RILEM TC 268-SIF

SURFACE DELAMINATION OF CONCRETE INDUSTRIAL FLOORS AND OTHER DURABILITY RELATED ASPECTS

GUIDE

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Foreword

This report is a guide document regarding different aspects of concrete industrial floors (the execution, surface delamination, wear resistance, deformation and cracking). It was compiled by the RILEM Technical Committee 268-SIF. The committee is chaired by Valérie Pollet and was active between 2013 and 2016, with annual meetings in Brussels, Belgium (May 2014), and Delft, the Netherlands (March, 2015).

Chapter 1 – INTRODUCTION

Main Author: Valérie Pollet, BBRI, Belgium.

Industrial floors, which are a current application for ready-mix concrete, play an important role in the construction industry. They are used, as their name suggests, in the industrial sector but also increasingly in the residential sector. Various factors can reduce their durability. These factors include top-delamination of the floor (Figure 1-1), a too low wear resistance and cracking.

The number of cases of industrial floor delamination increased in many countries in 2009: the UK, France, the Netherlands, Belgium, Italy, USA Sweden, etc. Delamination is the separation of a thin layer at the surface of the concrete from 3 to 10 mm thick (sometimes 30 mm) (Figure 1-2). It appears on industrial floors whose finishing is carried out mechanically. The separation plane is often located in the concrete, and not between the wear layer and the concrete. This distinguishes delamination from the cases of wear layer separation found in the past. The delaminated area varies from a few square centimetres to a few square metres. It can appear immediately after finishing or occur some days/months after the floor is put into use. This report presents the causes and includes recommendations for preventing this damage mentioned in the literature.

The range of applications of industrial floors requires them to have a certain wear resistance. The requirements concerning wear differ between countries, as do the assessment methods. The Böhme test method appears to be the most appropriate [i] for assessing the wear resistance of concrete industrial floors. A summary of the requirements established on the basis of the Böhme method is included in this report.

Figure 1-1: Delamination of a concrete floor.

Figure 1-2: Concrete core with delamination.

The cracking of industrial floors, even if inevitable, must be limited. This report reproduces recommendations and requirements for controlling this cracking.

[i] Seidler P., Rilem report 33, Industrial Floors, State-of-the-art Report, 2006.

Chapter 2 - THE MAIN STEPS IN THE EXECUTION OF INDUSTRIAL FLOORS

Main Author: Bram Dooms, BBRI, Belgium.

The concrete floor must be designed by structural engineers. Preparation of the substrate, the reinforcement and the choice of the concrete must be made on this basis.

Immediately after pouring, the concrete is spread manually, levelled and smoothed with a screed. In many cases, the concrete is compacted using a vibrating screed in order to remove the entrapped air. Vibrating screeds are surface vibrator that strike off and straightedge the concrete in addition to providing consolidation. They consist of hand-drawn or power-drawn single beam, double beam or truss assemblies. In some countries, like in Argentina[i], laser screeds are used to consolidate and to level the floor with a high accuracy (Figure 2-1).

Figure 2-1: Levelling of the concrete floor with laser screed.

The finishing of the surface (possible trowelling and polishing) is carried out a few hours after pouring the concrete, when it starts to stiffen and it is hard enough to be accessible without excessive deformation. The time to begin the finishing operations is determined on the basis of the bleeding and generally consists of assessing the imprint of a foot in the concrete.

In the Netherland, the time to begin the finishing operations is determined by the use of a standardised probe.
For this purpose, penetration using a Humm / Voton standardized probe must be a maximum of 35 mm. The measurement is carried out according to the method recommended in Annex B of the Dutch standard 2743[ii]. Two buckets (height 200 mm) are filled with concrete. At certain times, the probe is placed on one of the concrete surfaces, 25 times the weight is raised against the stop and dropped (see Figure 2-2). The depth of penetration is measured and the mean is determined.

Figure 2-2: Determination of the beginning time for the finishing with the sonde Voton.

The first concrete placed usually loses its bleed water sheen and stiffens first, so floating and trowelling operations have to take place in the same order that the concrete was placed.

The presence of excessive bleeding water during finishing work reduces the quality of the top layer, leading to a dusty, flaky, cracked surface. However, a moderate bleeding is a desired property showing that the delivered concrete has an appropriate composition. If there is lot of bleeding, the surface water must be removed before beginning the finishing (see Figure 2-3).

Figure 2-3: Elimination of the bleed water before starting the finishing operations.

2.1 Trowelling

The finisher starts with mechanical trowelling (using a power float that may or may not be equipped with a disc) (see Figure 2-4 and Figure 2-5) or manual trowelling (e.g. in the corners). Trowelling produces a hard, smooth surface that will be easy to clean and maintain. A single trowelling pass is done where skid resistance is more important than cleanliness. During each pass, the path followed should be perpendicular to the previous pass in order to compact the surface and bring out a very thin mortar layer. This mortar enables surface imperfections (e.g. holes) to be removed and large aggregates to be covered. Trowelling in only one direction creates a wave and repeated trowelling in only one direction accentuates the wave. These waves lower the floor flatness[iii].

During the surface finishing, a dry mixture of cement and wear resistant materials (e.g. quartz) having a specific granularity can be incorporated into the surface in order to reinforce the top layer. This mixture (which constitutes the wear layer) is generally made of one part of cement to two parts of wear resistant materials. It is distributed over the slab (with a shovel or using a distributor, (see Figure 2-6) either before or after the first trowelling pass and is incorporated into the surface during the trowelling that follows. The water present in the trowelled mortar acts to hydrate the dusted mixture. For the cohesion of the wear layer to be sufficient, there has to be enough water and the surface may not be too dry. Several trowelling passes may be required.

In Belgium, industrial floors are generally laid by incorporating hard aggregate toppings. In Argentina, hard aggregate toppings are spread “immediately” after the concrete is screed; thus before the first trowelling pass. The dry shake mixture is moistened (some minutes after) and then the vibrating bull float is passed.

In other countries, including Germany, a wear layer is applied "fresh in fresh" as a grout is generally used. The thickness of this mortar layer is between 6 and 15 mm on the surface of the concrete after finishing. When this layer of mortar becomes enough stiff, the finishing of the surface can continue (trowelling and polishing). These materials and their properties are described in the European standard EN 13813 [iv]. Unlike dry mixes for wear layers, this technique makes it possible to better control the thickness and the composition of the wear layer and also these performances.
Some liquid mixtures can also be applied to an already cured concrete surface.

In some countries, industrial floors are only trowelled: there is no incorporation of hard aggregate toppings. In some cases, they are previously vacuum treated for the dewatering process. Mats are applied to the surface after consolidation has been completed and they are connected to vacuum pumps. The suction applied by the pumps remove water and entrapped air from the region near the surface and close up the spaces formerly occupied by the water.

Figure 2-4: Power float equipped with disc for trowelling.

Figure 2-5: A double-rider (two rotors, each with blades) covering more area in less time than the walk-behind power machine.

Figure 2-6: Spreading a mixture of cement and quartz using a distributor.

2.2 Polishing

Trowelling can be followed by polishing which can also be carried out in several passes: the shine increases progressively. During the first pass, the rotor blades (normally smaller than those used for trowelling) are positioned as horizontally as possible against the surface and the polishing speed is fairly slow (see Figure 2-7). The blades are increasingly angled to increase the pressure exerted. The time for this polishing work depends on the surface area to be treated and the rendering required and can last several hours.

Figure 2-7: Power float fitted with angled blades for polishing.

2.3 Curing

Curing refers to the methods to keep concrete moist to develop the required strength, wear resistance and durability. A longer period of moisture retention permits more complete hydration of the cement.

Curing should start immediately after finishing. If the concrete is poured in a wind-still, indoor environment, the concrete can be considered protected by the presence of bleeding water the first hours immediately after the pouring.

The use of curing compounds is probably the most common curing method. Curing compounds are resins with solvent forming a film on the surface after evaporation of the volatile organic compounds or the water in case of emulsion. This film limits the water evaporation from the concrete. Care must be taken to correctly apply these compounds (see Figure 2-8). If they are spread too thin, continuous membranes may not form. The efficiency of the curing compounds can vary greatly. In Europa, there is a lack of a recognised criteria for the efficiency test of these curing compounds. Curing compounds leave a film that can interfere with the adhesion of other materials that could be applied to the surface as for example protective coatings. They always have to be removed before the application of coating (which is not always totally possible) or another curing method must be used.

Figure 2-8: Spreading of a curing compounds.

Other methods can be used in practice. Some methods like e.g. ponding or covering with a wet burlap or mats require adding water to prevent drying of the concrete. In the case of the curing compounds but also of the covering with a reinforced paper or plastic film, the mixing water is kept in the concrete during the curing period.

The covering with a plastic film is quite often used for the curing of industrial floors. Plastic film is a very efficient method for the protection of industrial floors. They can leave blotchy spots or folds on the slab and should not be used where appearance of the slab surface is important. But these films avoid leaving residue that can prevent the bond of protective coatings to the slabs.

Intermediate curing compounds appear on the market. They are intended to protect the concrete floor during the waiting period before trowelling. There is little experience with these products and their influence on the incorporation of the wear layer. During the waiting period before trowelling, bleeding of the concrete should protect concrete against drying out in principle.

[i] Pombo J.R., Experience in Argentina, TC Rilem Surface Delamination of concrete floor, 21 may 2014

[ii] NEN 2743, In het werk vervaardigde vloeren: kwaliteit en uitvoering van monolischisch vloeren en vervaardingen, 2003.

[iii] Concrete Craftsman Series: Slabs on Ground, CCS1-10; American Concrete Institute, 2010

[iv] EN 13813, Screed material and floor screeds - Screed material - Properties and requirements, 2002

Chapter 3 – SURFACE DELAMINATION

Main Author: Vinciane Dieryck, BBRI, Belgium.

3.1 Scale of the problem

In Belgium[i], the Technical Advice Service of the BBRI recorded more than 30 cases in 2010 and more than 20 cases in 2011(Figure 3-1). It is estimated that more than 200,000 m^2 of concrete industrial floors were damaged by delamination in 2009 and 2010 in this country.

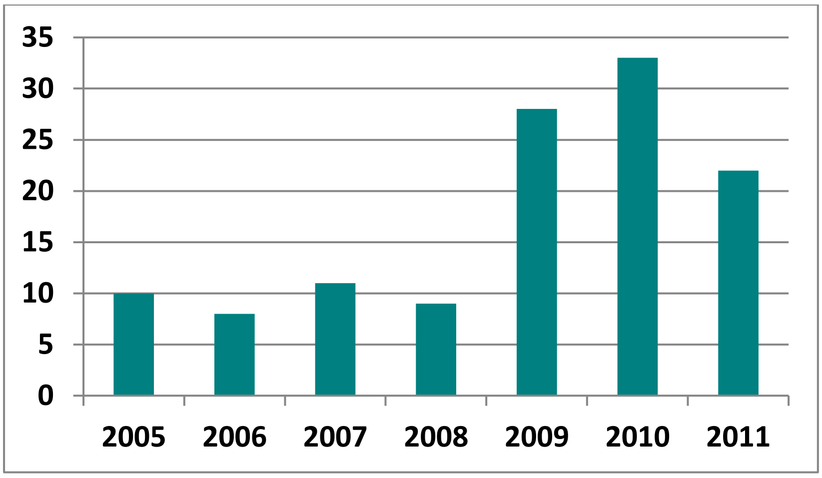

Figure 3-1: Number of identified cases of delamination recorded with the Technical Advice Service of the BBRI in Belgium.

In the other countries participating in the Rilem committee (Netherlands[ii], Argentina[iii], France, Sweden), it is more difficult to estimate the overall case as technical advice is less centralized.

3.1 Delamination causes

3.1.1 The two main causes

Delamination is essentially caused by **air voids** or **bleeding water** trapped under a dense polished concrete surface[iv,v,vi,vii.] This creates zones of weakness.

1. Where concrete contains entrained air, the intensive mechanical action of the blades of the power float used for polishing makes

the air voids move. At the top of the surface, air voids are destroyed and compacted down from the surface due to the forces from the trowelling. But beneath the top layer, these voids are deformed - they elongate and agglomerate. Their coalescence creates weak zones.

2. When concrete continues to bleed (i.e. its water rises to the surface) when the finishing has already been done, the bleed water is trapped underneath the finished surface.

These two situations are illustrated in Figure 3-2.

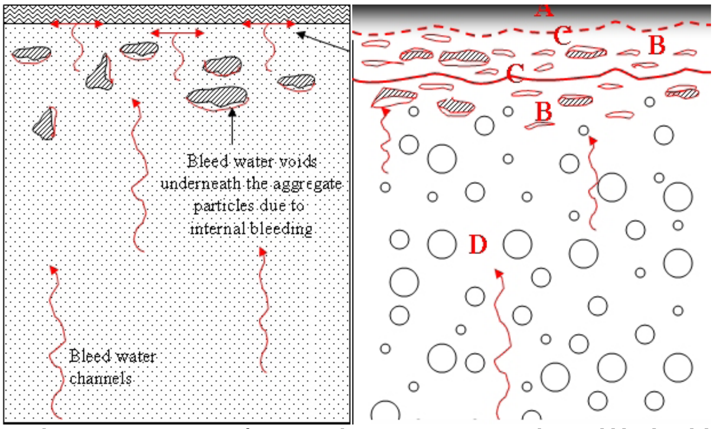

Figure 3-2: Schematic cross-section of concrete showing two scenarios that could lead to delamination of a floor; left: concrete of which the finishing is done before bleeding is complete; right: concrete with entrained air[vii]

The shrinkage generated then contributes to the separation of the top layer of the hardened concrete.

Note that separation of the wear layer, which can be confused with delamination, is itself caused by:

- Polishing too late on almost hard concrete, which impedes adhesion of the wear layer.
- Polishing of a too dry concrete preventing especially a good hydration of the wear layer.

The problem can be due to a bad polisher timing of the contractor. But other factors can contribute to this degradation: inappropriate concrete composition with a too small window of finishability (see 3.2.2) and dry climatic conditions.

3.1.2 Deformed air voids

Thin sections of the upper centimetres of the delaminated samples were made[i] perpendicular to the surface and were observed with a microscope using fluorescent light (Figure 3-3). It could be observed that in most cases the air content of the concrete was elevated. In addition, the voids closer to the surface are not predominantly round, as they normally are deeper in the concrete, but have an elongated shape.

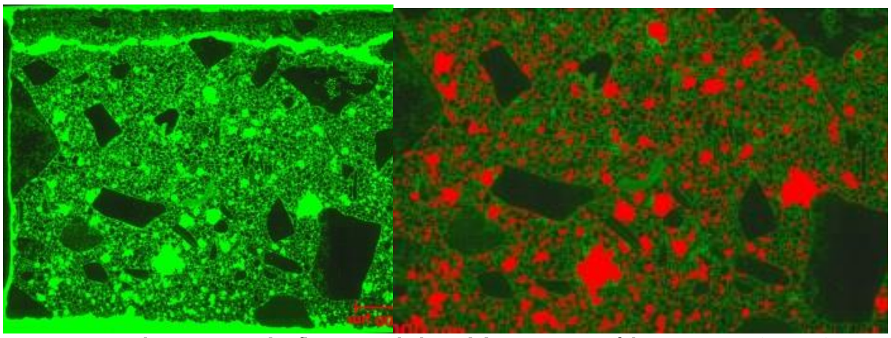

Figure 3-3: Thin section under fluorescent light and determination of the air content (~ 17%!).

The surface finishing operations (trowelling and polishing) produce vibrations in the concrete and shearing at the concrete surface. Concrete, being a thixotropic material, will become more plastic by the vibrations over a certain influenced depth and will segregate in this zone: the heavy components (aggregates) in this zone will sink and the light components (air, water, fines) will rise to the surface, thus forming a layer of fine mortar into which surface hardeners may be processed. It is difficult for air voids (entrained or entrapped) in this zone to 'escape' the concrete because of the shearing at the surface and the high viscosity of the mortar that is formed. Instead of escaping the concrete, the trapped pores form horizontally elongated voids under/inside the mortar layer. In sufficiently high concentrations the air voids can interconnect through micro cracks caused by the subsequent finishing operations or by the use of the floor, and thus cause delamination.

Another scenario is that the air voids are not connected directly, but initially only cause a weak zone parallel to the surface. As soon as "regular" cracks due to drying shrinkage reach this weak zone, the shear stresses at the tip of these vertical cracks can cause horizontal cracking of this weak zone and thus delamination. This explains the rather high width of cracks in areas with delamination.

It should be noted that there are two kinds of air: entrained air, which forms fine spherical voids of less than 1 mm, and entrapped air, which forms coarse irregularly-shaped voids larger than 1 mm that should be dissipated through correct pouring and vibration of the freshly poured concrete.

3.1.3 Trapped bleed water

Another possible delamination mechanism concerns the late bleeding of concrete, when the floor is already being finished. The bleeding water cannot reach the surface and accumulates under the viscous mortar layer, forming weakened zones that can interconnect through microcracks caused by the subsequent finishing operations leading to delamination.

3.1.1 Other related factors

If the water or air can escape before the concrete surface is closed, delamination has little chance of occurring. It is then seen that the **time when finishing is carried out** is also a crucial factor behind the development of this type of damage. The "window of finishability" is the period during which the finishing should take place (Figure 3-4). It is necessary to wait for a certain stiffening of the concrete, but if the finishers wait too long, they could not achieve the desired flatness or surface finish. Furthermore, the finishing operations should be completed before the end of setting in order not to damage the concrete surface.

Many industrial floor problems are related to the length of this window, which depends on the composition of the concrete and environmental conditions. Worksite experience has demonstrated that the length of this window can be greatly shortened with certain superplasticisers based on polycarboxylates

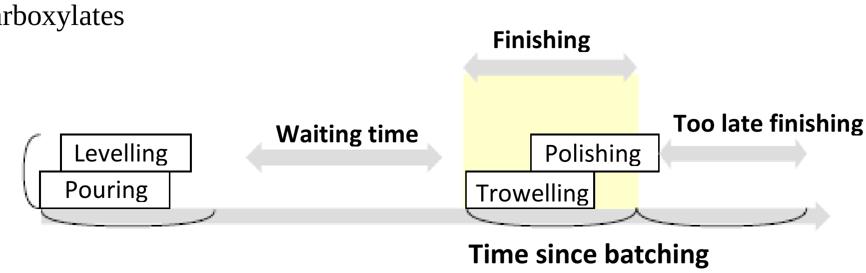

Figure 3-4: Window of finishability[viii]

If the concrete undergoes a **crusting** phenomenon, i.e. the top of the slab hardens faster than the underlying concrete, the bleeding water and air voids will also be trapped. Furthermore, in this case, assessing the concrete's stiffness, and thus the optimum time to carry out the finishing is made difficult. Indeed, the concrete seems to be ready, but the internal concrete is still plastic.

Crusting is indicated by the absence of bleeding water on hardened concrete while the underlying concrete is still plastic, like jelly. This is what finishers on site describe as a waterbed impression. With the formation of crust, the concrete surface prematurely seals off the air voids and the water present in the underlying concrete. Delamination is then much more likely to occur as the air and bleed water is trapped. Furthermore, crusting makes it harder to determine when to carry out the finishing. Indeed, contractors cannot always tell when there is a still plastic underlying layer. They only see that the surface no longer bleeds and stiffens, which requires them to start the finishing to create the required flatness. As there is an absence of bleed water sheen on a stiff concrete surface, the finishers try to finish the crusted surface with a power trowel. But the soft underlying concrete may bulge beneath the trowel, creating a wavy or cracked surface. If finishers wait for the underlying concrete to stiffen, the top surface can be too hard to float and trowel to an acceptable flat surface.

Concrete is subject to crusting when the evaporation rate exceeds the bleeding rate. Thus the factors behind this phenomenon are concrete with little bleeding (entrained air, high cement content, low W/C, ...), sticky concrete, concrete with delayed setting (with fly ash, certain superplasticisers, etc.), very dry environment, etc.

Concrete's **rheological behaviour**, and especially its viscosity, also plays a role in the development of delamination. If the concrete is viscous, it is harder for the air voids and water to escape. This phenomenon can be clearly illustrated by considering the difficulty of removing air bubbles from a bottle of oil. Furthermore, finishing is made more difficult and the finishing time is lengthened. Extended finishing further scores the surface layer and accumulates air and water under the surface.

According to Borsje[ii], the vibration of a concrete containing entrained air (not occluded air) would also favor delamination. After pouring the concrete, the concrete is smoothed with a straightedge but it can be a vibrating screed that allows to consolidate on the surface also. Consolidation or compaction by removal of the entrapped air is recommended. In the case of a concrete with entrained air, their removal is normally not achieved with vibrating equipment. However, the amount of energy introduced by a vibrating screed could by that high, that during compaction, surface air bubbles rise to the surface and just below they tend to agglomerate. And then the concrete is polished so that these bubbles would form lenses before leading to delamination. This hypothesis is based on microscopic analyzes on thin plates. In the delaminated part, there are no air bubbles and below they are larger than in the mass and deformed (see Figure 3-5).

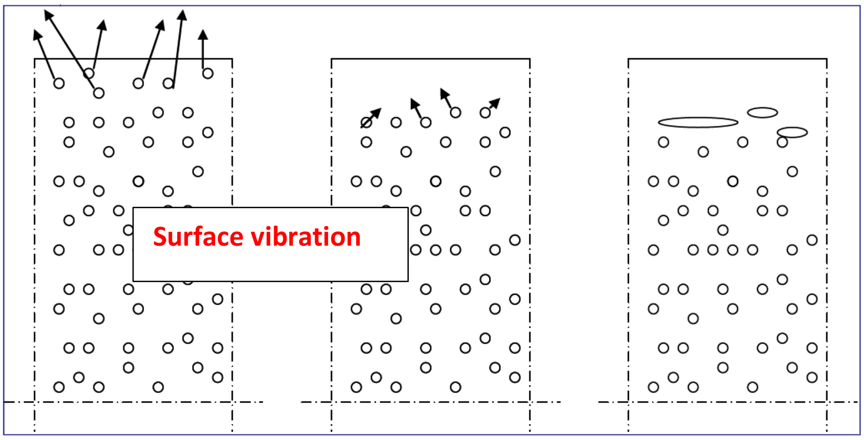

Figure 3-5: Influence of the vibration on the air voids

3.1.2 *Influence of the admixtures*

The influence of admixtures on the causes of delamination is described in the literature [i,iv,v,ix,x].

Air-entraining agents entrain air and then can cause delamination.

Certain admixtures can create undesirable excessive air entrainment. Examples include some retarders, water reducers and superplasticisers. Admixture manufacturers may overcome the problem of excessive entrainment by adding de-foaming agents. But according to the cement and concrete association of New Zealand[xi], care in using these products is required and air contents should be checked regularly both at the concrete plant and on site (unless risk of unintended air entrainment is known to be negligible).

Some admixtures that retard concrete setting times or impede the movement of bleed water to the surface can contribute to conditions that cause delamination by making it appear that the concrete is ready to finish.
Crushing can be favorited by some admixtures. These can deceive contractors into starting finishing too soon, thereby trapping escaping air and bleed water below the surface.

Looking at all the examined cases of delamination at the BBRI in Belgium[i], no clear common theme could be detected for the cement type, use of fly-ashes, use of steel-fibres, environmental factors (summer/winter), W/C ratio… In most cases however, powerful polycarboxylate-based admixtures (PCE) had been used. Laboratory tests have been executed to study the influence of superplasticisers on air content, bleeding and hardening properties of fresh concrete mixes. As shown in the experimental part of the project, the use of certain types of these PCE plasticisers can lead to unwanted air-entrainment and an unpredictable hardening of the concrete. In most cases, sea sand was used in the concrete mixes.

Concrete mixes were made with 320 kg/m^3 cement and a W/C ratio of 0.55, using different types of admixture (PCE “PCE1” “PE3”, “PCE4”, melamine “MEL” and naphthalene “NAF1” based), cement, aggregate grading curve, water content… The admixture was added in sufficient dosage in order to obtain consistency class S4.

Two aggregate distributions were applied: a distribution proposed by de Belgian Technical Specification concerning concrete industrial floors (“TV204/NIT 204”[xii]) and a distribution which is currently applied by concrete plants in Belgium (“Standard”). The most important difference between the two grading curves lies in the sieve size region from 0.4 to 4 mm (Figure 3-6).

The air content of the fresh concrete was measured (in accordance with EN 12350-7[xiii]) at different mixing times to simulate the transportation time in the concrete mixer truck.

It can be concluded that some types of PCE based admixtures can lead to a rather high level of air content of over 7% (Figure 3-7). For one type, this high level was present almost directly; for another type, this high level occurred after more than half an hour. Mixes with the ‘standard’ distribution generally contain more air than mixes with the ‘TV204/NIT204’ distribution. The generally accepted air content for upper limit for hard-trowelled concrete floors is 3%[xiv].

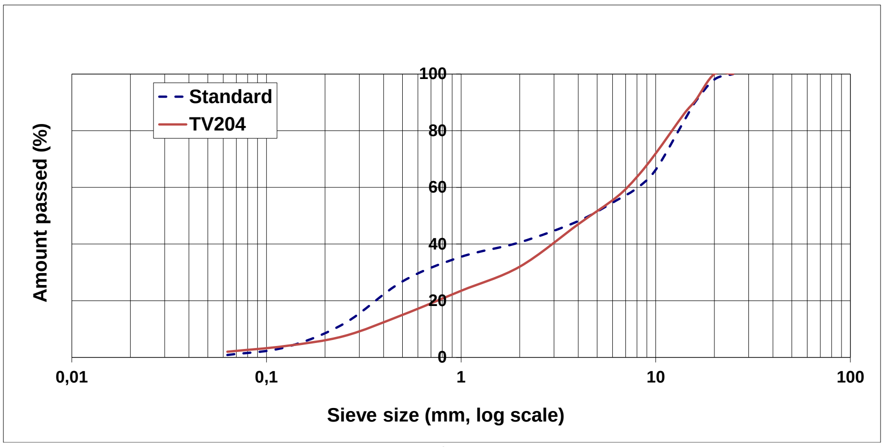

Figure 3-6: Comparison of aggregate grading curves.

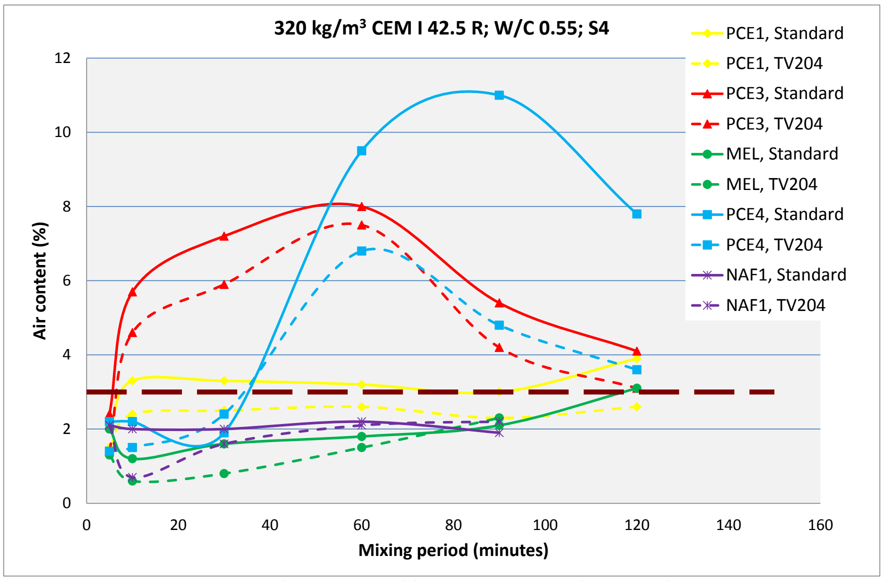

Figure 3-7: Evolution of air content of fresh concrete as a function of the mixing time.

The bleeding properties, determined according to EN 480-4[xv], also differ significantly between the mixes, both in total bleeding quantity and in bleeding rate (Figure 3-8).

It can be seen that mixes with PCE admixture generally bleed less but for a longer period compared to the other mixes. The same is true for the mixes with ‘standard’ distribution compared to mixes with the ‘TV204/NIT204’ distribution. A minimum amount of bleeding water is needed to protect against desiccation of the concrete surface. However, the bleeding must have finished when the surface finishing starts in order to avoid delamination.

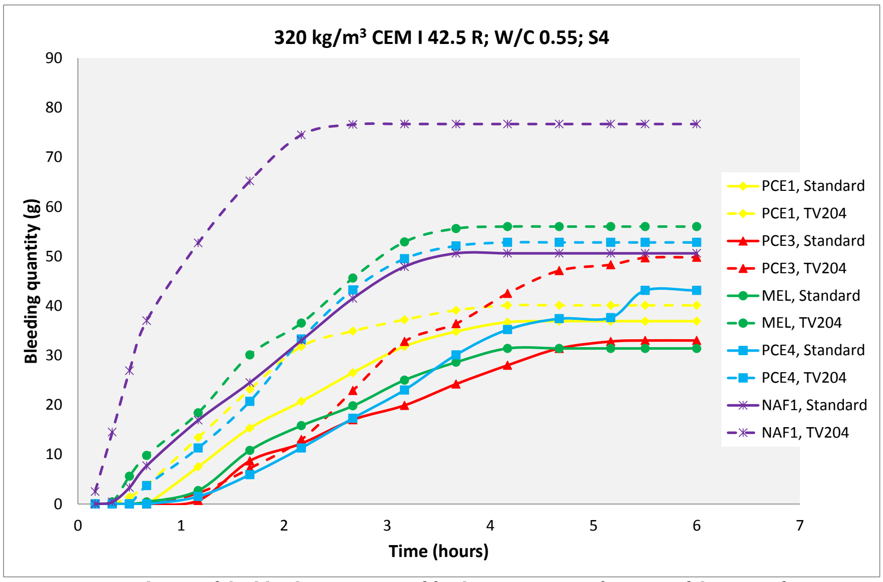

Figure 3-8: Evolution of the bleeding quantity of fresh concrete as a function of the time after mixing.

The stiffening of the fresh concrete mixes was measured using the ‘Voton’ probe (Dutch standard NEN 2743[xvi]). With this method, the so-called ‘Voton’ time of the fresh concrete can be determined, e.g. the optimal moment to start the surface finishing operations. The Voton time is reached when the probe, at 25 pulsations, penetrates less than 35 mm inside the concrete surface.

The mixes with PCE based admixtures tend to stiffen slower than mixes with the other admixtures (Figure 3-9). The same is true for the mixes with ‘standard’ grading curve compared to mixes with the ‘TV204/NIT204’ grading curve.

These observations, made in Belgium, support the recommendations of the Deutsche Bauchemie[xvii]. There are many types of PCE. Some are fast-absorbing superplasticisers with high initial plasticisation. Some are slightly adsorbing superplasticisers that retain consistency for a very long period. The viscosity of cement paste and the development of the strength of the cement can be influenced through the structure of the chain. According to the Deutsche Bauchemie, PCE superplasticisers that allow sufficient working time but only moderately increase the “open time” of the concrete and cause the concrete to re-stiffen after a short time are generally suitable for the construction of industrial floors.

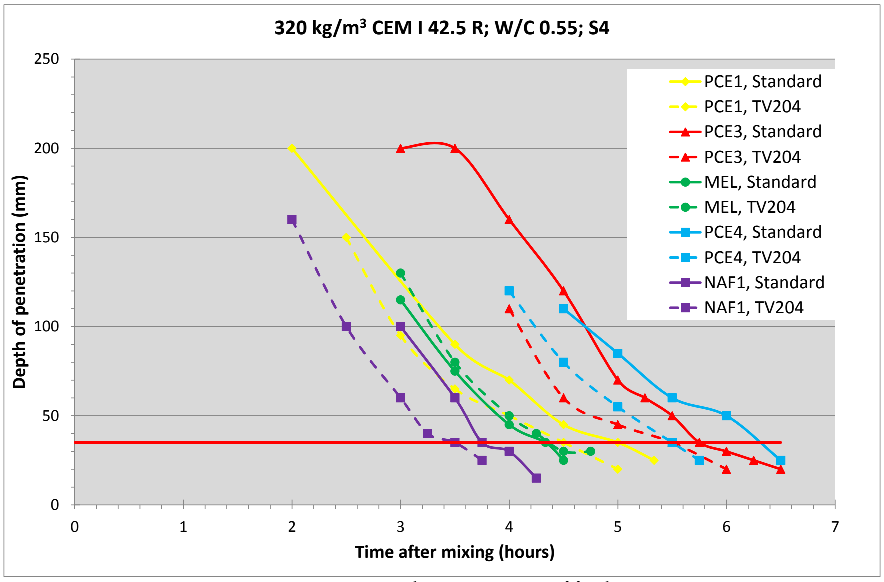

Figure 3-9: Determining the ‘Voton‘ time of fresh concrete.

3.2 Measurement of the air content and the bleeding

3.2.1 Measurement of the bleeding

The determination of the bleeding is generally determined using the standard EN 480-4.

Following this standard, a rigid cylindrical container with an inside diameter of 250 mm and an inside height of 280 mm is filled with a representative sample of concrete to be tested to a height of 250 mm as follows:

Using a scoop, the container is filled in three layers, each corresponding to a third of the whole volume, and each layer is compacted with 25 strokes of the tamper. The compaction of the concrete may be completed by vibration. The top of the concrete is levelled to a reasonably smooth surface. The container is covered with a suitable lid.

The water that has been accumulated on the surface is drawn off using a pipette at 10 min intervals the first 40 min and at 30 min intervals thereafter until cessation of bleeding.

After each withdrawal, the water is transferred to the measuring cylinder and the accumulated quantity of water is recorded.

The bleeding B is expressed as a percentage of the total water in the concrete as follows:

$$B = \frac{m_w}{w \times m_s} x100$$

Where:
m_w is the mass of the bleed water in grams
m_s is the mass of the sample in grams
w is the proportion of water in the fresh concrete by mass in percent.

3.2.2 Determining the air content of fresh concrete

The determination of the air content in fresh concrete is generally determined using the standard EN 12350-7[xviii].

There are two test methods, both of which employ the principle of Boyle-Mariotte's law. The two methods are referred to as the water column method and the pressure gauge method.

In case of the water column method, water is introduced to a predetermined height above a sample of compacted concrete of known volume in sealed container and a predetermined air pressure is applied over the water. The reduction in volume of the air in the concrete sample is measured by observing the amount by which the water level is lowered, the water column being calibrated in terms of percentage of air the concrete sample.

In case of pressure gauge method, a known volume of air at a known pressure is merged in a sealed container with the unknown volume of air in the concrete sample. The dial on the pressure gauge is calibrated in terms of percentage of air for the resulting pressure.

3.2.3 *Determining the air content of hardened concrete*

The air content of hardened concrete can be determined by different methods, such as the test method described in the standard EN 480-11[xix] or by image analysis of an impregnated thin section. The choice of method depends largely on the scale in which is to be focused. The analysis by means of a thin section is more accurate, but the sample size is significantly smaller. The preparation of a thin section is also much more elaborate than the preparation needed for determining the air content according to NBN EN 480-11. Other methods for determining the air content of hardened concrete are amongst other mercury intrusion porosimetry (MIP) and microtomography.

<u>Determining the air content according to NBN EN 480-11</u>

The pore structure of a sample hardened concrete, with dimensions 10x15 cm and a thickness of minimum 1 cm, is determined by image analysis of a mosaic image. First the sample is prepared, the test surface is totally blackened and the pores are filled with a contrasting white powder (as illustrated in Figure 3-1). By means of a motorised microscope a detailed mosaic image is taken of the sample by means of a stereo microscope (reflected illumination) and magnification (100 ± 10) x. On predefined parallel lines, covering a total length of 1200 mm (see Figure 3-11: The predefined test lines on which *the air content is analysed.*), the pore structure is analysed. The number of pores is counted and their length is recorded. In the standard, a mathematical analysis to calculate the total air content, the paste-air ratio and the spacing factor is described. Moreover, it takes into account the chance of the presence of an air void with a certain diameter and the volume of the air void.

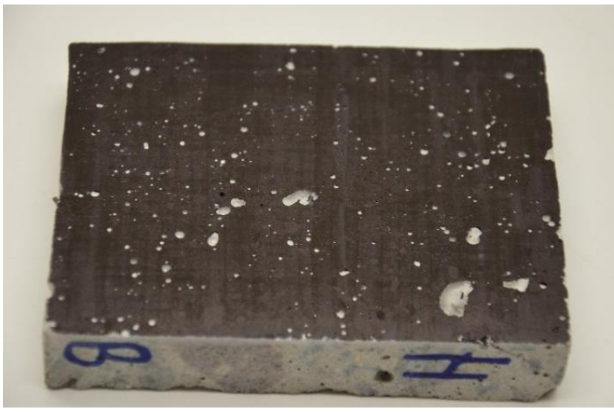

Figure 3-10: A prepared concrete sample for determining the air content.

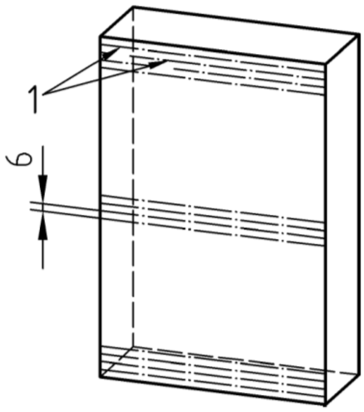

Figure 3-11: The predefined test lines on which the air content is analysed.

Determining the air content by means of a thin section

Petrographic examination of concrete is described in the American standard ASTM C856-17[xx]. In contrast with the method described above, an optical fluorescent-polarisation-microscope is used and the light is transmitted through the sample rather than being reflected. For this, a thin section of the to be analysed concrete must be prepared. A sample is cut to a size of 3 x 5 cm and a thickness of 1 cm and impregnated under vacuum with a fluorescent epoxy resin. After hardening the sample is grinded to a thickness of 0.025-0.030 mm. Finally, the thin section is covered with a glass cover slip to protect it from damage.

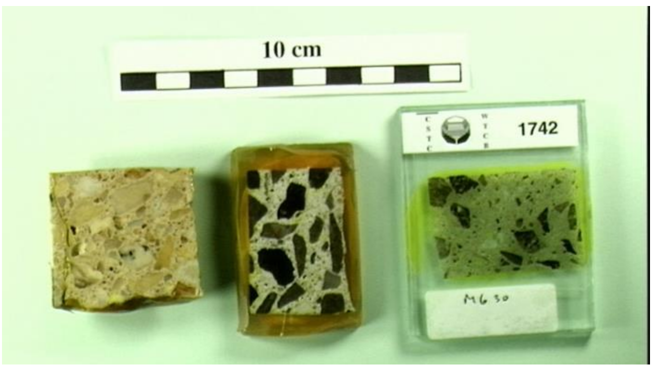

Figure 3-12: The different preparation steps for the making of a thin section.

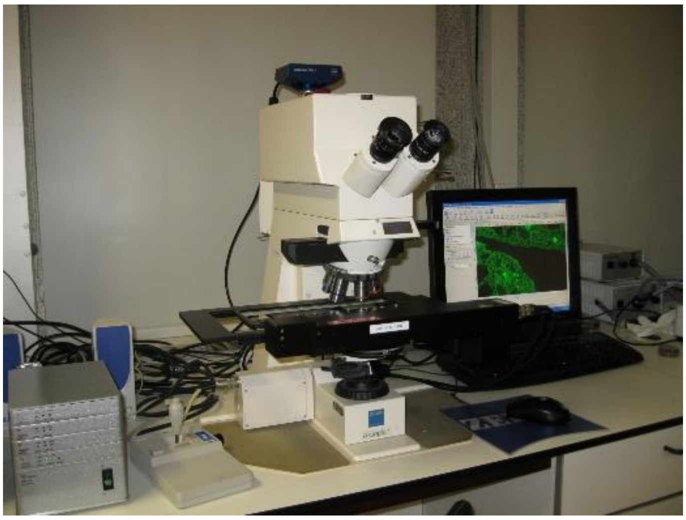

Figure 3-13: An optical microscope equipped with an automatic table for the making of mosaic pictures.

The fluorescent epoxy allows to easily recognize pores and cracks under fluorescent light as they light up bright green. By means of image analysis of a mosaic image of the thin section, the total pore content can be determined (in surface%) and also the percentage of the surface per pore size. A petrographic examination also allows to determine other characteristics of the concrete such as the aggregate type, size and distribution, the cement type, degree of hydration and the water-cement ratio.

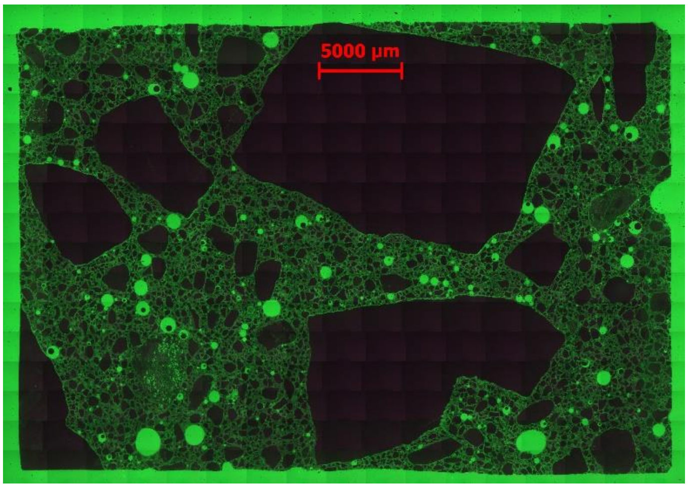

Figure 3-14: Example of a mosaic image of a thin section under fluorescent light.

3.3 Recommendations for preventing delamination

It is recommended to not use air entrained concrete for slabs that will receive a trowelled finishing.

The air content of machine-trowel finished concrete floors **may not exceed 3.0%**. Indeed, the literature mentions that concrete having more than **3% entrained air** is sensitive to delamination[xxi,ix,xxii,x]. The ACI Committee report 302 "Guide of Concrete Floor and Slab Construction" shows that concrete for interior industrial floors with normal density aggregates should not contain air-entraining agent and the air content should not exceed 3%. Deutche Bauchemie recommends a maxim content of 3.5% in a brochure on the use of PCE in concrete for industrial floors[xvii] . This air content must be checked on the work site and at the end of pumping, given the effect that the transportation time and pumping can have on this characteristic. This limitation of air content is recognised in many countries[xxiii].

This limitation of the air content can be problematic for outdoor concrete slab exposed to frost. Other finishing techniques should be chosen.

In Germany, Wiegring[xxiv] also mentions that the air content should be monitored when casting concrete with PCE, and that, depending on the temperature, the suitability test must cover the actual temperature during pouring of the concrete.

Deutsche Bauchemie[xvii] recommends **limiting the content in superplasticiser based on PCE to 1.0%** of the content by weight of cement in the concrete. In the case of PCE use, this should be suitable to the execution of industrial floors. Among the PCE superplasticisers, there are various categories and types of products, depending on application, that must be taken into account when selecting an admixture for laying industrial floors. PCEs with very long retention of consistency are not suitable to the production of trowelled concrete industrial floors.

To avoid an excess of superplasticisers, the concrete composition for interior concrete floors should have a sufficiently high cement content. The mortar fraction (cement + water + sand) of the mixture must be sufficient to provide the necessary workability and allow a correct finishing of the concrete floor. To ensure this, a **minimum water content of 180 l/m^3 of concrete and a minimal cement content of 320 kg/m^3 of concrete** is recommended in Belgium for the concrete composition when using PCE. According to the

Deutche Bauchemie, formulations containing between 320 kg/m³ and 340 kg/m³ cement have proven to work well for the production of normal concrete floors.

In Argentina, as there is a direct relationship between the shrinkage potential (cracking, curling, etc) and the cement content of the mix, it is recommended to use as less as possible cement content in it. As it is well known, the total water content has an important influence on the bleeding effect and also on the shrinkage potential, so it is recommended to use the lowest practical quantity of water. The concrete floors are formulated with cement contents between 280 kg/m³ to 320 kg/m³ and water content between 150 l/m³ and 180 l/m³. Argentina contractors think that the best admixture to regulate the slump of a concrete floor is a common one plasticiser, lignosulfonate based. One of the reason is that there is less influence in setting time of the concrete compared with any other plasticising admixture. Not only the delamination is minimised due to the absence of entrained air and late bleeding but also the risk of separation of the wear layer.

To avoid problems with segregation, water separation and shrinkage a stable concrete mixture should be used with a **continuous particle size distribution** of the inert skeleton (aggregates, including the sand).

The **content of fine material** (fine sand, chalk filler, cement) is very important and **must be deliberately selected**. A minimal quantity is needed to ensure the stability and pumpability of the concrete. Excessive fine material on the other hand increases the water requirement of the concrete, which in turn requires more superplasticiser to be added to it. This makes the concrete more viscous, increasing the risk of both accidental air entrainment and delamination. High cement content mixes and mixes containing additions (fly ash, silica fume) will be sticky to handle and may crust at the surface, leading to premature finishing. Site observations in New Zealand[xi] indicate that high sand content mixes may make delamination in slabs more likely.

Deutsche Bauchemie[xix] recommends **limiting the content of fines (<0.125 mm) to 370 kg/m³ of concrete and the content of fine sand (<0.250 mm) to 430 kg/m³ of concrete**, including fines.

A hard aggregate topping can only be reliably executed with concrete up to strength class C30/37 because the water content of these concretes is sufficiently high to allow the hard aggregate to be rubbed into the surface without weakening the bond. If a higher strength is required, a hard aggregate screed should be placed instead of a topping. According to the BBRI in Belgium and Deutsche Bauchemie, incorporation of the hard aggregate wearing topping cannot reliably be produced in concrete with W/C ratio of 0.45 or less. In this case, the use of fresh-in-fresh topping is recommended. According to Deutshe Bauchemie, it is not realistic to require a high class of frost resistance (European exposure class XF4) and for the same concrete a very high resistance to wear (German exposure class XM3).

Many factors influence the entrained air content: the particle size distribution, the fine material content, the sand used (type, origin), the type and dosage of plasticiser and superplasticiser, the concrete temperature, the transport time, … Consequently, the concrete plant must perform **new ITT tests for each change in the raw materials**, which should include simulation of the transport time.

During the bleeding of the concrete, an important amount of water is lost through the surface of the slab. This effect is increased when a **vapour retarder** is used to minimize the transmission of moisture upward through the slab from a bottom source, for example in the case where the floor will be covered by a coating. Under this condition, the probability of curling is strongly increased. The probability of delamination could increase also due to the late bleeding.
In Argentina, the use of a vapour retarder is specially avoided when it is not strictly necessary. And when it has to be used, special care is taken with concrete formulation and machine operations.

To find the correct time for finishing, the contractor can perform the Dutch **Voton test**. With a **penetration depth of < 35 mm** the concrete will be hard enough to finish the surface.

There are more qualitative tests and criteria. According to American Concrete Institute and the ACI Committee report 302[xiv], a person should be able to walk on the concrete without leaving a foot imprint more than 6 mm deep and the bleeding should be completed. When you use a heavy trowel machine as a double rider, the foot imprint could be less than 3mm[x, xi].

The surface of concrete must be worked during trowelling and polishing in the same order that it was poured and there should be no great differences in age when concrete surfaces are placed next to each other.

Not specifically to avoid delamination, but in order to avoid the desiccation of the concrete, floor slabs should not be exposed, even partially, to direct sunlight. When the finishing is complete, loss of moisture from the slab surface must still be reduced thanks to an appropriate curing.

To prevent delamination :

- **Max 3.0% air content in fresh concrete**
- **Max. 1.0% superplasticiser based on PCE to 1.0% of the content by weight of cement in the concrete**
- **Minimum water content of 180 l/m^3 of concrete and a minimal cement content of 320 kg/m^3 of concrete composition when using PCE**
- **Continuous particle size distribution of the inert skeleton (aggregates, including the sand).**
- **Limitation of the content of fines (<0.125 mm) to 370 kg/m^3 of concrete and the content of fine sand (<0.250 mm) to 430 kg/m^3 of concrete, including fines.**
- **To find the correct time for finishing, perform the Dutch Voton test. With a penetration depth of < 35 mm, the concrete will be hard enough to finish the surface.**

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xiv ACI 302.1R-09, Guide for Concrete Floor and Slab Construction, ACI Committee 302, Practioner's Guide, Slabs on Ground, ACI International, Farmington Hills, 1998.

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xvi NEN 2743, In het werk vervaardigde vloeren: kwaliteit en uitvoering van monolischisch vloeren en vervaardingen, 2003.

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Chapter 4 - WEAR RESISTANCE OF CONCRETE FLOORS

Main Author: Laura Kupers, BBRI, Belgium.

4.1 Introduction

A concrete floor has greater wear resistance if the exposed concrete has a dense, compact structure, a lower capillary porosity and high hardness aggregates. This can be obtained by [i, ii,iii,iv]:

- A surface finishing (trowelling and polishing),
- Incorporating hard aggregate dry-shake topping or finishing by applying a "fresh on fresh" topping.
- A good curing of the concrete

4.2 Evaluating the wear resistance

Concrete floors are in general submitted to two major types of wear :

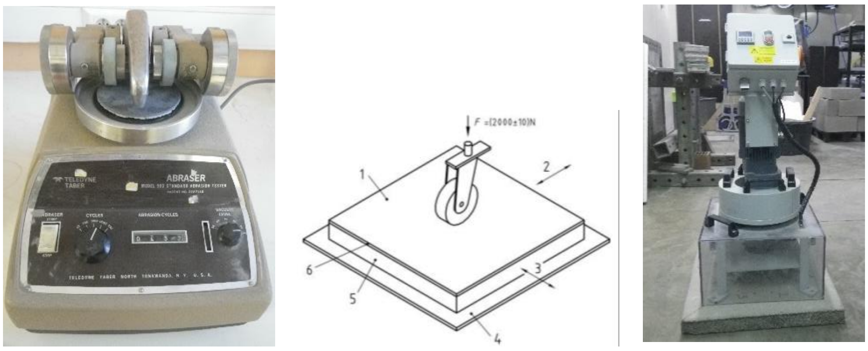
- Rolling wear: from e.g. the wheels of cars, forklifts, pallet trucks ... This type of wear generally works as low-intense adhesive wear and generally only affects the cement-matrix.
- Grinding wear: abrasive contact caused by pedestrian traffic, dragging boxes or pallets ... but also, for example, the rolling of wheels on a "dirty" floor. Grinding wear is generally more intense than rolling wear and causes more damage to the floor. Not only the cement-matrix is affected but also the hard aggregates.

Different test methods have been developed to evaluate the abrasion resistance of concrete. These different tests can be grouped according to the type of wear they simulate.

- Grinding wear (Figure 4-1): Böhme (EN 13892-3 [v]), Amsler (NBN B 15-223, lapsed), Capon (EN 14157 [vi]). These tests simulate the grinding by means of an abrasive sand that is applied between the sample and a rotating disc.
- Rolling wear (Figure 4-2): Rolling wheel test (EN 13892-5 [vii]), BCA (EN 13892-4 [viii]), Taber (EN 660-2 [ix], ASTM D 4060 [x]). These three tests are literally loaded wheels rolling over a test slab.

\- Böhme (EN 13892-3) Amsler (NBN B 15-223) Capon (EN 14157)

Figure 4-1: The various equipments for testing grinding wear.



Taber (ASTM D4060) Rolling wheel (EN 13892-5) BCA (EN 13892-4)

Figure 4-2: The various equipments for testing rolling wear.

It is important to keep in mind the wear property when choosing a test method to evaluate the wear as no single method simulates all of the wear mechanisms[xi,i]. As the grinding wear tests simulate a much more aggressive wear, they also tend to erode deeper in the test samples and thus test not only the denser surface layer but also the underlying concrete.

4.3 Evaluating grinding wear

Various publications recommend using the Böhme test to evaluate the grinding wear resistance of concrete[xii,xiii,xiv] and many standards also use it for wear-resistance classification (see Section 4.3.2). The Amsler method, although no longer being standardized, is still occasionally used in the Netherlands and in Belgium. The Capon test is mostly used for testing natural stone and less for concrete.

4.3.1 The Böhme test

For the Böhme test, a test specimen, with a surface of 50 cm^2, is clamped in a fixed specimen holder upon a rotating disc. The sample is loaded with a force of 294 N and an abrasive sand (artificial corundum) is strewn on the test track. In total 16 cycles of each 22 revolutions are performed. The loss in mass and height is measured after every 4 cycles and the abrasive sand is replaced. The abrasion resistance (A) is expressed as the loss in volume (ΔV) and is calculated by means of the loss in height (Δl) or loss in mass (Δm).

$$A\ (cm^3/50cm^2) = \Delta V = \frac{\Delta m}{\rho r} = \Delta l \times 5$$

Depending on the wear resistance of the tested concrete, 0,5 to 6 mm of the surface is abraded after being submitted to the 16 cycles. In general, the most upper surface layer of the sample is the most vulnerable to wear with a higher loss in volume per abrasion cycle than the underlying concrete.

4.3.2 Wear classes based on the Böhme test

In Belgium, the BRRC (Belgian Road Research Centre) assigns in its handbook for outdoor concrete industrial pavements (A82/11 *Handleiding voor industriële buitenverhardingen in beton* [xv]) a scope of application for six wear-resistance classes based on the Böhme test. The lowest class allows a maximum wear of 15 cm^3/50 cm^2. The highest class (for extreme wear loads) has a maximum wear of 1.5 cm^3/50 cm^2 (see Table 4-1).

The German Zement-Merkblatt (*Industriële betonvloeren. Zement Merkblatt* [xvi]) describes four classes of concrete properties (strength class, w/c-ratio and type of wear material) that could lead to different wear resistances (in accordance with Böhme) and assigns a scope of application for each (Table 2). The least severe class (for e.g. exhibition areas) has a maximum tolerated wear of 15 cm^3/50 cm^2. The highest class (for heavy industry) permits a maximum wear of 6 cm^3/50 cm^2. (see Table 4-2).

The Böhme test is also used for other materials and applications. Requirements regarding the tolerated Böhme wear are set for concrete prefabricated items such as concrete paving stones and Terrazo slabs in European standards EN 1338[xvii], 1339[xviii], 13340[xix], and 13748-2[xx]. The most severe class of requirements is the class setting a maximum wear of 18 cm³/50 cm³ (see Table 4-3).

Wear resistance classes according to the Böhme test (NBN 13892-3)	**Abrasion quantity in cm³/50cm²**	**Field of application for outdoor surfaces**
A15	15	Circulation of cars
A12	12	Circulation of cars and trucks. Forklifts with a load capacity up to 40kN and pneumatic tires.
A9	9	Intense circulation of trucks, forklifts with a load capacity to 100kN and pneumatic or solid rubber tires with contact pressures up to 2 N/mm².
A6	6	Heavy industrial activity, heavy forklifts with pneumatic, full rubber tires or full hard tires with contact pressures up to 4 N/mm².
A3	3	Most severe classes are applicable for extreme wear, such as the dragging of metal parts or containers, and for which the wear resistance is an important criteria.
A1,5	1,5	

Table 4-1: Maximum allowable attrition according to the Böhme test for different areas of application for (outdoor) concrete floors as defined by the BRRC[xiv].

Field of application	Compr. strength class	W/C-ratio	Aggregate grading and type of aggregates	Abrasion (cm^3/ $50cm^2$)	Böhme wear class
1. Exhibition rooms, light load, limited traffic with soft tires (capacity ≤ 10 kN, tire pressure ≤ 3 bar)	C25/30	0,53	Aggregate curve A/B 32: fine aggregates 0/2 and coarse aggregates 2/8 and 8/32.	≤ 15	A15
2. Average load, (underground) car parks, forklifts with pneumatic tires (capacity ≤ 40 kN, tire pressure ≤ 6 bar)	C30/37	0,47		≤ 12	A12
3. Heavy load, metal processing, repair garages, steelwork, heavy forklifts with pneumatic and solid rubber tires (capacity ≤ 80 kN, tire pressure ≤ 10 bar, contact pressure ≤ 2 N/mm²)	C30/37	0,42	Aggregate curve A/B 22: fine aggregates 0/2, coarse aggregates 2/8 and broken (hard) aggregates 11/22.	≤ 9	A9
4. Very heavy load, heavy industry, very heavy forklifts with solid rubber tires (capacity ≤ 80 kN, contact pressure ≤ 2 N/mm²) or solid hard tires (contact pressure ≤ 4 N/mm²)	C35/45	0,38	Aggregate curve A/B 22: crushed rocks 0/2, broken (hard) aggregates 5/11 and 11/22, or aggregates as for 1 and 2 with hard-aggregate flooring as described in DIN 18560-7.	≤ 6	A6

Table 4-2: Scope of application for concrete pavements with corresponding wear resistance classes as defined by Zement-Merkblatt [xvii].

Class	Scope of application	Maximum wear (cm^3/50 cm^2)
1	/	/
3	Pavements with low-intensity vehicular traffic (e.g. local or residential traffic, car parks).	20
4	Pavements subject to vehicular traffic of at least normal intensity	18

Table 4-3: The wear resistance classes for concrete paving setts, floor tiles and curbstones (EN 1338, 1339 and 1340)

4.3.3 Comparing the former Amsler wear classes to the Böhme wear classes

In Belgium, as in the Netherlands, the Amsler test served as a base for assessing the wear resistance of indoor concrete floors. The requirements set in these countries are difficult to compare given that the distance run by the wheel differs in the two countries. (NEN 2743[xxi], TV204/NIT204[xxii]).

The TV204/NIT204 (1997) defines wear load classes and the corresponding requirements for the wear resistance based on the Amsler test (Table 4-4). It states that resistance to wear of less than 3.5 mm can be achieved without hard aggregate wear layer and that a wear resistance of less than 2 mm can be achieved by making use of a hard aggregate wear layer. Whereas in practice, it appears difficult to obtain the limit of 2 mm even by making use of a currently used wear layer based on quartz and cement incorporated into the concrete during trowelling.

Now that the Belgian standard for the Amsler test is expired, it will be replaced by the European Böhme test in the revised technical document TV204/NIT 204 (publication expected in 2017) concerning concrete interior floors.

To define the new Böhme wear classes in the revised TV204/NIT204, literature was consulted and comparative laboratory tests were executed. Based on this, and from research at the BBRI with various concrete floors, a new and comparable classification to which a minimal wear resistance as well as wear load class for high-load industrial activities were added (Table 4-4). This new classification in the revised TV204/NIT204 corresponds with the classification in the German document Zement-Merkblatt (Table 4-2).

The examples of applications corresponding to the classes are based on measurements on concrete floors carried out in Belgium and on the German experience.

TV 204/NIT 204 (1997)		The proposed new classification in Belgium		
Wear load class	**Wear resistance in accordance with Amsler (mm/3000 m)**	**Wear load class**	**Examples of applications**	**Wear resistance in accordance with Böhme ($cm^3/50\ cm^2$)**
Ia	No requirement	Light	Offices, residences	≤15
Ib and IIa	≤ 3.5	Medium	Storage areas, supermarkets	≤ 12
IIb	≤ 2.0	Heavy	Heavy industry, hypermarkets	≤ 9
		Extreme	Metalworking companies	≤ 6

Table 4-4: Requirements for wear resistance according to TV 204/NIT 204(1997) and a proposal for a Böhme-based classification in Belgium.

The precise wear resistance of a concrete floor will depend on numerous factors that the contractor does not always have full control over (including the concrete composition, the bleeding, the environmental conditions, the hardening of the concrete, the amount of dry wear layer mixture incorporated, the efficiency of the curing, ...). Nonetheless, the requirement for a medium wear load can usually be met by applying a surface finish with a classic dry shake (quartz-cement mixture). In order to meet the needs for the heavy load or extreme wear load class, one could, for instance, use special dry shakes or toppings (applied "fresh on fresh") containing wear-resistant aggregates such as silicon carbide.

4.4 Evaluating rolling wear

To evaluate the rolling wear of industrial floors, the BCA-test is often used. The advantage of the BCA test opposed to the Taber and Rolling wheel test is that it can be executed on site with relatively little damage to the tested floor. The British Standard for Concrete Wearing Surfaces[xxiii] also uses the BCA wear for their classification.

In the following text, both the BCA-test and the Rolling Wheel-test are shortly described. The Taber test is not further discussed as this test is specifically developed for the testing of organic coatings and not concrete materials.

4.4.1 The BCA-test

The BCA testing device consist of three hard metallic wheels which can rotate in a circle with a diameter of 22.5 cm. The BCA test can be performed in-situ on the to be tested floor or on a test specimen with minimum dimensions 50 x 50 cm and a minimum thickness of 0.50 cm. Reference points are indicated on the test surface and the initial height of the 8 measurement points on the abrasion track are measured. For the test the BCA machine is secured on the testing surface and a force of 65 kg is evenly divided over the three wheels. In total 2850 rotations are performed. The loss in height for each measurement point is measured and the BCA wear (AR) is calculated:

$$AR = d_w - d_0$$

With d_w and d_0 the average measured height of the sample before wear and after wear respectively.

4.4.2 Wear classes based on the BCA test

The British standard BS 8204-2[xxiii] describes a classification for abrasion resistance of concrete floors based on the BCA test. Four wear classes are defined (Table 4-5).
of concrete properties (strength class, w/c-ratio and type of wear material) that could lead to different wear resistances (in accordance with Böhme) and assigns a scope of application for each (Table 2). The least severe class (for e.g. exhibition areas) has a maximum tolerated wear of 15 cm³/50 cm². The highest class (for heavy industry) permits a maximum wear of 6 cm³/50 cm². (see Table 4-2).

Class	**Maximum test wear depth**	**application**	**Service conditions**
AR0.5	0.05 mm	Very heavy duty engineering workshops, intensively used warehouses etc.	Severe abrasion and impact from steel or hard plastics. Wheeled traffic or scoring by dragged metal objects.
AR1	0.10 m	Heavy duty industrial workshops, intensively used warehouses, etc.	Very high abrasion; steel or hard plastics wheeled traffic and impact
AR2	0.20 m	Medium duty industrial and commercial	High abrasion; steel or hard plastics wheeled traffic
AR4	0.4 mm	Moderate abrasion ; rubber-tired traffic	Light duty industrial and commercial

Table 4-5: Requirements for wear resistance according to BS 8204-2[xxiii].

4.4.3 The Rolling wheel-test

The Rolling Wheel testing device consists of a fixed and heavily loaded (approximately 204 kg) rolling wheel. A test specimen with minimum dimensions 50 x 50 cm and a minimum thickness of 5.0 cm is placed on a support which can move horizontally in two perpendicular directions at different frequencies. Five measurement points are indicated on the test surface and the wear is expressed as the loss in volume caused by the rolling wheel after 10,000 cycles in the longitude direction.

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Chapter 5 – CONTROLLING DEFORMATIONS AND CRACKING

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5.1 Origin of deformation and cracking

Concrete shrinkage and thermal movements can cause distortion and cracking of concrete floors. Taking appropriate measures helps to limit deformation and control cracking.

Deformation of concrete floors due to bending (self-supporting floors) or differential settling of the ground (floors on earth platform) can also cause cracking.

5.1.1 Shrinkage

Concrete shrinkage consists in a reduction of its volume mainly due to evaporation of the mixing water. It is called *plastic shrinkage* in the plastic phase and *drying shrinkage* (or "hydraulic shrinkage") in the hardened state. Shrinkage due to the hydration reaction of the mixing water with cement (chemical or autogenous shrinkage) is less important in this application and will not be dealt with in detail.

5.1.1.1 Plastic shrinkage

Given the typical execution of concrete floors, the concrete surface can only be protected against drying after finishing (trowelling, polishing) which, itself, can only be carried out after a certain waiting time. During this waiting time, plastic shrinkage cracks can appear in the concrete surface. Indeed, concrete's deformability reduces relatively rapidly at the same time as the shrinkage stresses appear and increase in the concrete (Figure 5-1). The concrete's tensile strength at this time is not sufficiently high to absorb these and the concrete cracks.

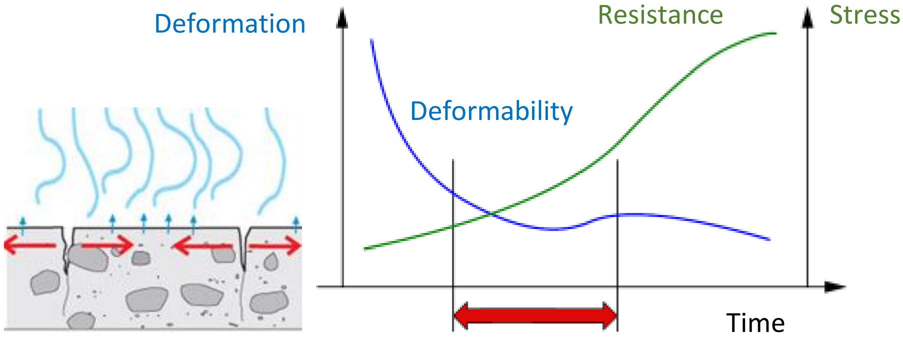


Figure 5-1: *The appearance of plastic cracking in concrete.*

Cracks due to plastic shrinkage can have a rather high width (up to 1 mm) and run in depth over the total thickness of the floor. When trowelling the surface, these cracks are usually eliminated at the top side of the floor (Figure 5-2), but they remain prime areas favouring later cracking through drying shrinkage.

Figure 5-2: *Crack due to shrinkage eliminated at the top surface.*

Therefore, it is important to limit plastic shrinkage as far as possible by ensuring execution of the floor out of the sun and wind and at a temperature less than 30°C. In this respect, slight bleeding of the concrete can be favourable as the film of water thus formed protects the concrete from the drying.

5.1.1.2 Drying shrinkage

Drying shrinkage starts during the concrete hardening phase, which gives the concrete its mechanical strength. There are two aspects of drying shrinkage that are of importance:

- The total amount of shrinkage, which is roughly between 0.1 and 0.8 mm/m. This highly depends on the total amount of water in the concrete, but also on the and in particular depends on the composition of the concrete (content in fines and cement, dimension of the largest aggregate, continuity of the grading range, etc.
- The speed in which the drying shrinkage takes place. This highly depends on the temperature and relative humidity of the ambient air, the thickness of the floor as well as any exchanges of humidity with the ground.

The method disclosed in European standard EN 1992-1-1[i] (Eurocode 2) permits determination of the order of magnitude of the drying shrinkage to be allowed for and assessment of the resulting tensile stresses in the concrete (see also [ii]). In certain cases, these stresses can be greater than those caused by the load planned for the floor. The tensile stresses developed in the concrete can cause the appearance of shrinkage cracks according to the strength of the concrete at this time.

Carrying out appropriate curing, as soon as the state of the concrete surface allows, can delay and reduce drying shrinkage. The concrete then has more time to develop its strength and this enables the production of the required shrinkage joints.

Correct dimensioning and placing of the reinforcements or the addition of fibres at the correct dosage can enable the drying cracks to be distributed and thus the width of the cracking to be limited. Generally, the percentage of reinforcement required for this purpose is around 0.3 to 0.4% of the concrete cross-section in order to limit the shrinkage. This percentage is about 0.6% of the concrete cross-section when it is in order to limit the amount of joints to the very strict minimum [iii].

A concrete floor usually dries faster at the surface than in its depth (differential shrinkage), which can cause cracking at the concrete surface. If this drying is slow, it causes the appearance of a little disturbing network of microcracks with relatively tight mesh (crazing, see Figure 5-4).

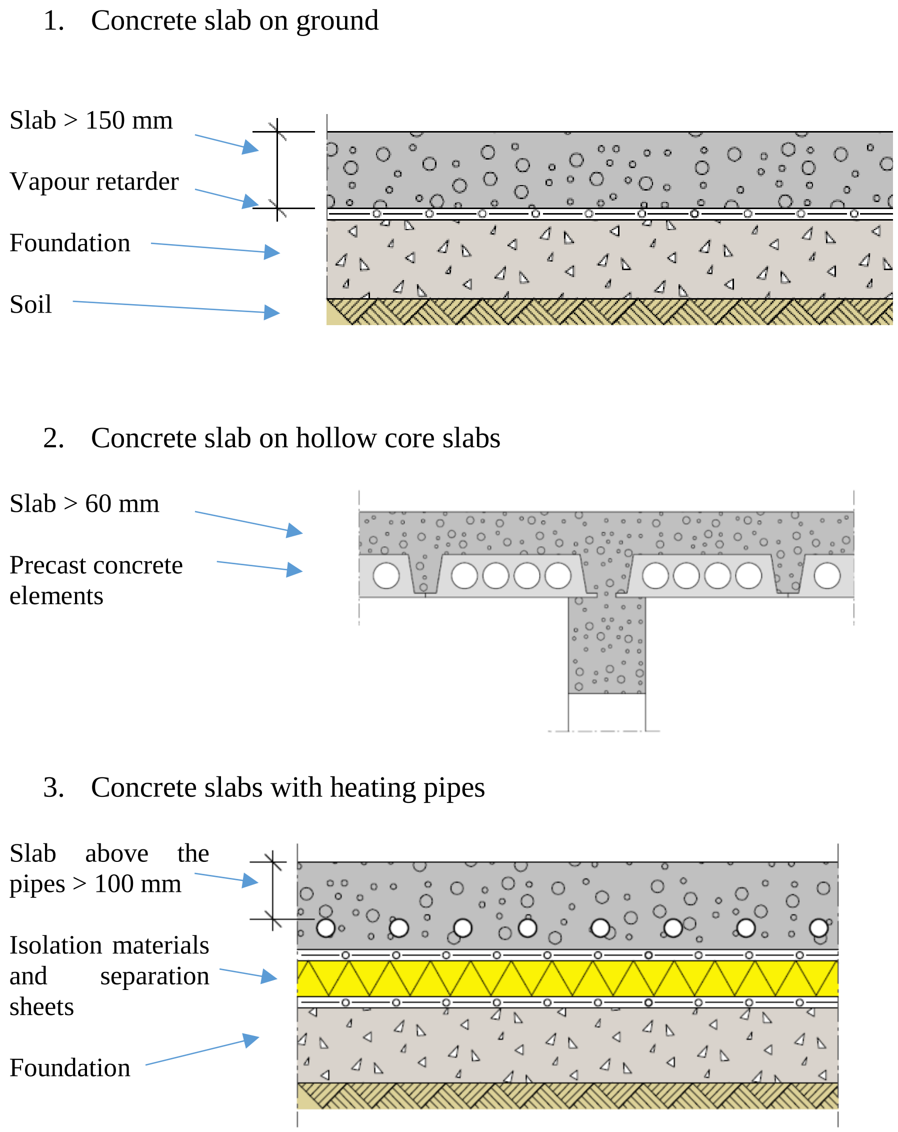


Figure 5-3: Some examples of configurations of concrete floors.

However, rapid drying usually leads to large cracks with a wide mesh (30 cm and more). Furthermore, curling can arise at the periphery of the slab, leading to a risk of additional cracking (
Figure 5-5). It is mainly on thin non-adhering floors (thickness < 150 mm) produced on the support (for example on a separation layer) that this forms an attention point. Slab floors with thickness less 60 mm are to be avoided

(see Figure 5-3). If there heating pipes in the floor, the thickness of the floor above these pipes should not be less than 100mm.
In some countries as in France, the minimum thickness of an industrial concrete floor has to be 150mm[iv].

The possible segregation of the concrete also contributes to differential shrinkage. By using a stable concrete mixture (continuous grading, no segregation, limited bleeding), the risk of differential shrinkage diminishes.

Figure 5-4: *Microcracks (crazing) at the concrete surface due to differential shrinkage*.

Figure 5-5: Practical example of curling.

5.1.2 *Thermal deformation*

Concrete's thermal expansion coefficient (α) varies between 7.10^{-6} and 14.10^{-6} [1/°C] according to the type of aggregate used. Thus, concrete based on calcareous aggregates has a lower expansion coefficient than concrete based on quartz gravel or crushed porphyry, for example. Apart from this measurement, there are few technical means for limiting thermal deformation.

Variations of the concrete temperature (and thus also the ambient temperature) lead to expansion and shrinkage of the floor. If these thermal deformations are not under control, they can create stresses in the slab liable to lead to deformations and cracking.

It is therefore recommended to limit fluctuations of temperature in the premises to 15°C by possibly taking measures for adapted thermal insulation. If this is not possible, for example in refrigeration rooms or in the presence of heat sources operating discontinuously like ovens, the required expansion joints should be planned.

If a concrete floor heats too quickly (for example in the case of steam cleaning a refrigeration room or putting underfloor heating into service), a thermal gradient appears in the concrete with the result that the floor risks lifting, cracking and flaking.

5.2 Joints

Apart from selecting the composition of the concrete and adequate reinforcement, joints contribute to limiting and controlling cracking.
With the correct choice and placing of joints, the stresses in the concrete floor can be limited and the deformation and cracking can be controlled. The plan for the joints should be decided by the engineering office responsible for conception of the concrete floor before starting its production.
There are three categories of joints that can be applied when producing interior concrete floors:

- Shrinkage joints
- Separation joints
- Structural joints

A fourth type, construction joints are not used to control deformation and cracking in concrete floors but to obtain clear and clean connections between the different concrete floor production phases.

Joints cause discontinuities in the floor. Passing wheels can lead to shocks (especially in the case of small diameter solid wheels), which can cause damage to the rolling stock and to the joint properly speaking (especially in the case of intensive traffic). Concentrated loading exerted near the joints can also cause weaknesses that further accentuate this phenomenon. Joints thus constitute weak points, which sometimes turn out to be worse than the cracks. It is therefore advised not to plan for more joints than those required.

5.2.1 Shrinkage joints

5.2.1.1 Principle

Shrinkage joints are required in concrete floors on earth platforms and on floating concrete floors that are not sufficiently reinforced (with standard reinforcements or steel fibres) to absorb the shrinkage stresses (design to Eurocode 2[i]). When producing shrinkage joints, locally weaker areas are created, where the concrete floor is more inclined to crack during the shrinkage, which helps to prevent erratic cracking on the floor surface (Figure 5-6).

Figure 5-6: The crack under the sawn shrinkage joint shows the joint's mobility.

In concrete floors adhering to structural floors (for example slab), shrinkage joints are superfluous and in some cases damaging given that they can lead to losses of adhesion and to curling of the concrete floor. Shrinkage reinforcements in these cases are required to take the stresses related to the shrinkage and to limit the width of the cracks.

5.2.1.2 Execution

One day after pouring the concrete floor (a little earlier in hot weather, a little later in cold weather), saw cuts of 3 to 5 mm wide are made with a depth of around 1/4 to 1/3 of the thickness of the floor according to the previously decided joint plan. Any top reinforcement is also sawn while absolutely avoiding any heating pipes (in the case of underfloor heating).
Vertical movements of the shrinkage joints and curling are prevented for the presence of the bottom reinforcement layer. If there is no such reinforcement or its presence is insufficient, a mesh of reinforcement can be inserted locally, or a dowel bar provided (see Figure 5-8) where the shrinkage joints are sawn (Figure 5-7). Dowel bars are comprised of smooth bars half plasticized or enveloped that are poured in the two floor parts. When the two floor parts move one in relation to the other, the dowel bar permit free sliding horizontally in the concrete or the sheath whereas vertical movement is prevented. Their efficiency depends on correct dimensioning and correct placing, that is quite parallel to the floor's direction of movement. This is why they are held in place by means of adequate supports.

Additional reinforcement or dowel bars can be required, for example, for:
- Floors with strict flatness requirement,
- Floor areas with very intense forklift circulation,
- Floors on ground with low mechanical strength,
- Heated floors.

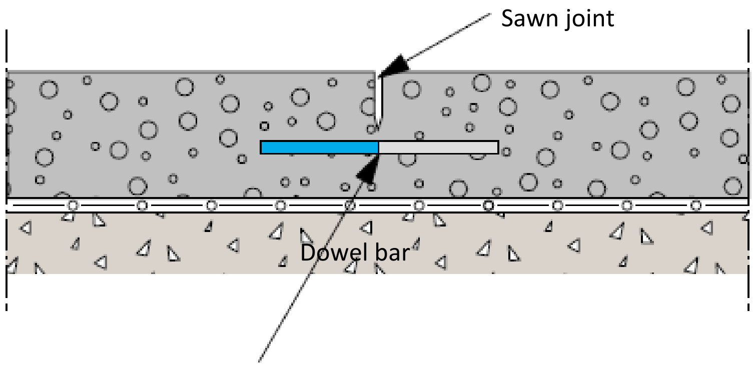


Figure 5-7: Dowel bar under sawn shrinkage joint.

Figure 5-8: Dowel bar, half plasticized.

If the floor is intended for intense traffic with forklifts it may be necessary to produce shrinkage joints according to their location like structural joints by making use of specific profiles to prevent damage at the joints.

In the case of a perpendicular connection of a shrinkage joint against a wall, the saw line can not be totally against the wall (see Figure 5-9). The shrinkage joints may possibly be passed on with a smaller rotary saw, but cracking in the extension of the joint to the wall can not be avoided.

Figure 5-9: Cracking in the extension of the sawn shrinkage joint to the wall.

5.2.2 *Separation joints*

5.2.2.1 Production

Separately from the selected production of the concrete floor, separation joints (or isolation joints) are to be planned along the bearing elements of a construction (walls and columns), along elements with their own foundation (for example heavy machinery) and along drains, gutters, etc. The joints completely isolate the floor from these elements, so that they can distort separately (e.g. through expansion, loading or differential settling) without damaging either (Figure 5-10 & Figure 5-11).

5.2.2.2 Production

Before pouring the concrete, compressible materials (for example, compressible foam) are laid.

The width of these joints is defined by the design office given the planned movements. It is usually around 5 to 10 mm.

It is usually impossible to provide these joints with dowel bars.

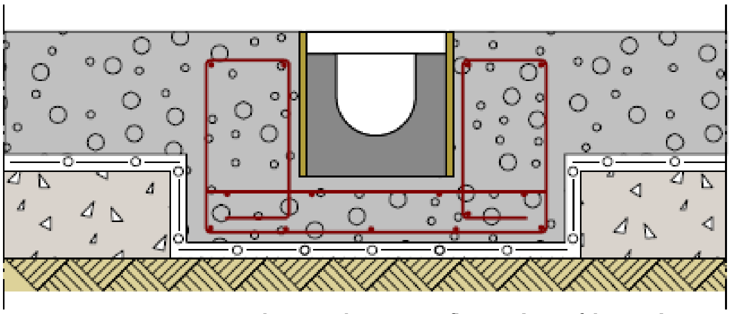


Figure 5-10: Separation joint between the concrete floor and a prefabricated gutter.

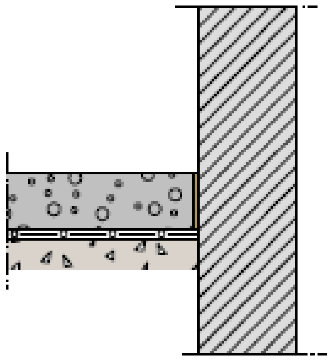


Figure 5-11: *Separation joint against a wall.*

5.2.3 Structural joints

5.2.3.1 Principle

Structural joints cut the concrete floor vertically into several parts separate one from the other and are intended to:

- Take the differential settling of the infrastructure or the ground between two parts of the floor: settling joints
- Take thermal movements (expansion joints)
- Replace shrinkage joints at places where heavy traffic with forklifts or high concentrated loads are expected.

With adherent concrete floors produced on structural floors (e.g. slabs), structural joints present in the infrastructure of the concrete floor must be repeated in the concrete floor.

With concrete floors on grade, settlement joints are planned for where differential settling of the infrastructure is expected (excavation or backfill). In the case of large floor areas, expansion joints must be planned. A flat foundation and good behaviour of the separation layer in this case are very important.

5.2.3.2 Production

Structural joints are produced according to a previously defined plan by inserting steel profiles (Figure 5-12) planned with or without compressible material. The type and dimensions of the joint profiles are selected according to the planned loading and expected deformation.

If respective vertical movements of each of the two floor portions have to be prevented (e.g. in the case of industrial applications), specific profiles (Figure 5-12 and Figure 5-13) can be placed. Before pouring the concrete, the profiles are height adjusted.

According to the set requirements, waterproofing is planned for in structural joints or the joints are finished with a covering plate or suitable mastic.

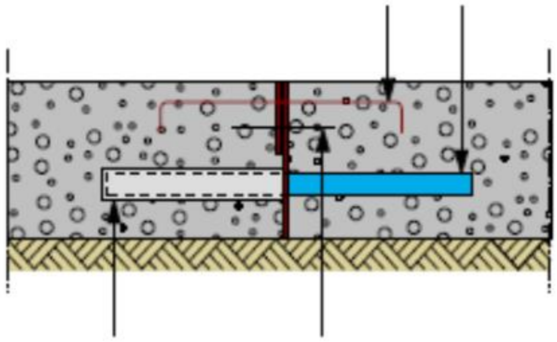


Figure 5-12: Steel joint strips with dowel bars.

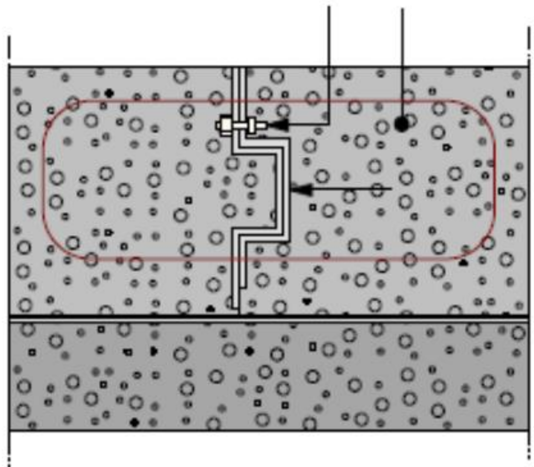


Figure 5-13: Double steel profile with "groove and tongue".

Figure 5-14:Profilé spécifique en acier de surface ondulée.

5.2.4 Construction joints

Concreting continuations appear by momentary interruptions of concrete floor production (at end of day or between two implementation phases, for example). When the work continues, pouring starts against an already hardened part of the concrete floor. If this is taken into account in the phasing of the work, it is possible to make these construction joints coincide.

5.2.5 Joint plan

The joint plan depends on the building, the shape and dimensions of the floor and the structure of the building (e.g. layout of columns, possible presence of structural joints). If severe stresses are planned for, it is desirable to have an installation plan of the machines, shelving, circulation corridors, etc., in order to prepare a joint plan that is as rational as possible.

If shrinkage joints are planned for, the maximum distance between these joints depends on the friction with the support (according to the presence or not of a single or double separation layer) and the composition and thickness of the floor slab. The general rule is "The thicker the floor slab, the greater the distance between the joints. A distance between joints[v] [vivii] at maximum 30 times the slab thickness is recommended, with a maximum of 6 m. For floor slabs 15 cm thick, this means that the distance between joints is at maximum 4.5 m, while for a thinner floor slab 10 cm thick, it means 3.0 m. In Belgium, the rule differs slightly: A distance between joints at maximum 50 times the slab thickness is recommended, with a maximum of 7 m

It is possible to have distance between joints bigger[viii][ix]. With shrinkage compensating concrete (see 5.4), the joint spacing of slab floor of 15 cm could be 30 m. With steel fibres, the joint spacing could be 25 m.

When preparing the joint plan, care is taken (see Figure 5-16) to:

- If possible divide the floor into square shaped panels or into panels whose length/width ratio does not exceed 1.5.
- Prevent inward angles, for example by columns (Figure 5-15).
- Prevent offsetting of the joints (layout with continuous joints).
- Prevent shrinkage joints near concentrated loading (shelving uprights, for example), in order to prevent weaknesses due to differential settling of the ground. Should this be impossible, for example specific structural joints or dowel bars under the shrinkage joint can be applied. The use of special profiles or dowel bars is also recommended for concentrated loads ≥ 60 kN on joints.
- Prevent shrinkage joints at places where vehicle traffic with forklifts is intense, like for example in circulation corridors between shelving. The use of structural joints or dowel bars can be necessary locally.

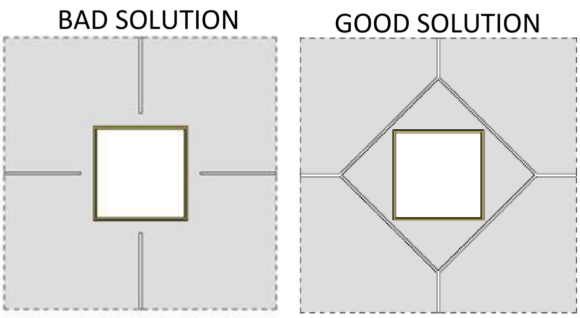
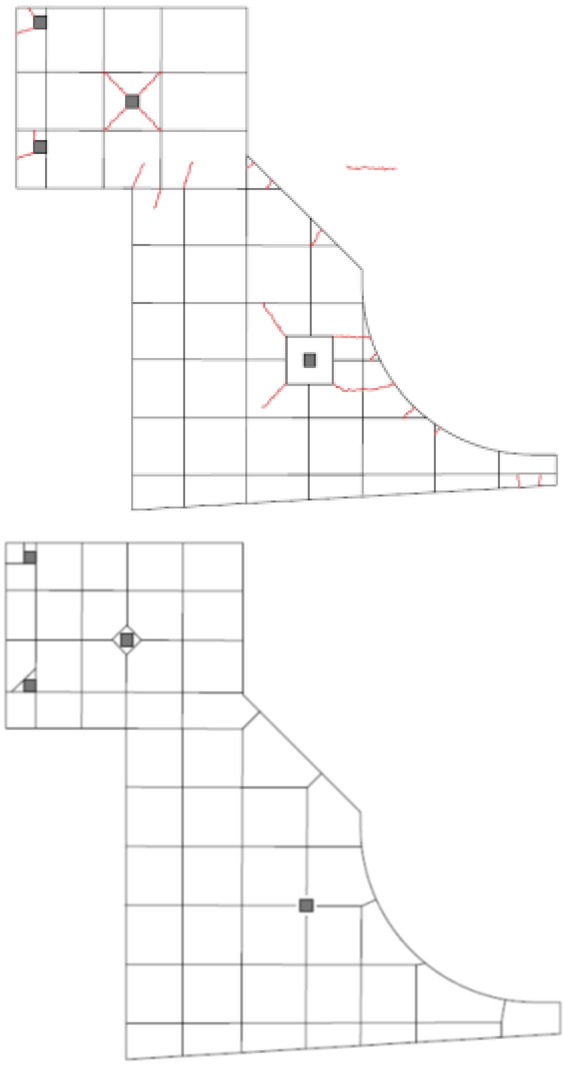


Figure 5-15: Separation joints and shrinkage joints and fractioning joints near columns (based on [x]).



NO

YES

Figure 5-16: Attention points when preparing the joint plan in a concrete floor.

5.3 Deterioration around joints

Deterioration around joints can occur. These disorders can be attributed to various factors, like for example:

- Insufficient compacting of the concrete by the joints, because of the presence of profiles.
- Too rapid drying of the concrete, which can cause the appearance of shrinkage cracks before implementing the shrinkage joints.

- The absence of dowel bars by the shrinkage joints on floors stressed by intense and/or heavy traffic leading to vertical movements at the edges of the joints.
- The perpendicular connection of a shrinkage joint against a wall, preventing the saw cut to continuing fully to make contact with the wall. The shrinkage joints can be continued further using a smaller angle grinder.
- Small aggregates ripped by the joint edge when making the saw cuts.
- The passing of small solid wheels and heavy loads on the concrete joint edges.

5.4 Influence of the concrete composition on shrinkage

The amount of shrinkage depends on many factors. [xi]

The higher the water/cement ration is, the larger shrinkage is, because the latter determines the amount of evaporable water in the cement paste and the rate at which water can move towards the surface of the concrete slab. The shrinkage of hydrated cement paste is directly proportional to the water/cement ratio between the values of about 0.3 and 0.6. At higher water/cement ratios, the additional water is removed upon drying without resulting in shrinkage.

Aggregates restrains the amount of shrinkage which can be realised. When the aggregate/cement ratio increases, the shrinkage is reduced. The elastic properties of aggregate determine the degree of restraint offered. For example, steel aggregate determine the degree of restraint offered. For example, steel aggregate leads one third less to shrinkage than ordinary aggregate.

More water is needed for the workability when fine aggregates are used.

More fine aggregates lead to an increase of shrinkage.

Including either fly ash or ground granulated blastfurnace slag in the concrete mix increases shrinkage. Silica fume increases the long term shrinkage.

Shrinkage compensating concrete has also been developed. Such concrete contains cement which, on hydration, can counteract the deformation induced by shrinkage. Concrete containing such an expansive cement expands in the first few days of its life. A form of prestress is obtained by restraining this expansion with steel reinforcement: steel is put in tension and concrete in compression. Restraint by external means is also possible. The use of expansive cement does not prevent the development of shrinkage. What happens is that the restrained early expansion balances approximately the subsequent normal shrinkage. To take advantage of the expansion, enough steel reinforcement is used in the top half of the stab to resist the expansion and to prestress the concrete to a low level.

Shrinkage reducing admixture should influence also the shrinkage. This quite new admixture works by reducing the surface stresses of the water present in the capillary pores. This process reduces the intensity of the forces which act upon the walls of the pores, and allows better dimensional stability and, therefore, a reduction in cracks caused by this phenomenon.

5.5 The presence of a vapour retarder and the influence of the floor depth

In the case of concrete on grade, the top surface dries and shrinks much faster than the bottom surface. Thin slabs will curve generally more than thicker slabs.
When the concrete floor will be covered by a coating, it is necessary to place a vapour barrier. But there is no common advice on the influence of a vapour barrier on shrinkage. In some countries, their use is advised for the concrete hydratation because an important amount of the water of the concrete slab is lost through the grade. In some other countries as in Argentina[viii] and in the ACI 302 recommendation[xii], curling and plastic shrinkage are considered to be more important with vapour barriers and they should thus be avoided if possible.

[i] EN 1992-1-1, Eurocode 2: Design of concrete structures - Part 1-1 : General rules and rules for buildings, 2004 + AC 2010

[ii] "De verhinderde betonkrimp - Voorspelling volgens de Eurocode 2 en beheersing met uitvoeringstechnieken" WTCB-Dossiers/Dossiers CSTC – Nr. 2/2009 – Katern nr. 3, 2009.

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[v] Seidler P., Rilem report 33, industrial floors, 2006.

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[vii] "Concrete industrial ground floors – A guide to design and construction" Concrete Society Technical Report No. 34, 2003

[viii] Pombo J.R., Experience in Argentina, TC Rilem Surface Delamination of concrete floor, 21 may 2014

[ix] ACI 360R-92, Design of Slabs on Grade, 1997

[x] Practioners Guide – Slabs on Ground, Chapter 6 Jointing, ACI, 1998

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[xii] ACI 302.1R-09, Guide for Concrete Floor and Slab Construction, ACI Committee 302, Practioner's Guide, Slabs on Ground, ACI International, Farmington Hills, 1998.