environment is very large in comparison with the volume of concrete. The internal moisture variation depends on the conditions of the interface with the supporting base and the humidity/temperature of the air in contact with the slab surface. The shrinkage process will progress from the upper surface, while the lower surface can remain rather saturated at the early age of the concrete. The strain distribution curve progresses with time showing a maximum slope in an intermediate stage (Fig. 3).

The shrinkage distribution through the slab depth is a non linear function of the time that can be split up in three parts, respectively a constant part, a triangular linear distribution part and a self-compensated non-linear part (Fig. 4). The mean shrinkage strain ε' creates the contraction of the slab panels. A period of minimum 12 months is necessary to notice the stabilization of this movement, mainly due to the friction on the sub-base and the creep of the concrete in tension. The differential linear shrinkage ε'' induces a bending of the slab, when it is not counter-balanced with the self-weight of the slab and the imposed load. When edges and corners are not sufficiently supported, they can lift, up to an excess of an inch, a phenomenon called "curling" or "warping" (Fig. 5).

The rocking movement of the unsupported edges and corners is the cause of most damages in concrete floors when they are subjected to traffic (Fig. 6). The influence of the self-compensated strain "ε" does not cause any major visible effect within the slab.

Technical solution to shrinkage

As discussed above, shrinkage can not be avoided completely, but its effects can be minimized by the use of a specific concrete mix design, or by reducing or controlling the stresses induced by restrained friction. It is crucial to improve the support of all edges and corners, by means of correct load transfer systems.

Reducing concrete shrinkage can be achieved with shrinkage-compensating agents or swelling materials. The chemical reaction mostly affects the critical early-age strain of the cement paste, and relies on the concrete strength to resist the long term drying shrinkage. Some other research leads to the development of shrinkage-reducing admixtures by changing the surface tension of the liquids towards the surface of concrete capillaries.

Post-tensioning of concrete slabs has been widely used to compress the concrete slab and reduce the tensile stress created by the friction-restrained movements.

Another approach has been widely used in road construction by ensuring a continuous reinforcement of the concrete with a high quantity of conventional steel bars. Crack control design requires a minimum steel section of 0.5% of the concrete section, i.e., approximately 130 lb/yd^3 (77 kg/m^3) for a two-way reinforcing effect. Crack spacing and opening can be optimized with a smaller bar size and smaller spacing.

The alternative discussed in this paper is brought by the SFRC composite and its homogeneous micro-reinforcement. A dense network of 3D-orientated fibers is able to create some micro-cracking tension release. High quantities of long fibers are requested to give a bridging effect of the cracks. Post-cracking toughness of the fiber reinforcement will have to keep the structural capacity of the slab under imposed loads with sufficient safety factors.

The key-aspect of SFRC material in large applications on site is obviously the quality control in order to ensure the even-mixing of the fibers in the concrete at very high dosages.

Cold-drawn metallic fibers have been extensively used in that field since the 1980s. The tensile strength of the steel can be increased up to more than 150 ksi (1,034 MPa) by the production process, and the shape can be optimized to improve the anchorage of the steel wire to the cement paste. In order to keep a practical dosage of typically 59 to 75 lb/yd^3 (35 to 45 kg/m^3), the aspect ratio of the fiber must be correctly chosen to optimize the number of fibers per volume.

USE OF STEEL FIBER AT HIGH DOSAGE

Fiber type and dosage

As discussed above, the toughness of SFRC is directly linked with the type of fiber used. Basically, to correctly bridge any crack induced in the cement paste, tensile stresses must be transferred to the reinforcing wires which need sufficient strength and stiffness.

The type of fiber considered in this paper is a cold drawn wire with a crimped shape and an aspect ratio of 50 to 60 (Fig. 7) During the process of cold drawing from raw machine wire down to a diameter of 0.039 in. (1 mm), the tensile strength of the steel is increased up to a minimum of 150 to 210 ksi (1034 to 1448 MPa).

The wire is deformed by continuous undulations with amplitude of 3/8 in. (10 mm) and wave depth of 0.026 in. (0.65mm), as described in the U.S. Patent 4,585,487 [7] with foreign priority date Dec 30, 1983. The anchorage is relying on the material stiffness and on its plastic deformation in bending in both directions within the concrete matrix. Bonding of steel to the cement matrix is not the major anchorage factor, and it is unlikely to see fibers breaking even for very large deformation as simulated in laboratory testing.

In order to optimize the reinforcing effect of fibers, one should increase the density of fibers, with sufficient anchorage length. As the theoretical distance between fibers decreases with increasing dosage, there is a limit to the number of fibers that can be evenly mixed in function of the aggregate size. Romualdi and Mandel [6] proposed the calculation of this distance (Eq. (1)).

$$s = 158 \frac{d}{\sqrt{V_f}} \tag{1}$$

where s, d and V_f are respectively the distance between fibers (in inch), the diameter of the wire (in inches) and the fiber concentration (in lb/yd^3).

Consequently, there is a balance to find between the fiber dosage and the concrete mix design, especially in terms of maximum aggregate size and cement paste as the shrinkage is a critical figure. Typical dosages of 59 to 75 lb/yd^3 (35 to 45 kg/m^3) have been widely used over a period of 20 years, with minor changes to the current concrete recipes. Higher dosage can be proposed with other kind of fibers with larger diameter for example.

Fiber distribution

Although the toughness depends on the fiber type and the dosage rate, it is evident that this is conditioned by the correct distribution of fibers in the concrete. The continuous aspect of any composite material requires a three-dimensional dispersion of the reinforcing component, in order to guarantee the same behavior in every direction with an even probability on the number of fibers crossing in a random section of the concrete structure.

The mixing becomes very delicate with high dosage of long fibers, to avoid the formation of “dry balls” (groups of imbricated fibers in which cement paste can not enter) or “wet balls” (bonding of a group of fibers with fine cement paste without aggregates during mixing). Once the correct dispersion has been reached, there is always a risk of segregation during transportation of the fresh concrete.

For short fibers at low dosage, the method of dropping the fiber box content directly into the hopper of the concrete truck can be used successfully, with a preference to mix the fibers with dry concrete before adding cement and water. For long fibers at high dosage, it is necessary to separate the fibers before adding to the concrete, which can be done on site with specifically designed pneumatic blasting machines (Fig. 8). This technique has different advantages: the control of concrete quality and workability before mixing the fibers, the speed of blowing the fibers all over the surface of the fresh concrete in the drum, and the ability of working on site with limited transport risks.

Another technique is to add some collated fibers that spread through the fresh concrete and separate with the force of mixing.

Specific SFRC mix designs

In addition to the maximum aggregate size as mentioned before, the concrete mixture must be specifically designed for steel fibers and for the application in industrial floors. To avoid balling of fibers, it is essential to respect a continuous grading curve of all aggregates. This basic requirement of the mix design is more important when high dosage of long fiber elements have to be mixed in a combination of spherical shapes. This is the reason why SFRC quality is usually improved in comparison to most common mixes.

The content of finer raw materials in the concrete mixture has to be correctly balanced in order to give a good anchoring paste to the fibers, to allow the correct finish-ability of the concrete and to avoid unnecessary water causing extra shrinkage.

Before mixing the fibers, the concrete must reach sufficient workability, which requires the use of a water reducing admixture to keep the effective water-cement ratio in an acceptable range of 0.48 to 0.55.

An example of acceptable concrete mix design is given in the case study of Interbake Foods in Front Royal VA at the end of this paper.

The environment and placement conditions are other very important issues, as concrete needs to harden evenly without cold joints and to allow the correct finishing operation of the slab surface. Mainly cement choice and quantity must be adjusted with the conditions of external temperature while controlling the aggregates.

Behavior of SFRC

With the random volume distribution of fibers and their narrow spacing, any possible cracking mode can be controlled. At the difference of conventional reinforcement, there is no unreinforced paste to cover the steel bars. Also, some stresses like punching shear will loose their critical aspect.

The post cracking ductility is commonly assessed on small beam test as specified in ASTM C1018 [3] or any equivalent standard. This type of test only simulates the flexural mode of rupture on small prismatic specimen, while we know that the design of concrete slab is much more complex.

If we consider the SFRC behavior more specifically towards the application in industrial floors that are mainly subjected to static point loads and traffic loads, we can summarize the advantages of using fibers as follows:

Flexural toughness—Flexural toughness tests on beams and slabs show that SFRC is able to hold considerable loads up to very large deflections. The toughness or ductility indexes give the ratio between effective dissipated energy and theoretical energy of a perfectly elasto-plastic material. The aim of using high dosage of steel fibers is to create a plastic or hardening effect of this post-cracking behavior. Typical beam tests are not very representative, due to the dispersion of the results, the size of the samples and the influence of the testing equipment stiffness, but they can be easily interpreted as the whole bending moment is concentrated in a single flexural crack. Circular plates as specified in ASTM C1550 [4] or even larger slabs are not easy to handle, but they lead to a better understanding of the real mode of failure of a concrete slab. The interpretation following the yield line theory gives the importance of the ductility in all cracks, without information on the complete stress-strain curve.

Shear—The shear rupture is very brittle in plain concrete or lightly reinforced structures, similarly to the tensile rupture of the concrete. Steel fibers do have the same occurrence in a shear crack than in a bending crack, leading to a similar ductile comportment in both modes of rupture. High dosage of fibers can increase the shear capacity by 50% and more [14].

Impact and fatigue—Despite the difficulty to evaluate these properties in laboratory, the performance of SFRC is known to be considerably improved under dynamic and cyclic loading. Effectively, the continuous micro-reinforcement of the composite will dissipate high level of energy under impact, and the material toughness will allow important deformations without failure.

Shrinkage—Real scale tests have shown that the amount of shrinkage can decrease of 10-15% with high dosage of steel fibers. However, the main effect of the fibers will be to release the shrinkage-induced tensile stresses. Considering the small fiber spacing, the tension crack release will lead to a narrow grid of micro-cracks that are not detrimental to the use of the floor and are hardly noticeable.

Design approach

A slab-on-grade is, by definition, directly supported by the sub-base material taken as an elastic continuous spring. Its role is to transfer the loads from the upper surface to its support, and to follow the deformations induced in the subgrade.

Under static concentrated loads, the stresses are caused by a combination of sagging moment and punching shear. Usually, this does not cause any problem in a floor, while the hogging moment in unloaded area could be more critical when subgrade conditions are not compatible with the forces applied.

Even though they have a lower value, the dynamic wheel loads from the material handling equipment can cause more problems, as they can move everywhere onto the slab surface, and specifically at the edges and corners created by joints in the floor, where differential shrinkage does lift the slab from its support.

Most design methods are conservatively based on an elastic approach of the materials and support. The concrete is considered un-cracked with an increased modulus of rupture. However, we know that, for many reasons, concrete can crack otherwise there would be no need for any reinforcement. Cracks are usually nonstructural and often appear due to poor detailing, at specific locations such as re-entrant corners, loading docks, pits, overhead doors etc. Taking the above into account, most floors can be considered as over-designed, except in a number of un-designed locations (such as re-entrant corners, lifted edges) which can be found anywhere on the floor surface.

Therefore, other design approach based on the yield line theory [1] can be proposed at the condition that the material has elasto-plastic comportment, for example: it is effectively reinforced with high dosage of performing fibers. As per structural design of concrete, safety factors are effectively applied on loads and materials, giving a minimum overall safety factor of 1.8 to 2.25. Furthermore, this methodology considers the concrete as cracked with its effective post-cracking capacity.

In practice for a point load, the ultimate load is directly given from the slab properties (thickness, concrete class and ductility brought by the fibers) and the contact surface of the load.

$$P_u = 2\pi\left(M_p + M_n\right) \text{ when a/l=0} \tag{2}$$

$$P_u = 4\pi\left(M_p + M_n\right)/\left[1 - a/3l\right] \text{ when a/l=0.2} \tag{3}$$

where P_u is the ultimate load, M_p and M_n are the ultimate sagging and hogging bending moment of SFRC, a is the equivalent radius of the load and l is the elastic length (relative stiffness of the slab with regards to the spring support). The value of P_u is interpolated between both expressions (2) and (3) when a/l is lower than 0.2. The radius of the load is calculated for a single load or an equivalent value for multiple loads.

Similar expressions can be used to check for an edge or a corner loading condition.

With this design approach, it is likely that slab thickness will decrease in comparison with traditional plain or lightly reinforced concrete. Indeed, the design thickness can be optimized because of the elimination of typical weak point in slabs (unsupported corners and edges).

JOINTLESS SFRC SLABS-ON-GRADE

Historical background

Originally, steel fibers have been used at low dosage in industrial concrete slab-on-grade as a replacement to wire mesh, typically 33 to 42 lb/yd^3 (20 to 25 kg/m^3). With the improvement of the mixing procedure and a better knowledge of the concrete mix design, steel fibers have really shown their performance to reinforce the concrete slabs, especially with regard to crack control.

In a US Patent 4,640,648 [8] with foreign priority date of March 10, 1983, X. Destrée and A. Lazzari outline their invention of making joint-free steel fiber reinforced concrete floors of bay sizes up to 35,000 ft^2 (3250 m^2), with steel fiber dosage from 50 lb/yd^3 (30 kg/m^3) and higher.

Since then typical jointless panel areas of 15,000 to 25,000 ft^2 (1393 to 2322 m^2) have been regularly achieved, and today, the limit of joint spacing is usually imposed by the quantity of concrete that can be delivered and placed in the same day, and the opening of the construction joints that concentrate all the shrinkage movements.

To our knowledge, the oldest jointless SFRC slab was installed in Breda, The Netherlands in 1983, with a panel size of 25,000 ft^2 (2322 m^2) and still performing to client's satisfaction. One can estimate that nowadays more than 50 million ft^2 (4.6 million m^2) of jointless SFRC slabs are installed yearly worldwide.

Key Aspects

As outlined in Ref. 8-9, the process of building large jointless panels remains completely dependent of practical aspects covering fiber mixing, concrete quality control, base preparation, detailing, installation and site conditions.

Free to move—any restraint of the concrete shrinkage can create tensile stresses in excess of the concrete strength, and therefore lead to cracking. Restraints can be caused by sub-base irregularities and friction, all fixed obstructions and structural tie bars. Fine grading and controlled levelness of the sub-base are essential conditions for jointless slabs. A polythene slip membrane is recommended to smooth the support roughness and to avoid the bonding of the cement paste with sub-base materials.

Compressible foam must be placed around all fixed obstructions such as building columns, manholes, edge of doors, with a particular attention to cover the entire slab depth. Each area presenting some risk of cracking has to be isolated and reinforced with deformed reinforcing bar, or additional wire mesh. Tying of the slab should generally be avoided.

Construction joints—when eliminating all saw-cut joints, there will still be a requirement for construction or day joints that will therefore take more movement. Being the only trafficked joints, these construction/day joints need to have essential qualities, such as: being free to move horizontally in both directions with the lowest vertical differential movement, having steel arris protection, having excellent load transfer capacities. Their load transfer capacity is also very important to decrease the deflection and stresses caused by unsupported edge condition.

In comparison to traditional dowel systems which are not suitable for two-directional movements, some proprietary systems have been developed with key-shape or flat plate dowels [Fig. 9]. They usually allow for opening in the order of 1/3 to 2/3 in (8 to 16 mm).

Joint layout is defined in function of the daily productivity, keeping in mind the aspect ratio of panels to maximum 3 by 2, avoiding important re-entrant corners and isolating from large restraint areas such as loading docks.

Site quality control—quality control before and throughout the concrete pour is essential to the production of SFRC jointless slab. Before pouring the slab, sub-base level check, as well as accurate level check of all pre-fixed formworks (dock levelers, manholes, construction joint etc.) need to be carried out, as well as a thorough inspection of all site conditions (weather tightness, access, lights etc.). During the pour, the site quality controls specific to a jointless SFRC slab are mainly focused on the concrete mix design quality and consistency, and the uniform distribution of steel fibers.

Skilled labor and HT equipment—supervision is always required; however the training, experience and motivation of the labor force remain the keys to the correct installation of a jointless concrete floor. Specifically, the mixing of high dosage of long steel fibers requires a specialized operator to handle the fiber blast-machine (see fig.7) and check the concrete quality and consistency. When applicable, other high-tech equipment, such as the Laser Screed and Mechanical Spreader are ideal for achieving jointless SFRC slabs.

Site conditions—in accordance with good working practice, it is crucial that the casting and curing works are carried out within a controlled environment. This will require the roof sheeting and cladding works to all elevations (permanent or temporary) to be complete, together with temporary sheeting to openings to be in place prior to casting.

STRUCTURAL SFRC APPLICATIONS

Historical background

Extensive laboratory researches have demonstrated the different structural performances of the SFRC material with regard to bending, shear, impact, fatigue etc.

Knowing the success in the application for slabs-on-grade, it was natural to extend its use to a different kind of large two-dimensional applications with higher need for structural performance.

The first field was slabs supported on piles, aiming to increase the speed of production using the same industrial equipment to lay the floor, such as the Laser Screed and the Mechanical Spreader.

The initial experience is summarized by X. Destrée in 1995 [10] including a list of 800,000 ft^2 (74,000 m^2) SFRC suspended slabs on piles, without mesh or rebar. The latest ACI 544-3R, "Guide for Specifying, Proportioning, and Production of Fibers Reinforced Concrete" includes in 3.1-Typical uses of fiber reinforced concrete-steel fiber only reinforced concrete suspended slabs on piles having a span to depth ratio up to 20.

Based on a full scale trial and the first applications in Belgium and in The Netherlands in 1994, the system has proved its efficiency and was officially approved by the Dutch Authorities in 1999 with a proposed method of design (COB, Staalvezelbetonvloeren op palen, 1999 [5]). England has rapidly adopted the product for many new industrial units that are built on poor quality substrates. In Ref. 11 of the year 2000, X. Destrée outlines a design method based upon the yield lines of Johansen.

Other structural uses of the SFRC like raft foundations and elevated slabs [12], have been carried out for a large range of applications such as water treatment plants, condominium foundations, clad-rack foundations, parking and office floors.

Slabs on piles

The slab is supported on piles cast or driven into the ground, down to a sufficient bearing layer.

The concrete is cast directly onto the pile heads and the sub-base which will only act as a temporary working platform. The slab is designed to span between the piles that are ideally laid on a square grid.

The concrete is reinforced with a very high dosage of steel fibers, ranging from 67 to 100 lb/yd^3 (40 to 60 kg/m^3), and could be combined with conventional reinforcement between piles or above pile heads only.

In order to optimize the productivity, the preferred option will be to use steel fibers only, and work with automatic screeding equipments and without the need of a pump. In this case where the material is homogeneous, the high stress positions have to be designed with extra thickness, or by stress reduction system such as enlarged pile heads. Again, for practical and quality reasons, the preferred option will be a flat slab with well designed pile grid and pile heads (Fig. 10).

Raft foundations

The slab is still supported by the ground, but the importance of the structural loads or the lack of bearing capacity requires a design for a thick raft foundation. Commonly, the design is governed by the slab deformations and the punching shear under concentrated loads.

The concrete is usually reinforced with the minimal steel section for shrinkage control that can be completely replaced by the correct dosage of steel fibers. The particular case of water-tight structures may still require a combination with traditional reinforcement.

In very thick applications (more than 2-3 ft [610-914 mm] thick), the continuous reinforcing effect of the steel fibers is particularly helpful for controlling the thermal stresses caused by the exothermic reaction of the concrete.

Elevated floors

A European Patent application EP 1 544 181 A1 on Dec.16, 2003 by X. Destrée, outlines the application of "only steel fibre reinforced concrete free suspended elevated slabs" of span to depth ratio up to 35 with high dosage rates of 130 to 200 lb/yd^3 (77 to 120 kg/m^3). The invention is used in several European countries since 2005. X. Destrée outlines testing, design, specification and installation in Ref.13.

In similar application, and in order to decrease the formwork operation, the SFRC at minimum 50 lb/yd^3 (30 kg/m^3) dosage rate can be combined with steel decking systems, with a limited spanning capacity and a lower steel fiber dosage rate, but with a proved advantage for fire rating.

CASE STUDIES

Interbake Foods, Front Royal, VA

The building, a warehouse for packaged food products, is 722 ft long x 224 ft wide (220 m x 68 m). It is divided into ten jointless slab panels of 144 ft x 112 ft (44 m x 34 m) keeping an aspect ratio of 1.285 (aspect ratio Length/Width should not exceed 1.5) (Fig. 11). Each jointless panels are delimited by load transfer metallic joints, allowing horizontal movement in both directions with excellent arris protection thanks to the two 1/5 in. (5 mm) steel plates (Fig. 9). The dock levelers are isolated from the main slab, to allow the free movement, by using the same metallic joint installed 3 ft (914 mm) away from the docks.

Design—the SFRC slab has a thickness of 6 in. and is reinforced with 67 lb/yd^3 (40 kg/m^3) of steel fibers. The sub-base Westergaard modulus of reaction is specified with a minimum value of 100 pci (27 MPa/m). The slab is specified to sustain racking leg load of 8,000 lb (35 kN) on base plates of 8 in. x 8 in. (203 mm x 203 mm) in a back to back situation with a distance of 12 in. (305 mm), but can easily accommodate 12,000 lb (53 kN) in the same configuration.

Concrete Mix Design—a 4000 psi (28 MPa) mix was used based on type II cement with a blend of aggregates (42% of #57 stone, 15% of #8 stone and 43% of sand content) and a water cement ratio of 0.49. The slump at arrival on site is maximum 4 in. (101 mm). A mid-range water reducing admixture is added on site before mixing the steel fibers with the special blast-machine (Fig. 8). At placement, the SFR concrete will have a slump of 5 to 6 in. (127 to 152 mm). The consistency of the concrete has to be inspected by slump testing and visual checking throughout the duration of the pour.

Installation—the 6 in. (152 mm) thick SFR concrete slab is installed on a 6 mil. (0.15 mm) polythene membrane (used as a slip membrane) by direct truck discharge and using the Laser Screed technology. After one pass of straight edge on the freshly laid SFR concrete, a premix quartz and cement based dry shake surface hardener is spread at a rate of 1 lb/ft^2 (5 kg/m^2) using a mechanical Topping Spreader. This will give great abrasion resistance to the slab surface, but will also improve the aesthetic appearance by covering most steel fibers that could be left embedded close to the surface of the floor. After power floating is completed, a curing agent will directly be sprayed on to keep the moisture from evaporating off the concrete. There are no saw cuts as the jointless panels will move freely. An opening from 1/3 to 2/3 of an inch (8 to 16 mm) can be expected at the metallic construction joint after 1 year.

Coca-Cola Clad-rack, London, England

The building, a 108ft-high (33 m) clad-rack warehouse for Coca-Cola products, is 220 ft x 260 ft (67 m x 79 m). The slab is supported on piles with a grid of 10.7 ft by 10.0 ft (3.3 m x 3.0 m) in accordance with the racking layout. Pile diameter is ranging from 1.33 ft to 2 ft (400 to 600 mm); they can carry up to 240,000 lb (1067 kN) and 380,000 lb (1690 kN). The racking load is the combination of the dead weight of the structure, the pallet load, the wind forces and dynamic crane forces. The leg load can be as high as 150,000 lb (667 kN) downward and 80,000 lb (355 kN) upward along the edge of the building.

Design has been achieved according to yield line theory for the ultimate limit state and with finite element analysis for the serviceability limit state.

The 5,000 psi (35 MPa) concrete has been reinforced with 75 lb/yd^3 (45 kg/m^3) of high tensile strength crimped fibers without any additional conventional reinforcement, and was pumped (Fig. 12). Slab thickness varies from 1.64 ft to 2.13 ft (500 to 650mm) along the edges.

The racking has been anchored directly onto the surface of the floor with resin anchored bolts and special fixing boxes for high upward forces (Fig. 13). It has been directly covered with the cladding and roof and now supports the pallet weight and all the building loads.

CONCLUSIONS

Jointless SFRC slabs are not designed for every type of building. These types of slabs are ideal for distribution warehouse and factories that have intense forklift traffic or require high impact and abrasion resistance. Once the building owners, consulting engineers, architects and general contractors have decided to opt for a jointless SFRC slab, they must take precautions in choosing the right concrete contractor for the job by selecting on various items, including, checking contractor's track record in jointless SFRC floors, making sure to visit jointless reference floors and ask the opinion of their users, checking site quality control procedures proposed by the concrete contractor, ensuring that adequate site conditions will be in place, working at an early stage with the concrete contractor to optimize detailing and design of jointless SFRC slab, limiting the number of split responsibilities within the contract (opt for a design build and ask for guarantees), and being aware and accepting the possibilities of controlled cracks. Building owners are increasingly aware of the problems of saw-cut joints, therefore jointless slab systems are becoming more specified and have proven to be a successful solution. The use of steel fiber reinforced concrete as presented in this paper is one such promising approach to meet this objective of constructing jointless slabs.

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Table 1—Theoretical distance between fibers with a diameter of 0.039 in. (1 mm)

Fiber concentration lb/yd^3 (kg/m^3)	Fiber spacing inch (mm)
55 (32.6)	0.839 (21.3)
60 (35.6)	0.803 (20.4)
65 (38.6)	0.771 (19.6)
70 (41.5)	0.743 (18.9)
75 (44.5)	0.718 (18.2)

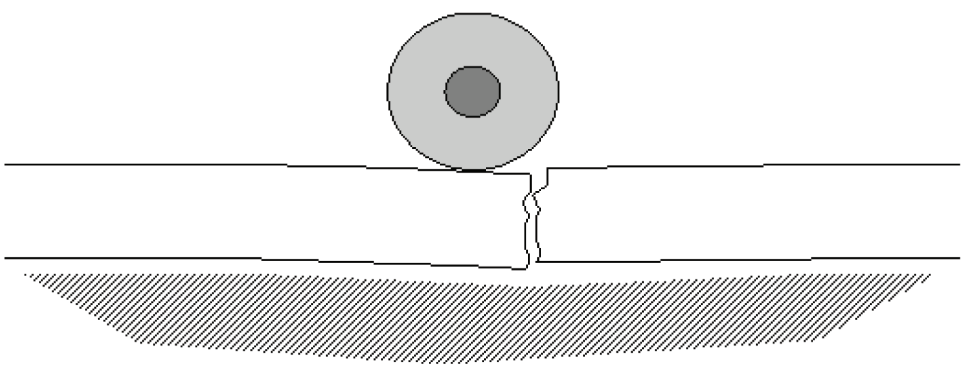

Fig. 1—Effect of differential shrinkage on induced joints (curling, rocking, and spalling).

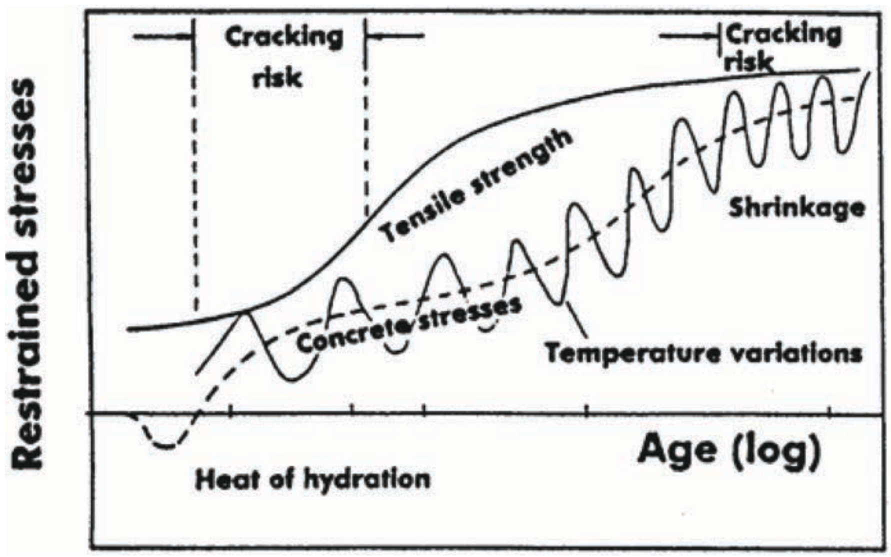

Fig. 2—Evolution of concrete strain and strength with time (Holderbank 1994).

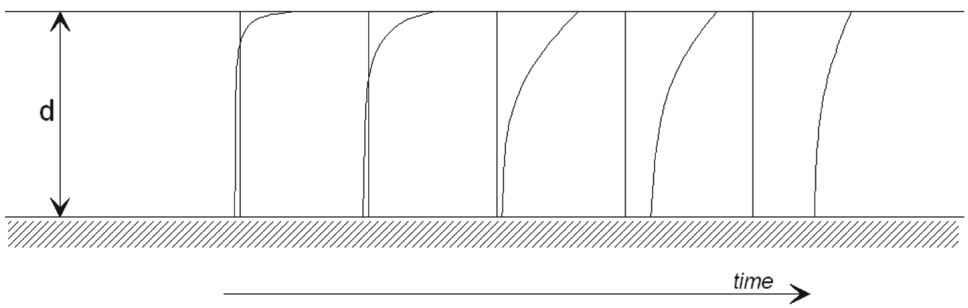

Fig. 3—Evolution of shrinkage with time in a slab-on-grade.

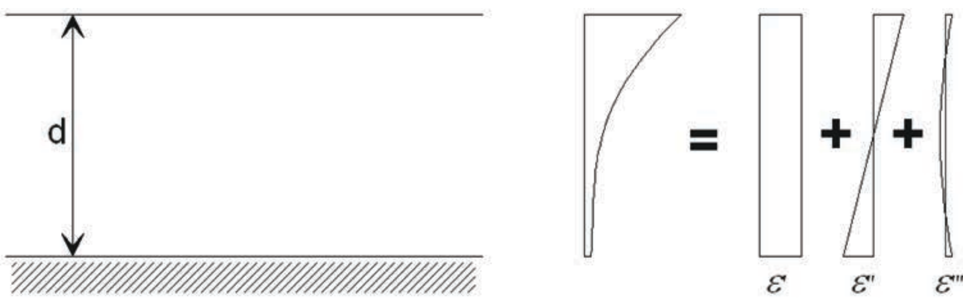

Fig. 4—Decomposition of the shrinkage strain distribution in a slab-on-grade.

Fig. 5—Curling effect.

Fig. 6—Rocking and spalling of a nondowelled saw-cut joint.

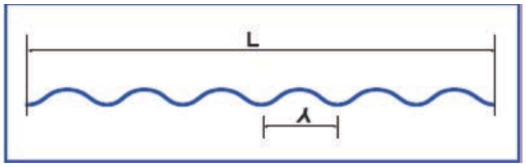

Fig. 7—Crimped steel fiber shape.