Cracking in Floor Slabs

by Terry J. Fricks

Industrial floor slabs have always had cracks. Frequently the cracks were acceptable, sometimes they were not. The difficulty is that frank discussions of the differences between acceptable and unacceptable cracking seldom occur before the floor slab has been placed. The owner's expectations (and the cost of meeting those expectations) are frequently not addressed until the floor slab is in place and it is too late to economically correct the cracking or to determine responsibility. It is vital that expectations and standards, responsibility, and remedy for cracking be established well before the first concrete arrives on the jobsite.

Crack standards

The standards for cracks in industrial floors are now being critically examined in much the same way as floor flatness standards were studied a few years ago. Owner awareness of the long term productivity gains achieved by flatter floors led the construction industry to respond with innovative techniques for more accurately measuring and producing flat floors. As design professionals began specifying and enforcing stringent floor flatness tolerances, some contractors developed the skills necessary to consistently provide concrete floors that met the design criteria. Owners realized that the flatter floors cost more initially, but understood that those costs were offset by productivity gains. Design professionals could accurately express how flat the floor needed to be, easily determine whether or not it had been achieved, and stipulate (in advance) the necessary remedy for substandard performance. Contractors knew that the stringent standards would be rigidly enforced, but they also knew that the measurement techniques employed would virtually eliminate ambiguity regarding what constituted "meeting the specifications." Improved specifications reduced misunderstandings, disappointment, and litigation.

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Standards for cracks will be much more difficult to enforce unless they are very carefully crafted. The reason is that while floor flatness is almost totally under the control of the concrete finisher, cracks can be significantly affected by:

- The slab and building design produced by the architect and engineer,
- The mix design as specified by the engineer and provided by the concrete supplier,
- The sub-slab conditions that were researched by a testing laboratory, accommodated by the architect and engineer into the design, soils prepared to design criteria by a site preparation contractor, and the preparation work verified by a soils engineer,
- The efforts of the industrial flooring contractor who placed the reinforcement and concrete according to design specification.

Clearly, many people have an opportunity to affect the occurrence and prevention of cracks in floor slabs. Effective standards enforcement requires that responsibility and control be properly matched.

Most objections to cracks are not based on the actual effect of cracks on floor slab or facility performance. Most objections, in fact, are aesthetic.

There are essentially two types of cracks: structural and shrinkage. They differ in:

- Their causes,
- Their significance to a building owner,
- Whose responsibility they may be.

The other dimension useful in describing cracks is width. Some cracks are so narrow as to actually defy measurement outside of a laboratory, while others are wide enough to disturb material handling and production operations. It is critical that owners and designers be equipped with specification language that clearly informs all involved parties of the owner's expectations, methods of measurement and evaluation, and systems for defect remedy and assignment of responsibility.

While it is recognized that this article cannot fully discuss the topic of industrial floor slab cracks, much

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less resolve specification and responsibility issues, it may serve to clarify some of those concerns and encourage a productive dialogue between owners, design professionals, and contractors. At this time it does not appear that there exists a universally "right solution" for floor slab design, concrete mix design, or concrete placing and finishing technique that insures no floor slab cracking. It is more reasonable to recognize that the "Chinese menu" of previous attempts to solve floor slab cracking has reflected the very real differences in owner needs, environmental variables, and differences in available materials.

Too many owners believe that if construction specifications are written following the various agency guidelines (ACI, ASTM, PCA), they will receive a crack free floor. Unfortunately, the guidelines are written based on norms and assumptions that, while generally true, do not always apply perfectly to the specific case. This difference between owner expectations and jobsite reality dooms many projects before they start. A more profitable pursuit is to clearly define the problem and establish standards for describing and classifying cracks so that responsibility and remedy can be discussed and appraised.

Crack types and causes

As previously mentioned, there are two basic types of cracks: structural and shrinkage. It could be said that if point loading is less than the compressive strength of the concrete, virtually all structural cracks are the result of subgrade failure. This is because perfect subgrade would be fully compacted and have no hydrological effects (such as water intrusion or vacation causing soil heaving or collapse). Under such conditions, the concrete slab would serve essentially as a wear surface, keeping the stable subgrade from rutting or dusting. Industrial floor slabs therefore need to become structurally strong in order to offset inherent imperfections in the subgrade.

It stands to reason that the designer must either over-engineer the slab or fully understand the subgrade's strength's and weaknesses. Likewise, if subgrade testing and preparation has not been performed properly, the designer may under-engineer the floor slab through no fault of his own. If this happens, the loading from the concrete slab mass and spot floor loading from equipment and storage racks can cause structural failure of the slab and result in structural cracks in the floor slab. Structural cracking creates concern because the sub-slab conditions that caused the failure are typically not fully understood when the cracks occur (or they would have been taken into account in the design) and it is extremely possible that existing cracks will worsen and new cracks will occur as the sub-slab processes continue.

Since most structural cracks originate from sub-slab conditions, cracks appearing on the surface are likely to eventually penetrate through the slab. If the crack results from sub-slab pressure, the crack will be wider on the surface than the bottom, while cracks caused by a sub-slab void will be widest at the bottom. Repeated and/or continuous loading on this area is likely to result in further deterioration of slab integrity unless successful remedial work is performed.

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Shrinkage cracking occurs due to the normal volumetric changes associated with drying. Since less initial water in the concrete mix means that less drying is necessary, if all other factors are equal, the wetter mix will result in more shrinkage and produce more crack area. Since normal concrete can only be stretched about 0.002 inches per foot without rupturing, and normal shrinkage is about 0.006 inches per foot (± 25 percent), cracking is virtually inevitable.

The difference between the elasticity and shrinkage of the concrete determines the amount of crack area that must appear. The design of the floor slab determines where the cracks will occur and how wide they will be. Reinforcement serves to restrain the shrinkage, effectively subdividing the slab and hence distributing the crack area more evenly. This produces smaller and more numerous cracks than would occur in an unreinforced slab of the same dimensions. The actual crack area remains essentially the same. Saw-cuts create a weakened plane, relieving tension and providing an "engineered crack." The further the saw-cuts are from each other, the greater the probability that unplanned cracking will occur between them. Saw-cuts "open up" to the extent that they are successful in relieving the tension in the concrete and concentrating the crack area along the saw-cut line.

Since the shrinkage cracks are caused by the drying process, they (unlike structural cracks) will be evident soon after the floor slab hardens and will not increase in length, width, or number after the drying process is completed. An exception would be when a structural crack follows the weakened plane of the shrinkage crack. A rule of thumb for projecting drying (and the associated cracking) is that about 30 percent of the drying typically occurs in the first 30 days, 60 percent in the first six months, and 90 percent in the first year.

Objections to cracks

Many times an owner is less concerned with the cracks themselves than with what the cracks may indicate. Since it may sometimes be difficult to determine the cause of cracks, any crack may lead one to worry that structural problems exist that will continue to worsen as time goes on. Another concern is that the cracks may expose reinforcing steel to corrosive elements. This concern may arise, for example, in areas using highway salt if trucks are driving into the facility. There are several perspectives to this issue, but one that cannot be ignored is the fact that conventional concrete is not water impermeable, and that cracks can only accelerate a process that will occur anyway if other preventative steps are not taken. In a similar vein, under the right conditions cracks that absorb water could damage the floor slab if exposed to sufficient cold. The freeze-thaw cycle can be destructive, but most floor slabs do not experience sufficient temperature variation to cause much problem from freezing water.

Cracks are areas that may harbor dirt and bacteria. While this is not a significant issue in most cases, food and pharmaceutical manufacturing and distribution facilities frequently demand extremely clean work environments. Cracks are very difficult to clean out and hence pose a sanitation problem. Shrinkage cracks are a much less significant problem since repairs can be done and the problem essentially forgotten. Structural cracks may continue to widen or new cracks appear, making maintenance considerably more difficult.

In much the same way as contemporary flatness standards permit owners to pay for (and receive) exactly the flatness that they want, owners need to determine (and be able to specify) the width and types of cracks that are acceptable and unacceptable.

Cracks are subject to spalling when exposed to traffic. This is true of both shrinkage and structural cracks. Spalling tends to occur more rapidly with wider cracks, because the effects of equipment wheels are more severe when they must "jump" a larger gap. Although the effect of crack width on spalling is affected by factors such as vehicle travel speed, wheel hardness, wheel diameter, and loading, a general rule of thumb is that under most traffic conditions, cracks that remain less than 0.015 inches wide are not susceptible to spalling. It is certainly worth noting that sawcuts are generally at least 0.1 inches wide, far wider and more prone to spalling than many of the cracks that the sawcut is designed to prevent.

In spite of the previous discussion of objections to cracks, with the possible exception of concerns about spalling, most objections are not based on the actual effect of cracks on floor slab or facility performance. Most objections, in fact, are aesthetic. The operational and financial implications of this fact are enormous. In an effort to reduce cracking, more sawcuts and construction joints are added, even though sawcuts in traffic patterns are likely to spall unless carefully maintained. Construction joints (not otherwise necessary) are an even more serious concern since their greater width makes them more spalling-prone and also opens up additional opportunities for load transfer problems to emerge.

Attempts to design "crack-free" floors raise the costs of floor slabs while directing attention away from the potentially more productive direction of producing floor slabs that are designed to have well distributed cracks that are all narrower than 0.015 inches. The concept of a crack free floor is similar to that of an absolutely flat floor — incredibly expensive to obtain and almost never necessary. The fact is, at some level of measurement, all concrete floor slabs have cracks. In much the same way as contemporary flatness standards permit owners to pay for (and receive) exactly the flatness that they want, owners need to determine (and be able to specify) the width and types of cracks that are acceptable and unacceptable. At that point everyone will be able to objectively evaluate the relative costs of floors with varying levels of acceptable cracking.

Crack prevention

Structural cracks are prevented by:
- Understanding sub-slab conditions and limitations,
- Understanding structural and operational stresses and loads,
- Designing a floor slab that accommodates sub-slab, structural, and operational constraints,
- Installing the floor slab according to specifications,
- Monitoring to insure that processes and materials meet specifications.

Quite simply, structural cracks are prevented by "doing it right." It takes time and money to obtain accurate information that lets a design professional understand sub-slab conditions. When evaluating a project's cost, several alternative approaches must be weighed. Extensive sub-slab testing can be costly in time as well as money. The owner and the design professional must decide how to trade the testing expenses against the risk of over-engineering the slab (and spending too much in construction), or under-engineering the slab (and experiencing a failure).

While it is technically possible to produce concrete floor slabs with no visible cracks, the cost/benefit tradeoffs of a crack free floor must be evaluated.

If the floor slab has been properly designed and specified, it only remains to verify that materials and labor perform as specified. Excellent materials and workmanship cannot make an inadequate design work any more than one can design around poor materials and shoddy workmanship. For a project to be successful it is critical that clear lines of responsibility and methods of performance evaluation be stipulated before the project beings. Responsibility in all cases must be placed on the entity that has the greatest ability to affect the outcome of each element of the project.

As previously mentioned, shrinkage cracks in a floor slab occur because the natural volumetric change that results from drying is about 0.006 inches per foot (± 25%) and the elasticity of the concrete is only

0.002 inches per foot. The difference between the shrinkage and elasticity is accounted for by crack area. The amount of cracking can therefore most easily be minimized by reducing shrinkage.

Since shrinkage occurs as the concrete volume changes during drying, the most obvious solution is to reduce the amount of water, thereby reducing the amount of drying that will take place. A certain amount of water is necessary for hydration, workability, and finishability, but any excessive water that is present for placing and finishing convenience will result in more shrinkage cracking than is absolutely necessary. If normal shrinkage ranges from 0.0045 to 0.0075 in. per foot and elasticity is 0.002 in. per foot, it is obvious that the amount of shrinkage cracking likely within the "normal" range of shrinkage spans from 0.0025 to 0.0055 in. per foot.

The specification and enforcement of acceptable crack standards is especially vital for those members of the design/construction team that strive to meet or exceed specifications.

When shrinkage cracking is important, it is clear that a skilled and experienced design and industrial floor contracting team can significantly reduce the incidence of cracking without needing to employ exotic mix designs or techniques. Shrinkage cracking is minimized by a number of mix design variables, including concrete temperature control, the use of more coarsely ground cement, and the largest sized coarse aggregate allowed. Coarse and fine aggregates should be clean and well graded.

Every effort should be made to limit the amount of water in the mix while maintaining workability and finishability without excessive use of water reducers. Much better shrinkage control results could be achieved by specifying a water-cement ratio and maximum allowable water content rather than slump.

Once the design has been decided upon, the architect/engineer needs to know the results of a shrinkage test of that exact mix design. Why should crack prevention measures be based on norms and assumptions when far more relevant test data is available? With fewer variables left to chance the design professional is better equipped to determine if sawcuts are necessary, and if required, where to place them.

Proper curing affects shrinkage cracking in several ways. Perhaps the most obvious is that the concrete has an opportunity to increase in tensile strength before significant shrinkage occurs. Another effect is the reduction of surface tension that otherwise builds up when the top of the slab dries (and shrinks) at a much greater rate than the bottom. This shrinkage difference creates enough stress to cause curling, and part of that tension is relieved by surface cracking. Since proper curing permits the top and bottom of the slab to dry at a more evenly matched rate, the resulting cracking is reduced.

Shrinkage compensating concrete can reduce cracking by causing the concrete slab to expand in an amount approximately equal to the drying shrinkage. This produces fewer shrinkage cracks than conventional concrete under comparable conditions. Comparable conditions is a key issue, since the more common application for shrinkage compensating concrete is to place larger joint-free areas than would normally be possible, anticipating no more shrinkage cracking than would be expected on a smaller placement using conventional concrete.

Crack repair

Hairline or very narrow cracks usually require no repair at all, while cracks that are subject to spalling must be repaired. Probably the best method is to fill the cracks with a high strength rigid epoxy. This method is most successful when the floor slab has completely dried (at least one year after placement). If drying is not complete, a semi-rigid epoxy must be used to accommodate future movement. This is accomplished by routing out the top portion of the crack and filling the routed area with semi rigid material.

Re-evaluation of crack standards

Because of the differences in such variables as ambient temperatures, humidity, aggregates, sand, and cement across the country it will never be possible to create a "standard" solution to problems in floor slab cracking. It is important, however, to differentiate between the various types of cracks and their significance to the owner. While it is technically possible to produce concrete floor slabs with no visible cracks, the cost/benefit tradeoffs of a crack free floor must be evaluated. Crack free floors would require:

- Very small construction joint spacings,
- Special curing processes,
- Longer construction times,
- Considerably higher construction costs,
- Higher maintenance costs (because of additional joints).

It is the responsibility of the design/construction team to accurately inform the owner of what cracking is anticipated as well as the time, financial, and maintenance costs associated with reducing cracks.

In light of the difficulties and costs associated with crack free floors, it would seem more productive at this time to concentrate attention and effort on:

- Establishing a standard nomenclature for describing cracks,
- Specifying and enforcing acceptable levels and types of floor slab cracking,
- Placing responsibility for crack prevention and remedy with those parties most able to prevent cracks,

• Determining acceptable remedy options for cracks that fail to meet specifications.

The specification and enforcement of acceptable crack standards is especially vital for those members of the design/construction team that strive to meet or exceed specifications. The honest competitive process is destroyed when standards are not enforced since the low bidder in such cases will inevitably be the firm that plans to deliver less than has been specified. Standards are most effective when rigidly enforced, and if lower performance is acceptable, lower standards should be stipulated.

Nomenclature recommendations

Crack width

Hairline crack	$\leqslant$ 0.004 in.
Very narrow crack	$\leqslant$ 0.015 in.
Narrow crack	$\leqslant$ 0.030 in.
All other cracks	actual width

For purposes of evaluating crack widths under field conditions, it may be helpful to note that a new dollar bill is 0.0043 in. thick, a national (Mastercard, Visa) credit card is 0.030 in. thick, and a dime is 0.053 in. thick.

Structural crack

Contract language should define how to identify and prove the type of crack and establish responsibility.

Shrinkage crack

Contract language should define how to identify and prove the type of crack and establish responsibility.

Crack area

Total crack length multiplied by the average width of the crack. This area may be subdivided into hairline crack area, very narrow crack area, etc. Since measurement of the crack area for the entire floor is probably practical at this time, a system for determining how to evaluate the floor based on sampling may be specified at the project's onset.

Contract language

Many construction contracts succeed in assigning responsibility to entitities that have little control over outcomes. An example might be:

"the Industrial Flooring Contractor shall examine the subgrade, and notify general contractor in writing of *unsatisfactory conditions.* The work shall not proceed until unsatisfactory conditions have been corrected. Commencement of work *implies acceptance of the subgrade* by the Industrial Flooring Contractor. . . ."

As a result, the industrial flooring contractor is in the position of making the final decision as to whether the sub-slab conditions are adequate. This is in spite of the fact that the flooring contractor:

• Did not determine which tests should have been conducted on the sub-slab area,

• May not have seen the results of any tests that were run,

• Should not be expected to have the technical expertise to evaluate the test results in order to determine their appropriateness for the particular design being constructed,

• May believe that the subgrade is inadequate due to "field indicators" such as excessive concrete truck tire penetration. The industrial flooring contractor must either accept subgrade that experience suggests is inadequate or cost the owner significant amounts of unbudgeted time and money in subgrade improvement not dictated by conventional standards.

Clearly, steps must either be taken to re-empower the design professionals to assume responsibility for protecting owner's interests, or owners will need to assume more of that responsibility through the use of owner's representatives or outside consultants. In either case, authority and responsibility must be placed with those who have the most control over outcomes.

Conclusion

Cracks are a natural and expected characteristic of concrete slabs. It is the responsibility of all members of the design/construction team to accurately inform the owner of what cracking is anticipated as well as the time, financial, and maintenance costs associated with reducing cracks. Acceptable and unacceptable crack conditions must be clearly stated before the project begins and responsibility for crack prevention assigned to those parties best able to prevent the cracks. Remedy for unacceptable levels of cracking must also be clearly stated prior to project commencement and those standards should then be strictly enforced.

By setting reasonable crack performance standards in advance, many problems associated with cracks can be avoided.

Unnecessary reliance by architects/engineers on "norms" can be reduced by designing industrial floor slabs based on actual shrinkage test data. The shrinkage test reliability is best when performed using the actual mix design that has been specified for the project and having that design tested under conditions corresponding as closely as possible to those anticipated on the jobsite. The concrete should be mix designed to minimize the water-cement ratio and total water content without excessive reliance on water reducers, while still maintaining acceptable workability and finishability.

By setting reasonable crack performance standards in advance, many problems associated with cracks can be avoided. Since not all cracks are actually problems in terms of facility performance, reasonable crack standards can save owners a significant amount of money and reduce risks for all members of the design/construction team. Not properly establishing owner expectations can lead one to believe (when cracks develop) that the slab has failed when it has in fact performed as would reasonably be expected.

Selected for reader interest by the editors.

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