and curling therefore need to be monitored and managed as part of any facility's ongoing maintenance programme.

RECOMMENDATIONS TO MINIMISE UNDESIRABLE CONSEQUENCES OF CURLING

- Avoid the temptation to design/cast industrial floors too thin. Most slabs exhibiting excessive curling are thinner than 200 mm. Advise clients of the disproportionate compromise in flexural strength and risks of malfunction due to drying shrinkage and curling if the floor thickness is shaved in the interests of a slightly reduced initial material cost. Most clients would naturally assume that lost strength and increased risks vary in direct proportion to thickness, whereas in fact these factors vary exponentially. As a rule-of–thumb, a change of just 25 mm in the thickness of a 200 mm-thick slab on ground will double or halve its flexural strength!
- In jointed unreinforced floors, do not exceed a joint interval of 4 m. If a joint interval of more than 4.5 m is specified, the risks of curling and joint distress rise disproportionally.
- Where possible, use a proven low shrinkage concrete with a maximum water content of 180 L/m^3 and 26.5 mm stone (aggregate).
- Pre-empt the inevitable and temper client expectations by explaining the risks and consequences of curling to the client upfront (at tender stage) rather than waiting to do so after problems due to drying shrinkage and curling have started to manifest. A well-informed client is more likely to agree to prudent design proposals at inception and is less likely to complain and demand compensation after symptoms of curling manifest years after taking occupation. A specialist flooring contractor might even include a clause in the contract in which it is explicitly stated that some drying shrinkage and curling is to be expected, that it is not a latent defect, and that the contractor will not be responsible for the costs of remedial work necessary to correct symptoms, but that he would be willing to undertake remedial work and maintenance work for some mutually acceptable fee.

REMEDIATION OF FLOORS EXHIBITING SERIOUS SYMPTOMS OF DRYING SHRINKAGE AND CURLING

Reinstating support under edges and corners

Traditionally, cementitious grout has been injected through pre-drilled holes near the edges of panels to fill the empty space and reinstate support. (Note that it is prudent to check that rocking and relative movement are a consequence of curling and not due to loss of support which may need more drastic treatment.) More recently, expanded polyurethane (PU) foams have gained popularity due to their lower viscosity, ability to expand into voids and their faster curing times (Figure 6).

Typically, such treatment involves drilling holes (approximately 6 to 8 mm in diameter at centres of approximately 300 mm) through existing saw-cut contraction joints where relative movement can be detected, and injecting proprietary polyurethane foam into the void space(s) under slabs. A two-component polyurethane is injected (in liquid form) into any voids beneath the joint where it reacts and expands (by about 2.5 times the volume of the parent ingredients) to form a rigid foam as it solidifies. If applied optimally, this expanding foam will infiltrate and fill the vertical space created by drying shrinkage at saw-cut-induced cracks. This may reinstate load transfer at these joints, but the longevity of this restored load transfer is difficult to predict with certainty, because it depends on many factors, including traffic loads and frequency, the extent to which the foam penetrates the joint, foam density, the cleanliness of the joint, etc. This PU foam injection technique has been used internationally with success for several decades and has recently (in the last 10 years) been used locally in the stabilisation of some rocking freeway slabs on the Griffiths Mxenge Freeway in Umlazi in KwaZulu-Natal, on the N1 Freeway, as well as in several commercial facilities.

Figure 6: Joint filling and rocking slab stabilisation by injection of polyurethane expanding foam into the void beneath saw-cut contraction joints at regular intervals; as the foam expands, it rises and infiltrates the joints from the bottom up (Photo: Chris Howes Construction)

Polyurethane foam has some advantages over cementitious grout, including its ability to flow into very narrow spaces without stiffening in transit (which is a problem with cementitious grouts) and the fact that it cures rapidly, which minimises the quarantine time before the slab can be put back into service (generally less than one hour). The cost of PU foam support reinstatement is generally less (by about half) than the cost of slab demolition and recasting, and it is quicker and less disruptive. It should be noted that this is a specialised operation that requires a bespoke polyurethane formulation and specialist skills. If it is undertaken by a novice, there may be an unacceptable risk of failure. One possible mode of failure entails the expanding foam lifting entire floor panels so that they project above the rest of the floor. This would inevitably be remedied by demolition of the raised panels.

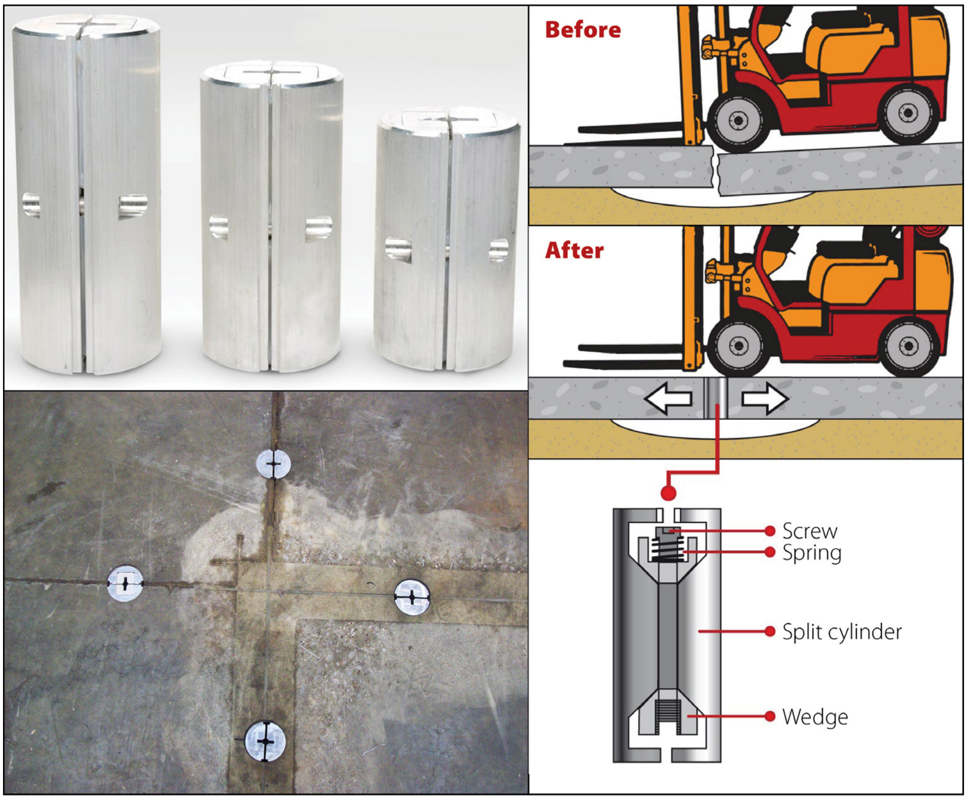

Figure 7 Aluminium joint stabilisers (cans) (Source: Face Consultants).

Joint stabiliser cans

Proprietary aluminium joint stabilisers (or cans) comprise 75 mm diameter aluminium cylindrical mechanisms that are inserted into 75 mm diameter vertical cylindrical cavities drilled through the problematic joints with a diamond-tipped core drill, so that the equators of the holes coincide with the joint lines (Figure 7). The cylinder is then expanded inside the cavity by means of an Allen key applied to a hex-head cap screw so that it exerts a large outward/lateral thrust between adjacent panels. The system has the advantages of being quick to install and individual stabilisers can be tightened/stressed further in future as panels shrink/curl further. These devices may be suitable for indoor use in applications where the diurnal temperature fluctuation is minimal. They should not be deployed externally or where ground slabs are exposed to sunlight because the cans effectively immobilise joints, precluding their closure and thereby preventing them from accommodating thermal expansion. (These stabiliser cans are manufactured by Concrete

Grinding in England and are supplied in South Africa by Royal Floors.

Full-depth joint reconstruction

Where joints are badly damaged and exhibit deep edge spalling, full-depth repair is usually the best remedial option. The handbook Concrete Industrial Floors on the Ground by Marais and Perrie (1993) gives several options (method statements) for detailing the thin strip of concrete to be reinstated.

Grinding

In a warehouse where there is high racking and/or very narrow aisles, and therefore an onerous requirement for a tight tolerance on surface regularity, it may be possible to grind the high spots at panel edges/joints to level the floor. This often necessitates removal of a large volume of concrete from the edges and corners of panels. The grinding process is messy/dusty and noisy, and likely to disrupt operations. Grinding reduces the thickness of the panels at the corners where stresses are greatest. Unless support has been reinstated under elevated corners, these are likely to rupture since they are effectively unpropped unreinforced cantilevers. Furthermore, grinding permanently changes the aesthetics of the floor. Ground areas will expose the flat faces of aggregate particles in a sea of cement paste. Unground areas will have a more uniform flat grey appearance.

It should be appreciated that concrete grinding is a specialised process best undertaken by professionals with specialist equipment. With care it may be possible to target high spots on general warehouse flooring by flooding the floor with water and grinding the high spots, which happen to be those parts that dry first. However, unless this is skilfully done, grinding may exacerbate an already irregular floor. (Note that this applies to general warehouse flooring, but not all warehouse flooring. Grinding of very narrow aisles and defined movement floors is a highly specialised process best undertaken by specialist grinding contractors using specialist laser grinding equipment.)

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CAUTION

Before embarking on any major remedial work described above, conduct a trial in a non-critical area to refine the application technique and evaluate the result.

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EDITOR'S NOTE

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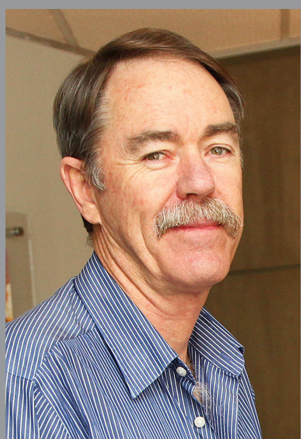

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