CCANZ TECHNICAL REPORT

CCANZ
concrete answers

TR 16
Best Practice in Casting Concrete Ground Floor Slabs and Pavements

THE NEW ZEALAND
READY MIXED CONCRETE
ASSOCIATION INC.

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This publication is not intended to replace existing New Zealand Codes, but to be used in addition to these documents and to be accepted as part of the resource used to promote industry best practice. It explains why casting should be done in a particular way, as well as the correct procedures. It is a compilation of information from several recognized sources, but is not intended to be used as a design or specification document, or as a tool to absolve responsibility for the various parties involved in the commercial process of designing, and contracting to supply, place and cure a slab-on-ground.

TR 16

ISSN: 1171-4204

ISBN: 0908956185

ISBN: 978-0-908956-23-4 (online)

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INTRODUCTION

The construction of concrete ground floor slabs, also called 'Slab on Grade' requires a background of skill and experience to produce a slab without defects. The concrete placer has to contend with a number of variables, namely a range of weather conditions, concrete properties and ground conditions. Defects in concrete slabs or pavements represent the majority of concrete defects, resulting in significant costs for repair, and associated disruption in the use of the floor or pavement.

This publication outlines the most common defects in concrete ground floor slabs and best practice to avoid them. It is particularly relevant to specialist concrete placers, but also to supervisors of concrete slab construction. Commercial slab construction is often carried out by specialist subcontractors. Clients and main contractors should satisfy themselves that the subcontractor has the necessary skills and experience to undertake the slab in question.

Most defects occurring in concrete ground floor slabs and pavements are cracks in the slab. Cracks may merely provide an unexpected visual impairment to the concrete surface. However, cracking can be more serious, threatening the durability of a slab or the surface wear performance. Cracking in concrete can be reduced through good design, planning, and skilled execution. However it is a fact that the large surface of the comparatively thin concrete section is exposed to the uncertainties of the weather. To minimise this it is recommended that concrete slabs be poured under roof cover to lessen the effect of weather on the pour.

This publication details five common defects in concrete slabs, explaining why they occur and how to avoid them. They are:

- Plastic Shrinkage Cracking.
- Delamination.
- Thermal Cracking.
- Drying Shrinkage Cracking.
- Plastic Settlement Cracking.

There are other less common slab defects which are not covered in this publication.

At least one of the following two characteristics of concrete has an impact on all of these defects – namely: **early age concrete performance** and **bleeding characteristics** of the concrete.

As freshly placed concrete begins to harden, the development of the tensile strength to resist cracking and the stresses imposed upon the concrete matrix are complex. The tensile strength gain of the 'immature' concrete has a role in preventing microscopic cracking in the first few hours after finishing.

1. EARLY AGE CONCRETE PERFORMANCE

Concrete is weak in tension, and reinforcing steel or mesh is generally placed in concrete to prevent cracking. It is only when cracks form that the reinforcement starts to carry any appreciable load; prior to that the concrete is effectively behaving as unreinforced. When considering the effects of movement on a structure, there are two approaches that can be adopted. The first is to **avoid cracking**, by limiting the stresses induced in the concrete and restricting the amount of movement and/or the level of restraint. The second is to assume that cracking will occur and to **control crack widths** by providing sufficient, correctly detailed reinforcement. The former approach may be practical for specialist applications, but typically sufficient reinforcement must be provided in critical regions of the structure to prevent visual cracking.

Any number of unforeseen events can conspire to cause sufficient contraction or sufficient restraint (or both) for the tensile stress to exceed the tensile strength of the concrete resulting in cracking. If the load capacity of the reinforcement is greater than the force which causes the crack, any cracks will be controlled so that they will usually be narrow and visually unobtrusive. Also, the more reinforcement that is provided, the finer the cracks will be. The provision of minimum percentages of reinforcement to control early age cracking is generally well understood and guidance is given in documents such as CIRIA Guide C660[1] and NZS 3106[2]. However, while this deals with the problem in the immature concrete (say about three days old); a higher minimum percentage may be required for the mature concrete (at say two years), for example to control cracking due to long-term shrinkage.

As explained in UK Concrete Society Technical Report 67[3] *Movement, restraint and cracking in concrete structures*, the minimum percentage will depend on the **actual** concrete strength and not the specified value, leading to a higher percentage. However, long-term loading tends to lower the tensile strength of concrete. The net result is:

- Minimum percentage = f_{ctm}/f_{yk}
- Where:
  - f_{ctm} is the mean tensile strength of the concrete (from Chapter 5 of NZS 3101[4]).
  - f_{yk} is the characteristic strength of the reinforcement.

This will be around 1.5 times the percentage required in the immature case.

[1] CIRIA Guide C660 *Early-age thermal cracking in concrete.*
[2] NZS 3106:2009 *Design of concrete structures for the storage of liquids.*
[3] UK Concrete Society TR 67 *Movement, restraint and cracking in concrete structures.*
[4] NZS 3101:2006 *Concrete structures standard.*

2. BLEEDING OF CONCRETE

Concrete requires more water to make it workable than is required to hydrate the cement to develop compressive strength. This is sometimes called the 'water of convenience', and is significant, being approximately one-third of the total water. After vibrating and floating the concrete off, much of this excess water, being lighter than cement or aggregate, rises to the surface of the concrete as 'bleed water'. This often brings some fine cement particles in suspension with it. The presence of very fine angular crushed aggregate particles, like crusher dust, will significantly reduce bleeding owing to the larger surface area to be wetted compared to natural sand with a more rounded particle shape. Likewise, the increased cement content of stronger mixes may require more water for hydration, and as a consequence reduced bleeding.

The amount of, and the rate of bleeding have an effect on the ideal timing of finishing a concrete slab; a low rate of bleed increases the risk of surface defects, such as plastic shrinkage cracking, in hot, dry or windy weather. A higher ambient temperature can increase the rate of bleeding, however the total amount of bleed is unaffected. However, in winter, slow bleeding can cause problems with delayed finishing and tendency to finish whilst there is still bleed water on the slab surface.

A sufficient amount of fine material is always required to obtain a cohesive concrete mix which can be transported, placed and compacted without segregation. Aggregates and sand having a continuous, relatively smooth grading curve will generally produce mixes with fewer large voids between particles. The amount of cement paste required to fill these voids is thereby minimised.

If an aggregate grading is deficient in fines, i.e. there is not enough sand to fill the voids between coarse aggregate particles, or if the sand is coarse, the concrete mix will be harsh, difficult to place and finish, and will tend to bleed excessively. On the other hand, aggregate combinations with excessive amounts of sand, particularly excessively fine sands, will require more cement paste to fill the voids because of the larger surface area of the finer particles, but bleeding will be reduced. Optimising concrete mix proportions is the role of the Concrete Plant Engineer to balance the sourcing of suitably graded aggregates and sand to produce a cohesive mix, against the cost of concrete mix ingredients including material cartage costs, and in particular cement quantity.

Entrained air has a marked effect on bleeding. Small air bubbles, deliberately introduced into the mortar by an air entraining admixture have the effect of reducing water demand and the amount of bleed, while improving workability. An air entraining admixture is usually used in New Zealand in all concretes up to 25 MPa which is a typical concrete strength for concrete slabs. At higher strengths, entrained air increases porosity and reduces strength and is not used.

Mix factors leading to an increase or decrease of bleed water are illustrated in the table below.

Increase Bleed Water	**Reduce Bleed Water**
Use of a set retarder	Reduced water content by using a: • water reducing admixture or super-plasticiser • lower slump mix
Lower strength concrete	Use of an air entraining admixture
High slump mixes with or without super-plasticiser	Use of an accelerating admixture
Coarse graded harsh mixes lacking in fines	Use a well graded sand and suitably graded aggregate
	Higher strength concretes – low w/c ratio
	Use of supplementary cementitious materials – silica fume, slag or flyash
	Use of fibres, particularly polypropylene fibres

Surface defects which are in part due to concrete mix characteristics, typically result from concretes with low bleed or slow bleed.

A plastic membrane under the slab will increase the bleeding as it prevents the ground absorbing moisture from concrete, so more water will be available for bleeding to the surface. In winter this may introduce excessive bleeding and delayed finishing.

3. PLASTIC SHRINKAGE CRACKING

Plastic shrinkage cracks form due to the too rapid loss of moisture from the surface of a concrete slab before it has started to set typically during hot, dry and windy conditions. Upwards water movement into the concrete surface layer forms menisci between the fine particles of cement and aggregate, causing surface tensile forces to develop.

Bull floating takes place immediately following screeding and before bleed water appears on the surface. Susceptibility to plastic shrinkage cracking occurs in the period between bull floating and power floating, after which time bleeding has virtually ceased and the concrete has started to stiffen. Floating whilst there is still bleed-water on the surface will result in a very weak, watery surface, which can scale and separate from the concrete below, or can result in 'dusty' surface.

The critical conditions exists when the rate of evaporation of surface moisture exceeds the rate at which rising bleed water can replace it, and the top surface begins to dry out. Bleed water is virtually sucked out of the concrete surface in these conditions leaving 'tearing' type cracks in the surface.

These cracks appear in the surface of the concrete whilst it is still plastic, that is before the concrete has begun to harden, although they may not become visible until sometime later. Usually, plastic cracks form in a random pattern and may range from as little as 25 mm to as much as 2 m in length. Typically they are less than a metre apart, fairly shallow and vary from a hairline to perhaps 2 mm in width. Plastic shrinkage cracks are fairly shallow but can go the full depth in the case of 100 mm thick slabs.

The nomograph overleaf may be used to estimate the likelihood of plastic shrinkage cracking occurring, and therefore the need for suitable precautions to be taken.

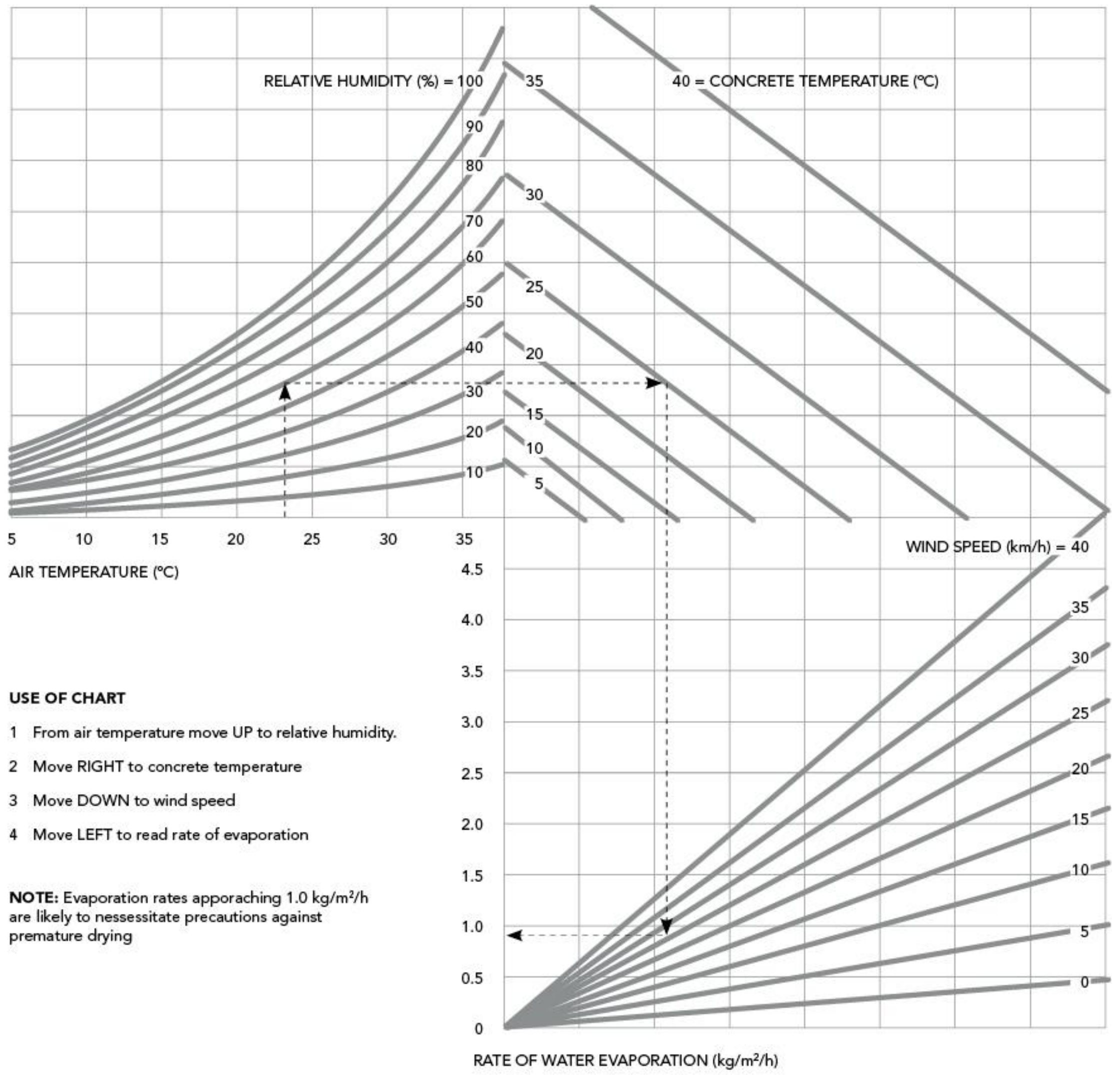
The factors which affect the rate of evaporation of moisture from the surface include:

- Wind velocity.
- Relative humidity.
- Concrete temperature.
- Air temperature.

A strong wind can greatly increase the evaporation of water from the surface of a slab. It is therefore an important variable in the initiation of plastic shrinkage cracking. A low relative humidity will also increase surface evaporation. Wind blowing over the surface may also chill the surface leading to map cracking or cracking associated with the curling of the floor due to temperature or moisture gradients through the slab.

Wind can also cause the top of the slab to crust, potentially meaning that the placer starts the finishing process while there is still bleed water trapped within the underlying concrete. If this occurs, there is a risk that the surface will delaminate.

Nomograph for Estimating Evaporation Rate



Effect of concrete and air temperatures, relative humidity and wind velocity on the rate of evaporation of surface moisture from concrete (after ACI 305, 1999)

A weather advisory for plastic cracking can be found at http://alliedconcrete.wxadvisory.com. The Weather App, has been developed using the nomograph above developed by the ACI Committee 305[5] and uses other data derived from international weather databases.

Where the four factors above combine to produce a rate of evaporation greater than between 0.5-1.0 kg/m²/hr, then plastic shrinkage cracking is likely and precautions should be taken. High air temperatures are not always necessary for plastic shrinkage cracking to occur; as concrete temperature and wind velocity will have a more marked effect.

[5] *ACI 305R-10: Guide to hot weather concreting.*

3.1 Prevention of Plastic Shrinkage Cracking

The most effective way to reduce the risk of plastic shrinkage cracking is to prevent rapid loss of moisture from the surface of the concrete.

Practices to achieve this are:

- Dampen the subgrade and form, ensuring any excess water is removed prior to placing concrete.
- Add polypropylene fibres to the concrete mix. These fibres intersect the bleed channels and prevent the widening of plastic cracks or propagation of plastic cracks.
- Avoiding using mixes with aggregates smaller than 19 mm and mixes with high sand contents for flatwork outdoors exposed to rapid drying.
- Where feasible, erect wind breaks to reduce wind velocity over the concrete surface. Pouring under cover is preferable by scheduling the roof ahead of the ground floor.
- Postpone casting on hot windy days. Programme pours for early in the day to avoid temperature extremes.
- Use aliphatic alcohols ('antivap') sprayed over the surface following bull floating which form a light film over the surface slowing down the rate of evaporation. This should be applied at approximate hourly intervals and also when the surface film is broken by refinishing.
- Commence curing promptly after finishing is complete and ensure the surface is subject to continuous curing. This increases the degree of self healing of the cracks.

3.1.1 Revibration

If plastic shrinkage cracking does become evident before the concrete has taken its initial set, the cracks can sometimes be closed by revibration of the concrete over the full depth of the cracks. However, surface revibration may be only partially effective, as it may not close the cracks if they are dry, particularly for thin sections. It is then likely the cracks will reappear as the concrete dries out further.

4. DELAMINATION

Delamination is the detachment of the top surface of a power trowelled concrete slab from the concrete below.

The thickness of the detachment can vary from paper thin up to 8 mm thick, depending on the mechanism involved.

The size of the delaminated area can vary from 100 mm square to several square metres. The actual delamination may not become apparent until between one and two weeks after the placing and finishing process is completed.

4.1 Causes of Delamination

Delamination can occur from a number of causes, but early finishing trapping rising bleed water is the most common:

- When fresh concrete is placed and compacted, the solids (cement and aggregate) settle. This natural settlement causes excess mix water (bleed water) and entrapped air to be displaced, and the lighter materials migrate toward the top surface. If finishing operations start prematurely and close or seal the surface before bleeding is completed, air and/or water are trapped under a densified surface mortar layer. As concrete hardens, subsurface voids develop where the water or air is trapped. These voids create weakened zones right below the surface that can eventually detach during slab use. Very thin mortar layers covering delamination may detach when struck with a hammer, as you try to gauge the extent of the delaminated area.

- The American Concrete Institute (ACI) explain the causes of delamination as being due to the formation of a closed surface layer of paste that seals the concrete prior to the completion of bleeding. The surface layer is normally closed when it is steel trowelled. If this trowelling occurs too early, air and water in the underlying concrete may continue to rise until it becomes trapped beneath the layer of dense surface paste. The trapped water or air can create a plane of weakness that may cause the top to delaminate due to subsequent drying shrinkage or disturbance by traffic. It is perceived that most cases of delamination are caused by trapping bleed water below the surface of the finished slab, brought about by early finishing. However other causes include:

    - Placing concrete on a cold subgrade can retard the set of the lower portion of the slab. There is a risk that the top of the slab is finished before the bleed water from the lower layers has had the opportunity to escape and delamination can occur.

    - When the finishing process is started too late in some areas delamination can occur. In these instances the finisher may attempt to move the paste around the surface to achieve the desired finish. In isolated spots where the surface has already set, this paste may simply sit on the surface rather than form a monolithic mass.

There is a perception that delamination seems to have increased in recent years due to larger slab sizes and the associated use of ride-on trowels challenging the placers' skills. With ride-on trowels the operator is more remote from the slab surface than is the case for walk behind trowels.

The New Zealand Master Concrete Placers' Association (NZMCPA) is a valuable resource which is addressing concrete industry skills in concrete placement. The member requirements to be a Master

Concrete Placer dictate a high standard of knowledge and practical experience which must be demonstrable, both in terms of workmanship and business acumen.

The reasons behind the formation of a localized and weakened top surface are many and varied. A Cement & Concrete Association of New Zealand (CCANZ) publication 'Project Slab'[6] provides guidance to help reduce the risk of delamination occurring and covers such areas as:

- Placing and finishing techniques.
- Environmental factors.
- Specification and supervision.
- Material factors.
- Mix design.

Corrective measures for delamination are typically similar to those used to avoid plastic shrinkage cracking, e.g. not pouring in hot windy weather (although there may not be flexibility to change pour dates), by spraying the surface with antivap, and by pouring under cover.

4.2 Materials

Whilst the prime cause of delamination is finishing too early, the materials that make up the concrete, in particular the aggregate grading and particle shape of the sand, and the cement, have an influence on the rate of bleeding and are significant contributors to delamination.

Concrete which uses blended cements that display little or no bleed water such as fly-ash, slag or silica fume, have retarded setting times and may have an increased risk of premature finishing. Also, mix designs with higher cement contents (for high strength floors) may produce a sticky or tacky mix which may have a tendency to crust prematurely, therefore increasing the risk of delamination due to the finishing operations commencing too early.

4.3 Admixtures

The use of concrete admixtures can effect setting times and may deceive concrete placers into commencing finishing too soon, thereby trapping escaping air and bleed water below the surface. Concrete manufacturers are experienced in the use of admixtures and the choice of admixtures in the proposed mix for the anticipated pour conditions. These should be discussed with the contractor and placer at a pre-pour meeting.

Specific issues associated with admixtures that may lead to a delamination problem include:

- Chemical factors that retard concrete setting times, or impede the progress of bleed water to the surface can make it appear that the concrete is ready to finish. Avoid using retarders unless there are long travelling times between the concrete batch plant and the construction site.
- Lower w/c ratios achieved with water reducers and superplasticisers will give less total free water and thus exhibit altered bleed and set characteristics.
- Air entrainment above 3% through an air entraining admixture (AEA) can increase the risk of delamination[7]. This is caused by micro structural features and tearing action as a result of the

[6] CCANZ MS 4 *Project Slab: Comparison of industrial concrete floor slabs in the Auckland & Christchurch markets.*

hard trowelling action, rather than trapped bleed water or interruption of the bleeding process. In New Zealand concrete mixes 25 MPa and below usually contain AEA.

4.4 Placing and Finishing

Correct placing techniques, used by experienced placing sub contractors, have the potential to overcome many of the problems seen in the industry. The benefits of a pre-pour meeting to discuss potential issues cannot be overemphasised.

Adequate and uniform compaction (vibration) evenly densifies concrete allowing for more uniform bleeding rates. Consistency of slump of successive concrete loads is very important, as this can affect bleed and setting characteristics, particularly when more than one batching plant is used to supply the site. The variability of the total water content between trucks, based on the batch records, will be reflected in the consistency of slumps.

The number of placers and the minimum equipment required will be relative to the area of pour and in accordance with industry best practice or New Zealand Master Concrete Placers Association (NZMCPA) recommendations.

The prevailing weather conditions and mix characteristics can have a significant effect on correct timing of the finishing operations of a slab. Cold subgrades and vapour barriers contribute to differential setting between the slab surface and the underlying concrete. Be aware that the concrete below the surface may take longer to stiffen.

The timing issue for finishing operations to commence is recognised as key to providing a durable and long lasting surface. Correct timing is critical to avoid delamination problems arising, particularly when bleed water evaporation is to be considered. There is a strong correlation between the use of low bleed concretes and the incidence of delamination and plastic shrinkage cracking. Traditionally, the loss of sheen to the surface of the slab has been the accepted criteria to determine the commencement of the finishing operation. The most common problem encountered by finishers is that the surface sheen has disappeared from the slab surface, possibly due to it 'crusting' while the concrete below the surface is still plastic and not yet sufficiently stiff to support a power float – referred to by some as the 'jelly effect'. A concrete truck load with a high slump compared to the slump of adjacent loads will also take longer to stiffen, increasing the risk of finishing too early.

4.5 Screeding

There is a choice of screeding techniques, free screeding and those using screed or beam systems on rails, or ride on finishing with control by laser. The relationship between the screeding method and delamination is unclear, though it is believed that methods and concrete mixes that create a thicker surface paste maybe more prone to delamination. The method of screeding will impact on the mix design:

- ***Free screeded floors*** – require more labour to achieve flatness and levelness, so the concrete placer will prefer a more workable mix. Concrete placer preferences should be balanced with negative mix factors that increase paste, retard mix, or slow bleed.

- ***Vibrating screed/beam vibrators*** – mixes can contain a coarser aggregate because of the higher compactive effort compared to free screeding. This ensures a high degree of flatness and levelness before the finishing operations begin.

- ***Laser Screed and ride-on finishing*** – with casting of large area warehouses, laser screeds and ride-on trowels are necessary.

[7] Landard, D. *Air entrainment and delamination.*

4.6 Finishing Processes

Do not start finishing until the bleed water sheen has gone from the surface and a footprint leaves an indentation no greater than 3-6 mm in the surface for a walk behind power float, or 3-4 mm for a ride-on power float. The window of finish-ability varies for each concrete mix and can even vary from batch to batch on the same project.

Specific issues associated with the finishing process that may lead to a delamination problem include:

- Delaying the floating and trowelling as long as possible to avoid closing the surface – this is the key to avoiding the formation of blisters and surface delamination.

- There is a potential for delamination where the bleed takes longer than the placer expects and or the amount of bleed is masked by reduced water content as in the case of a super-plasticised mix. Be aware of bleed water from previous truckloads seeping into fresh concrete loads.

- Bull floating should be completed prior to any bleed water appearing. Care should be taken to avoid overworking the surface. Too much paste can lead to sealing.

- Repeated assessment of the slab surface for finishing requires a regular walk over the floor to determine how far along the pour a ride-on machine can operate. If the floating operation is throwing paste, wait until the surface has stiffened before resuming power floating. Due to the remoteness the operator feels on the ride-on, it is good practice to carry out a trial using the walk behind machine first to establish the readiness of the slab to commence finishing with the ride-on. The slab needs to be somewhat firmer for a ride-on machine than a walk behind machine.

- Trowelling is done at some time after floating with the delay to allow some stiffening of the surface. Time should be allowed between each pass to allow the water to evaporate that has been squeezed to the surface.

  The first trowelling pass is done with the blades as flat as possible. Additional trowelling may be used to improve the density, smoothness or wear resistance of the surface. Successive trowelling should be done with the blades tilted at an increasing angle to the surface. If blisters form behind the trowel then the angle of the trowel is too great. These blisters should be immediately pushed down with a magnesium float or a flat trowel and the angle of the blades reduced.

- Machine trowelling an air entrained concrete slab may also cause air to be squeezed out from under the surface causing delamination.

4.7 Resourcing

The potential for delamination appears to increase when the slab is poured by free screeding and finished with ride-on trowelling machines. This could be related in part to the capacity of the finishing team to cope with the greater rate of slab being placed.

The use of ride-on trowelling machines is quite prevalent in the industrial floor market. These are replacing the traditional trowelling method of walk behind power trowels.

The correct time to commence trowelling is when the bleed water has evaporated, assessed as being when foot pressure leaves a print no deeper than 2-3 mm. However, ride-on machines exert less pressure on the surface than a foot. This, combined with the operator’s remoteness from the slab, means they are less sensitive to the surface of the slab, with the possibility of trowelling too early.

4.8 Burnished Floors – Craze Cracking

Crazing is the development of a network of fine random cracks or fissures which appear on the surface of concrete. This occurs from alternative cycles of wetting and drying as the surface expands and shrinks.

Craze cracks are rarely more than 3 mm deep. The irregular hexagonal areas enclosed by the cracks are typically no more than 50 mm wide, often as small as 20 mm. Generally, craze cracks develop at an early age and are more noticeable on steel trowelled surfaces, particularly if the surface is overworked. Overworking pushes the coarse aggregate down leaving a rich cement paste at the surface.

Craze cracks are generally very fine and do not affect the performance of the slab surface but may be visually obtrusive. However, such surfaces are typically extremely slippery.

5. THERMAL CRACKING

In the 2001 study comparing industrial slab defects, cracking was found to be significantly more prevalent in Christchurch than in Auckland.

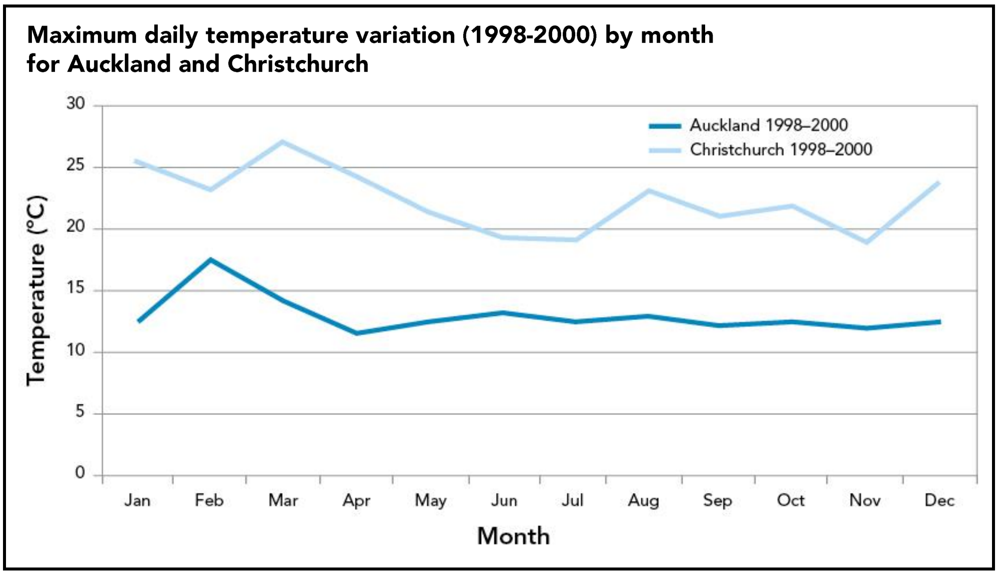
The difference in the concrete properties in this study between Auckland and Christchurch was not sufficient to explain the prevalence of cracking in Christchurch, leading to investigation of thermal cracking as the cause. The temperature difference between the ground under the slab and the top surface reflecting the air temperature is increased by the presence of wind on the slab surface and decreased by pouring the slab under cover or insulating the top of the slab with polystyrene or a thermal blanket.

A large drop in the ambient temperature on the night following the pour can lead to cracking caused by restrained thermal contraction as a result of the concrete temperature differential between the top and underside of the slab. These cracks may be hardly visible at first but often open up as the slab dries and shrinks in the first 2–3 days. Slabs which have random cracks despite the presence of saw-cuts at regular intervals (<6 m), have usually suffered from restrained early thermal contraction. Cracks running approximately parallel to saw-cuts indicate that the cracks were present prior to saw-cutting.

The probability of these cracks occurring can be reduced by the:

- Use of early entry saws. With these saws the slab is cut within two hours of finishing.
- Use of crack inducers cast into the slab.
- Use of antivap particularly for low bleed concrete.
- Avoidance of concrete strengths under 25 MPa in flatwork.
- Insulating the top of the slab to reduce temperature gradients in the slab.

Whilst these criteria are in common with other forms of shrinkage cracking, the mechanism for thermal cracking is quite different. The prevalence of thermal cracking in Christchurch is considered to result from the diurnal swing, the difference in the air temperature over 24 hours. When comparing the peak day night temperature swing occurring once each month between Christchurch and Auckland, in Christchurch this is 20°C compared to Auckland's 13°C, a significant difference. The summer months leading into autumn has the largest diurnal swing.



In addition, NZS 3109 sets out precautions to be taken with casting concrete in cold weather. This includes not casting in ambient temperatures below +5ºC with the temperature descending or below +2ºC with the temperature ascending. The surface of freshly laid concrete should also be protected from frost until the strength of the concrete has reached 3.5 MPa.

It is therefore recommended that precautions (as listed above) to prevent early thermal contraction cracking should be taken if the slab is restrained, and the ambient temperature is likely to drop more than 13°C over the 24 hours following finishing the slab.

6. DRYING SHRINKAGE CRACKING

Hardened concrete shrinks, i.e. it reduces in volume as it loses moisture due to:

- The hydration of the cement.
- Loss of 'gel water' on drying causing chemical contraction of the cement paste.
- Evaporation – the loss of moisture from the concrete results in surface tension in the capillary pores.

The shrinkage caused by moisture loss is not a problem if the concrete is completely free to move unless dimensional accuracy is important. However, in reality concrete is nearly always restrained, and tensile stresses will develop. If that stress exceeds the tensile strength of the concrete, which is around a tenth of its compressive strength, the concrete will crack. In design the tensile strength of concrete to prevent cracking cannot be relied upon and reinforcing steel or mesh is used to take tensile stress once the concrete cracks. Shrinkage will commence as soon as the concrete starts to dry out. A number of factors influence the shrinkage of concrete; in particular the total water content of the mix is important in limiting shrinkage.

Other influencing factors include:

- The quantity, stiffness and other physical properties of the coarse aggregate. The stiffness of coarse aggregate directly effects shrinkage by providing restraint to shrinkage of the cement paste.
- Pump mixes which typically may have a higher sand content, may in turn have a higher water demand resulting in higher shrinkage. Mixes using natural sands or the use of pump-aid admixtures may negate the need for additional water.
- Some admixtures, especially those containing calcium chloride may increase shrinkage.
- Low relative humidity will result in early shrinkage.
- Poor curing conditions allowing the slab to dry out prematurely may result in early shrinkage.

Shrinkage of a particular concrete mix is measured by a standard concrete test (AS 1012.13[8]) which measures the characteristic shrinkage under accelerated drying conditions of 50% RH for a period of eight weeks, after one week saturated curing. This test is recognised as a method to compare the characteristic shrinkage of different concrete types.

Typical shrinkage values for New Zealand concretes are given in TR 11[9]. Values range between 450 µm and 1,250 µm, this wide variation is due largely to the aggregate types and source. The shrinkage of a concrete in-situ will usually be less than the characteristic shrinkage value, owing to restraint to movement, differences in drying conditions and exposed surface area to volume when compared to the standard shrinkage test.

In order to reduce the total shrinkage of concrete:

- The water content should be minimised (consistent with the requirement for placing and finishing).

[8] AS 1012.13:2015 *Methods of testing concrete Determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory.*
[9] CCANZ TR 11 *Properties of New Zealand concrete aggregates.*

- The amount of fine material should be minimised consistent with a cohesive mix.
- The coarse aggregate proportions should be optimised.
- The largest possible maximum aggregate size should be used.
- Good curing practices should be adopted, however curing only delays the drying process and timing of shrinkage.
- The use of shrinkage reducing admixtures (SRAs) should be considered. SRAs are special admixtures which reduce the surface tension in the microscopic pores of the concrete which results in concrete shrinkage. These admixtures are only viable where there is significant cost benefit from shrinkage reduction.

However, simply reducing the shrinkage of a concrete will not necessarily reduce cracking since this is also influenced by the restraint, detailing, geometry and construction practice etc.

6.1 Reducing the Risk of Cracking Due to Drying Shrinkage

Reducing the risk of uncontrolled cracking, due to drying shrinkage, starts with the designer. Appropriate design and detailing is essential. Specifically, attention should be given to the following:

- The provision and location of adequate reinforcement to take up the tensile stress resulting from drying shrinkage movement at the induced shrinkage joints. This is particularly important in floors, slabs-on-ground, and similar applications where reinforcement may not be required for load-carrying or structural reasons.
- The provision, location and detailing of control joints to isolate restraint and permit differential shrinkage movement between discrete parts of the construction. Slab thickenings around the perimeter edges are preferable to footings which cause restraint to shrinkage.
- In some instances, two sheets of plastic membrane act as a slip layer and reduce the friction of a slab sliding on the ground due to shrinkage.

Construction practice is also important for it should ensure:

- That the concrete is properly placed, compacted and cured in order to minimise the magnitude of drying shrinkage.
- That the designer's curing details are correctly put in place before the concrete starts to dry out.
- The removal of restraint to movement by the formwork.

6.2 Shrinkage Control of Residential Slabs

Shrinkage control of residential floor slabs is a special case to prevent slab damage under earthquake action and minimise building damage. Requirements are specified in the New Zealand Building Code Clause B1/AS1 - Amendment 11. This specifies a maximum control joint spacing for 100 mm thick residential floor slabs of 6 m, and limits the aspect ratio of a shrinkage bay bounded by control joints to a maximum of 1.8:1. These are sometimes termed ‘tied joints’.

Slabs which are 100 mm thick shall be reinforced with 2.27 kg/m^2 steel reinforcing mesh (Ductility Class E in accordance with AS/NZS 4671[10]) and placed at 30 mm cover to the top of the slab.
The Building Code B2 states that saw-cutting must be carried out within:

- 24 hours of pouring the slab where the average ambient temperature is above 20°C.
- 48 hours of pouring the slab where the average ambient temperature is below 20°C.

Free movement joints where differential movement can take place between each side of the joint are to be spaced at a maximum of 24 metres or every fourth joint.

These requirements are summarised in the CCANZ publication *Residential concrete slab-on-ground floors*[11].

6.3 Shrinkage Control of External Slabs and Pavements

Exposed slabs and pavements are potentially larger and more exposed to the weather than residential floor slabs and control joint spacing should be conservative. The early placement of control joints is critical to avoid random shrinkage cracking.

Saw-cut joints shall be sawn 3 mm wide, where a sealant is being used the joints shall be widened to 5 mm at the time the sealant is installed. Saw-cutting shrinkage control joints shall take place to a depth of at least 25 mm so as to not cut the mesh. The mesh, which is continuous across the joint, holds the two sides of the crack together and load transfer is by aggregate interlock.

Uncontrolled shrinkage cracking is often put down to saw-cutting a slab too late. Saw cutting should take place 12-18 hours after completion of pouring depending on the rate of drying out of the slab under the ambient weather conditions. If cracks are already apparent at the time of saw-cutting, then it is likely that saw-cutting has taken place too late and subsequent shrinkage movement will take place at the shrinkage cracks rather than the saw-cuts. This is a significant issue, possibly the programming of saw-cutting on other jobs, conflicts with the requirement for saw-cutting. Warm winds blowing across the surface of the slab can result in crusting of the top surface and early onset of shrinkage of the slab, so timing of saw-cutting is critical.

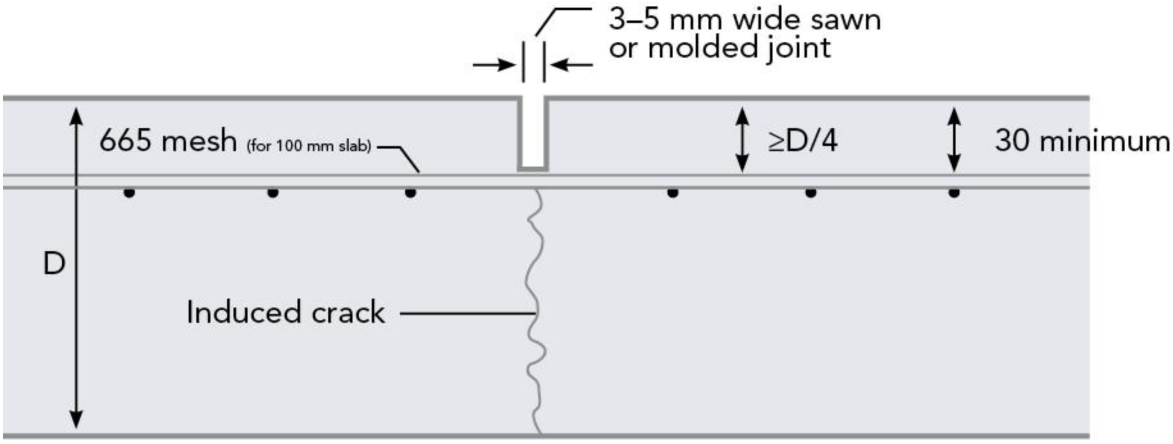
Early cutting of decorative or concrete to be exposed in particular is important. Delayed cutting will not only risk random shrinkage cracking but also spalling of the joint surface.

The use of a special Early Entry or Dry Cut saw which can be used to cut a joint around eight hours after finishing are an option to avoid premature cracking. Alternatively the use of crack inducer made of PVC or steel can be are cast in to the pour by fixing to the slab base or to reinforcement ensure that any movement following on from casting, will take place at this weakened section and this will virtually eliminate the risk of random cracking prior to saw-cutting. A crack inducer can also be trowelled into the surface of the fresh concrete with a special tool.

[10] AS/NZS 4671:2001 *Steel reinforcing materials.*
[11] CCANZ MS 17 *Residential concrete slab-on-ground floors.*

7. JOINTS

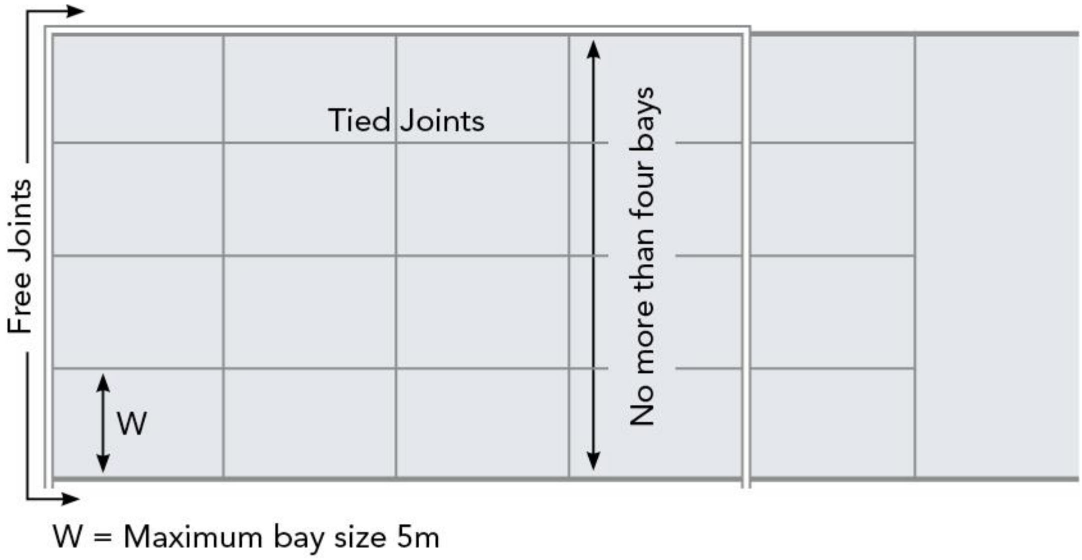
7.1 Control Joints



It is recommended that all slabs be reinforced with mesh to ensure that cracking takes place at each control joint. Ductile mesh can be used as for residential floor slabs, however for pavements 665 mesh is typically used for 100 mm thick slabs, or 663 mesh for 150 mm thick slabs.

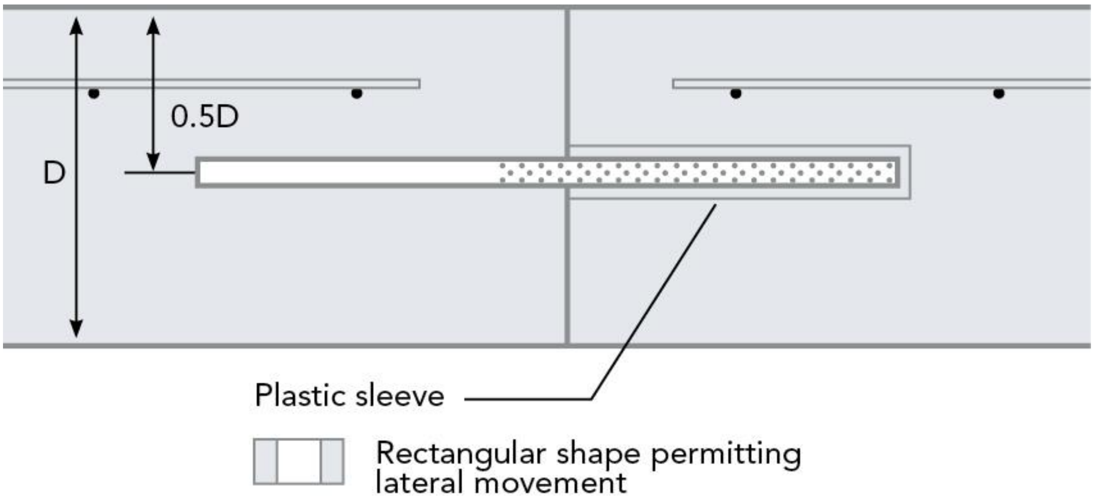
Mesh should be placed at a minimum of 30 mm cover to the slab surface, however in hot dry conditions which risk settlement cracking, mesh should be lowered to 40 mm.

Spacing of control joints should be no greater than 5 m reduced to 4.5 m for decorative slabs where any cracking may spoil the surface appearance.



7.2 Free Movement Joints

Free joints where slab reinforcement shall be terminated and there shall be no bonding across the joint between the concrete faces, shall be placed at a maximum of 20 m centres or every fourth bay. Floors carrying wheeled traffic shall have D12 dowel bars 600 mm long, debonded on one side, placed across the joint at 300 mm c/c for load transfer.



Dowels can also be used to prevent upward movement across a joint which is subject to slab curl. However, the use of dowels is only practical for slabs 125 mm thick or more.

7.3 Jointless Floor Types

For industrial floors carrying hard polyurethane hard wheeled forklift traffic with high wheel loads, floor joints can spall and repairs can be costly in terms of repair methodology and associated downtime. Jointless floors are being specified more frequently and are more economic in the medium-to-long term. Post tensioned floors, steel fibre or steel fibre combo floors are more commonly being used in high stacking warehouses with hard wheeled forklift traffic.

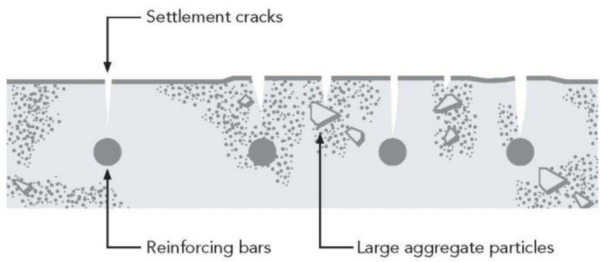
8. PLASTIC SETTLEMENT CRACKING

After concrete is placed, bleed water rises to the surface as the solid particles settle. The bleed water evaporates and there is a loss of total volume - the concrete has 'settled'.

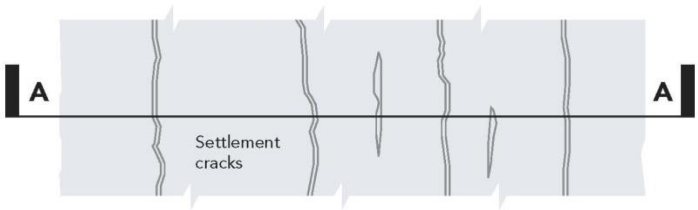
If there is no restraint, the net result is simply a very slight lowering of the surface level. However, if there is something near the surface, such as a reinforcing bar, which restrains part of the concrete from settling while the concrete on either side continues to drop, there is potential for a crack to form over the restraining element.

Differential amounts of settlement may also occur where there is a change in the depth of a section, such as at a beam/slab junction.

Settlement cracks tend to follow a regular pattern coinciding with a restraint, usually the reinforcement, or a change in section. Generally, the cracks are not deep but, because they tend to follow and penetrate down to the reinforcement, they may reduce the durability of a structure.



SECTION A-A



PLAN

Factors which may contribute to plastic settlement include:

- Deep cross-section of member.
- Large diameter of reinforcing bar.
- Low top cover to reinforcing bar.
- High rate of bleeding.
- Extended time before concrete starts to set (e.g. cold weather or set retardation).

8.1 Precautions to Prevent Plastic Settlement Cracking

Plastic settlement cracks may be prevented, or rather closed, by revibrating the concrete after settlement is virtually complete and before it has begun to set, e.g. after half an hour to one hour. Revibration closes the cracks, and enhances the surface finish and other properties of the concrete. Careful timing is essential to ensure that the concrete recompacts under the action of the vibrator and that the cracks close fully. Applying vibration too early may allow the cracks to reopen. Revibrating too late after the concrete is in its final setting phase, may damage the bond with reinforcement or reduce the concrete's ultimate strength.

Other procedures which may help reduce plastic settlement cracking include:

- Using lower slump mixes.
- Using more cohesive mixes.
- Using an air entrainer to improve cohesiveness and reduce bleeding.

Where there is a significant change in section, the method of placing may be adjusted to compensate for the different amounts of settlement. If the deep section is poured first to the underside of the shallow section, this concrete can be allowed to settle before the rest of the concrete is placed. However, the top layer must be well vibrated into the bottom layer.

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