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Experiences with the Design, Construction, and Performance of High Volume Synthetic Fiber Reinforced Concrete Slabs on Ground

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Abstract

High volume synthetic fiber reinforced concrete has many features, advantages, and benefits for use, especially in slab on ground applications. The design process involves making some decisions based on some of the performance assumptions about fiber reinforced concrete during manufacture, construction, and in service. Further, some of the designs are based on material substitution for conventional steel reinforcement and not original designs based only on fiber reinforced concrete properties. Discussion about the design process for slabs on ground with fiber reinforced concrete is analyzed for consistency and compared with other design procedures, based on what is known and not known about the material behavior from testing and field performance. Detailed case histories are presented about how the high volume synthetic fiber reinforced concrete was designed, how it was constructed, and how it has performed. A discussion follows regarding what was and was not expected or even predicted.

Keywords: high volume synthetic fiber reinforced concrete design projects

1 Introduction

Design decisions are complex. They include material choices based on analysis and should include a best-fit evaluation of other criteria established by the designer. Other criteria include project parameters defined as performance-quality, schedule, or cost. Additional criteria may be established that are not as scientific such as experience or preference. Most criteria or choices have features, advantages, and benefits that are also compared for best fit. Evaluating and documenting the results of these decisions and how they were made is better understood afterwards than during the design process. The veracity of why decisions were made cannot be completely determined in this design process. Reverse engineering is after the fact, and therefore can only be analysis and not design. How this analysis compares with what was actually built, can and should be documented for the next design project.

The design decisions associated with the design process and the subsequent use of fiber reinforced concrete are significantly further embedded in a decision diagram of the design

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process. The logic includes a level of detail beyond the available time and interest of most designers because they have to work through their original designs first without fiber reinforced concrete. This situation encourages a line of reasoning to design the "way we have always done it." Also, designers would rather "deal with the devil" they know and not take on a different set of problems. Hence, a resistance develops to try something new or even different. These types of design decisions are not based on the best-fit design solution for a specific application and an evaluation of the features, advantages, and benefits of those choices.

Suppliers of fiber reinforced concrete sell the features, advantages, and benefits of their fibers, concrete, and fiber reinforced concrete to best fit the project design. Further, the designer and fiber supplier want engineering based calculations to justify design decisions and sales performance.

2 Design and Discussion Limits

The material type series of decisions in projects can include many alternatives or other potential choices such as, not to use concrete. However, the following are a sequence of choices assumed to have been made in some logical order: the use of concrete, reinforcement, fiber reinforcement, synthetic fiber, and then high volume dosage (fiber amount usually greater than 0.2% by volume). There are potentially many other choices in this in this embedded logic referred to above. The highest number of project applications for fiber reinforced concrete (FRC) is slab on ground (SOG). Slab on ground are subject to the loads and materials and the design associated with the calculation techniques. Calculations use the material properties and an understanding of the load effects. But as identified earlier, some design decisions are not done completely by engineering science. The significant areas of discussion regarding these type applications are as follows: thickness, saw-cut locations, and reinforcement.

Thickness can be calculated by various mathematical approaches and methods. However, this is not intended to be a discussion about methods to design slabs on ground but more how might the slab thickness be affected by high volumes of synthetic fibers. Therefore, a slab on ground thickness is assumed and not necessarily questioned but used as a starting point for further discussion as reverse engineering.

Saw-cut locations are compared with the "rule of thumb" for un-reinforced concrete versus concrete reinforced with a high volume synthetic fiber dosage. However, saw cuts can only be generalized and are never necessarily uniform but only approximations because of the dimensional specifics of the actual jobs.

Reinforcement can be used or not in most slabs on ground. However, a conscientious approach would be to understand what the reinforcement is expected to do in this type of application. Design choices for reinforcements are: none (no reinforcement), steel deformed rebar, steel mesh (welded wire fabric), and fibers. Each of these can be used by themselves or in combinations with the others. However, slabs on ground that either use some steel or none at all are the easiest designs to explain by calculations and the use of fibers.

The harder design to change is one that uses another fiber type or dosage because the capacity of the existing fiber should be known to compare the capacity of the new fiber to be used. This problem is not as difficult if the fiber type does not change but only the dosage of the fiber. The efficiency of fibers between types or brands is not readily available due to the many factors, which influence FRC property behavior and may also be proprietary to the FRC supplier. The approach is not to change the loads but to compare them with contributions by the individual reinforcement and substitute with some fiber dosage to work with the steel or in some cases eliminate it completely.

3 Thickness Calculations and Fiber Effects

Typically concrete highway pavements are un-reinforced. This type of SOG assumes in the design a homogeneous and uniform material property in three dimensions throughout the slab. Further, but not necessarily fully explained, the flexural fatigue endurance limit of the material concrete is incorporated into the design. Earlier design methods by Spears seemingly hid this endurance limit as a factor of safety of 2 or 50% of the concrete material property capacity [1]. A later edition of this manual for SOG design explains this “factor of safety” as the endurance limit [2]. An endurance limit can be defined as the infinite number of repeated same loadings where the material does not fail. The flexural fatigue endurance limit is typically defined as a percentage, which expresses a percentage of the flexural strength, which concrete can sustain for an infinite number of flexural fatigue loading cycles. Failure is defined as cracked concrete. Consequently, if the number of loadings is known for the design, the allowable stress (load) on the concrete can be adjusted with a percentage factor of the flexural strength for 1 loading and concrete failure.

Ramakrishnan, Pancharin, and others have documented and published the increased endurance limit of FRC [3]. Recently, this same concept of an increased endurance limit with FRC has been incorporated into the ACI 360 committee documents. With increasing fiber dosage and a specific fiber type, the percentage is understood to increase from 50% to 100% of the flexural strength or modulus of rupture. It must be clearly understood this percentage is the strength before the concrete cracks and not the load carrying capacity after the concrete cracks. The increase in fatigue capacity is not entirely understood. It is thought to be partially explained as a micro mechanical and fracture mechanics phenomenon of the fiber affecting the macro material properties of the concrete by bridging and restraining at locations where cracks start on a micro scale.

By whatever calculation method for thickness, the basic and fundamental underlying equation used in the calculation is the extreme fiber stress from a rectangular shape and assumed uniform beam cross section. Therefore, only one unknown is in the equation (height) and it can be solved directly for thickness as follows by manipulating the normally memorized equation “stress is equal to the moment times half the height divided by the moment of inertia.” The resulting equation to solve the height directly is not as easy to recount from memorization but is as follows “height is equal to the square root of this quantity, 6 times the moment divided by the width divided by the stress.”

Table 1: Stress and Height Equations

Stress Equation	Height Equation
Stress = Moment x Height / 2 / Inertia	Height = SQRT (6 x Moment / Width / Stress)
Inertia = Width x Height x Height x Height / 12	
Stress = 6 x Moment / Width / Height / Height	

The mathematics of the effect of this range in endurance limit and stress needs to be understood. Even a little increase in fatigue capacity will be of benefit. An increase in endurance limit or allowable stress from 50% to 75% of the flexural strength results in an 18% reduction in thickness. As an example, from a 150-mm (6-inch) thick slab and a 50% factor, the thickness reduces 27-mm (1.1-inch) and would be 123-mm (4.9-inch) thick with a 75% endurance limit of the flexural strength.

4 Saw Cut Spacing and Fiber Effects

Un-reinforced concrete SOG uses the following “rule of thumb” for saw cut spacing “2 to 3 times the thickness in inches for spacing in feet” (24 to 36 times the thickness in millimeters) and “length to width is kept below a 1.5 ratio.” These ratios change with increasing fiber dosage and also construction conditions. Construction conditions to affect this with FRC are sub grade with two layers of a vapor barrier for the slab to slip on or the other extreme with well-compacted sharp angular base providing miniature anchors. Therefore, sub grade restraint may dictate closer saw cuts as related to what can be calculated as the sub grade drag coefficient.

Since rules of thumb are expected by definition to be empirically developed, FRC can be just as consistent and have no other basis for estimating a range of values. With a 0.5% dosage of high volume synthetic FRC, the imperial unit “rule of thumb” is 5 to 10 (60 to 120 times the thickness in millimeters) rather than 2 to 3 and the 1.5 slenderness ratio (length divided by width) is increased to 5. This FRC rule of thumb has been estimated from fiber supplier case histories, field inspections, and at least 500 personal SOG project experiences since 1994. Preference should be given for what works with other landmarks such as saw cuts at column lines or width of the concrete placement finish equipment.

5 Steel Reinforcement and Fiber Effects

Analysis in reinforced concrete is discrete or separate for concrete and reinforcing steel [4]. A simple steel reinforced concrete beam in flexure needs to have the forces reconciled above the neutral axis in compression and below the neutral axis in tension. Further assumptions are then made by further calculation to locate the neutral axis and assume that the steel carries all the tension and the concrete carries no tension but only compression. This well-known model for calculations has been called the Whitney stress block. One engineering mechanics type proof of this transforms the area of the steel into an equivalent area of concrete and then uses a superposition technique to prove the efficiency of steel over concrete in tension. Further, the steel behavior is described as being elastic and concrete is described as stiff and very brittle.
FRC is easily understood as homogenous with behavior as a mass. However, most reinforced

concrete education teaches discrete behavior with fixed stress strain diagrams that never proportionately mix (every pun intended). Steel and concrete do have discrete and distinctly different load deflection diagrams or stress strain charts. The significant difference between reinforced concrete (RC) and FRC is the shape of the curve after the concrete cracks. In RC, the load carrying capacity would be expected to increase with deflection initially after the concrete cracks and only the steel is holding the concrete together. In most FRC dosages, the load carrying capacity would be expected to decrease with deflection initially after the concrete cracks and only the fibers are holding the concrete together.

The load and deflection after the concrete cracks with FRC is obtained by testing and the residual energy is called toughness, which is obtained by measuring the area under the resultant curve. The testing is performed with FRC beams and according to ASTM C 1399 Average Residual Strength (ARS) [5]. This is not the only test method to obtain toughness values but it certainly is the easiest to understand and use for SOG applications and the required design calculations. By analogy only, the ARS is expressed as a stress, which mathematically is a percentage of the flexural strength, and the endurance limit, discussed earlier, is expressed as a percentage of the flexural strength. Additionally, ARS is more related to the fiber properties and adhesion to or in the concrete matrix and not discrete for the fiber and concrete as individual and separate components. Fortunately, ARS is in units that can be plugged into the previously discussed extreme fiber stress equation as “stress is equal to the moment times half the height divided by the moment of inertia.”

When a SOG incorporates reinforcement steel and regardless of the steel purpose, the steel imparts some bending moment capacity to the SOG by discrete calculations. The homogenous behavior of the FRC also has some moment capacity due to the fibers after the concrete cracks. The moments are compared from each system meaning RC and FRC.

If a practical dosage and resultant ARS gives more moment capacity than the steel, the fibers at that dosage can be used. The comparison does not include a factor of safety because the underlying assumption is the loads are already factored and redundant factors of safety are not efficient.

If the practical fiber dosage does not have sufficient moment capacity, then the rebar can be sized down or spaced differently and still use the practical fiber dosage. The underlying assumption is that superposition holds true with FRC and conventional RC.

6 Example Calculations for FRC SOG

The original design used 12 mm rebar (1/2 inch, # 4) at 230 mm (9 inch) on center each way in the center of a 150 mm (6 inch) thick SOG. The assumptions for the bending calculations are in Table
2. The steel placement might indicate that the steel is specified for tensile shrinkage cracking resistance. Therefore, an equivalent tensile capacity should also be included for a complete evaluation of equivalent fiber performance. However, experience has shown that the design is controlled by bending and not tensile temperature steel. Furthermore, the steel has not been instructed to behave as either tensile or bending. The fibers provide isotropic, 3-dimensional, behavior while the steel is 2-dimensional and placement dependant.

Table 2: Calculation Assumptions

Equation	Explanation
T = C	Tension equals compression
T = As Fy	Tension equals steel area times yield
C = 0.85 F'c B A	Compression equals 0.85 times width times A factor
A = As Fy / 0.85 F'c B	Substitution from above equals A factor
Ms = As Fy (D – A / 2)	Moment steel is the tension through a modified distance
Mf = ARS B H H / 6	Moment fiber is the ARS times width times height squared divided by 6

The steel strength was 414 MPa (60 ksi) and the concrete was 28 MPa (4 ksi), which resulted in a steel moment of 4.49 MPa (39.7 kip inch). Using a target fiber capacity or ARS of 1.72 MPa (0.250 ksi) from the FRC, the FRC moment was 2.07 MPa (18.3 kip inch). The shortfall of 2.42 MPa (21.4 kip inch) was the difference between the RC and FRC moments. The shortfall was made-up using the same size rebar at 432 mm (17 inch) spacing rather than 230 mm (9 inch).

This increase in spacing allowed for safer construction. The workers were able to step through the rebar rather than step on or trip through. Less rebar was unloaded resulting in labor and equipment savings. The increased rebar spacing eliminated some schedule and coordination of work on site.

7 Project Case Histories for FRC SOG

7.1 SOG Experiment with 4 Conditions

The original SOG incorporated 12 mm rebar at 457 mm on center each way in the center of 27.6 MPa strength concrete at 152 mm thickness. The project building had 4 bays, 9.1 m by 27.4 m. The project developed into an experiment with 2 different fiber lengths, 38 and 57 mm long, and dosages, 0.25% and 0.50% by volume. The slabs were placed on well-compacted grade and with one of the 4 possible conditions in one bay. All the other conditions were held as constant as possible for the experiment to only compare between the fiber length and dosage. The same concrete mixture proportions, placement, crews, and finishing techniques were used in all placements at the same time and weather conditions. After 54 months of service, there is 1 crack across the slab that essentially broke in half for a length of 13.7 m rather than 27.4 m. All slabs are understood to have received the same treatment and loading from the operations, which include impact, machine vibrations, and fork truck traffic.

Saw cuts were eliminated and the necessary coordination of that work to be done on time. Also, the reduction in joints has been of benefit to the production workers and eliminated some maintenance. The unbroken slab slenderness ratio is 27.4/9.1=3.0 and the broken slab is at the standard ratio of 1.5.

7.2 Warehouse SOG

The warehouse addition footprint is a thick L-shape with the vertical leg, slab B, 26 m by 35 m wide (85 ft by 115 ft) and the horizontal leg, slab A, 18 m high by 40 m wide (60 ft by 130 ft). The 18 m (60 ft) construction joint is located where the horizontal leg meets the vertical leg. Saw cuts were intended to be square at 5 m (15 ft) on a side and would total 565 m (2,150 ft). The slab is 152 mm thick (6 inch) and was placed on 2 layers of plastic poly slip-sheets on top of well-graded and compacted fill.
The warehouse sees fork-truck traffic for material handling of produced products and storage until shipping out the dock doors. The pick-up truck traffic is for storage of snow removal equipment and other operations. The SOG has stacked pallet loads of cardboard boxes containing finished products and intermediates. There are many corners in each slab perimeter for the building column boxes. The slab butts up to the exterior strip foundation wall that integrates the column footings.

The SOG was placed using 0.5% high volume synthetic fibers or dosage 4.55 kilograms per cubic meter (7.50 pounds per cubic yard). The slabs were built to the construction joint discussed above on 2 consecutive days in May 2004 with slab A placed first and then slab B. The slabs were placed with a laser screed and then finished with riding power trowels.

No saw cuts were provided in the slab to experiment and see where cracks might occur. By conventional rules, saw cuts should have been provided at about 5 m centers to prevent uncontrolled cracking or 5,000 mm divided by 152 mm is about 33 and within the range 24 to 36 discussed previously. After 8 months in service, the slab B 35 m side has cracked in half so the slab sizes are now about 26 m by 17,5 m. Slab A has a 2 hairline re-entrant corner cracks at locations where diagonally placed steel rebar was inadvertently left out. Slab B originally had a slenderness ratio of 35/26=1.35 and now has 26/17.5=1.49 and the slab A ratio is 40/18=2.22.

8 Conclusion

There are many issues involved with designing slab on ground. After all, the loads, materials, and calculations are all estimated and approximated to reality. The slab on ground is then built, used, and evaluated from a whole host of assumptions for cost, schedule, and performance dictated by the passionate needs, wants, desires, and requirements of everyone involved. The easier design or choice is to substitute fibers for steel based on mathematical substitution or equivalency. The harder job of design is a fiber reinforced concrete floor.

Further information is necessary to fully understand how fiber reinforced concrete behaves and what other ‘concrete’ factors influence this behavior. Simply put, define the separate and combined influence of the fibers and concrete. These definitions are necessary going into a design, making a choice, and afterwards for analysis, how good was that choice. Since concrete differences are driven by geography, the fibers may be one of few constants that can be shipped in and used.

9 References

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