Experimental Study on the Restrained Shrinkage Cracking of FRC Composite Metal Decks

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Abstract: - This paper presents the results of an experimental study that compares the performance of macro synthetic fibers and the conventional steel mesh in controlling shrinkage cracking. The experiment tested two sets of relatively large slab strips cast on corrugated steel decks as well as free shrinkage prisms tested according to ASTM C-157. Each set consisted of four slabs, S1 to S4, reinforced with a steel mesh, 2.4 kg/m^3 (4lb/yd^3) of fiber, 3.0 kg/m^3 (5lb/yd^3) of fiber, and 3.6kg/m^3 (6lb/yd^3) of fiber respectively. The intent was to investigate each reinforcement option for its performance as a secondary reinforcement, controlling shrinkage cracks on composite metal decks. The evaluation was based mainly on the shrinkage crack width for each specimen measured up to a period of 450 days. However free shrinkage strain results and total crack openings were also referred to. The steel mesh and the 2.4 kg/m^3 (4lb/yd^3) fiber dosage were chosen according to the minimum requirements for temperature and shrinkage reinforcement allowed by the ANSI-SDI-C2011. This facilitated a direct and practical comparison to examine their performance. The results showed comparable crack widths between the 2.4 kg/m^3 fiber dosage and the steel mesh, demonstrating the viability of the tested fiber in restricting shrinkage cracks. However increasing the dosage to 3.0 kg/m^3 (5 lb/yd^3) is recommended to better control the shrinkage cracking in composite metal decks.

Key-Words: - Macro Synthetic Fibers, Composite Slabs, Steel Deck, Restrained Shrinkage, Crack width.

1 Introduction

Perhaps serving as the major accelerator to the deterioration of concrete structures, and often overlooked, is shrinkage cracking. Shrinkage-induced micro-cracks rapidly propagate to visible, surface cracks, then to macro-cracks, compromising serviceability and strength performance if not well controlled [1,2]. To guard against excessive shrinking cracking both welded wire fabric (WWF), as used traditionally and the more recent steel and synthetic fibers are being commonly used as secondary reinforcement in concrete. However the effectiveness and performance of each type is still under debate.

For steel composite decks in particular, the ANSI-SDI-C2011 [3] permits the use of any of WWF, reinforcing bars, steel or macro synthetic fibers to control shrinkage cracks. The WWF limited to a minimum requirement not less than the area of a 6 x 6 in. – W1.4 x W1.4 mesh; the steel fibers to a dosage not less than 14.8 kg/m^3 and the macro synthetic fibers to a dosage not less than 2.4 kg/m^3. To put things into perspective, the minimum requirement on the steel reinforcing by the SDI is nearly 60% lower than the temperature and shrinkage steel limit of 0.18% - 0.20% specified by the ACI-318 [4]. Considering that these ACI-318 requirements are designed only to keep the crack width within an acceptable range, any substantial crack-arresting requirements are going to demand higher reinforcement percentages than the SDI limits. For very tight crack control, ACI 224 [5], for instance, requires an area of steel percentage of about 0.60%.

The literature holds very little in direct comparative studies between WWF and synthetic fibers with regards to shrinkage cracking. This is especially the case for composite metal deck applications. This paper presents the results of an on-going experimental program to investigate the effectiveness of one type of macro synthetic fiber and the conventional steel mesh in controlling shrinkage cracks in composite metal deck concrete slabs.

2 Literature Review

Trottier et al. [6] compared the performance of a variety of commercially available low-denier-fibrillated and monofilament-synthetic fibers, at low fiber content, to that of a conventional, commonly used 150 x 150 mm 3.4 mm/3.4 mm gage (6 x 6 in. 10/10 gage) welded wire fabric (WWF). The researchers tested against plastic shrinkage, by casting rectangular plate specimens 900 x 600 x 50 mm, restrained with metallic and wooden fixings systematically placed at the bottom and sides of the molds. The specimens were evaluated for the total number of cracks, the average crack widths and the total area of cracking – corresponding to the sum of the length of each crack multiplied by its average width. The study demonstrated that the use of low-denier monofilament and fibrillated-synthetic fibers at low fiber dosages (0. 3 to 0.9 kg/m^3) is considerably more effective in the control of plastic shrinkage than the conventional WWF. The WWF-reinforced specimens incurred the largest average crack width of all specimens including the plain concrete, and a total area of cracking representing 82.9% of that of the plain concrete, while, on the other hand, specimens reinforced with a combination of multiple-denier, multiple-length fibrillating fibers proved extremely successful displaying the smallest average crack widths of all and almost insignificant cracking.

Shah et al. [7] also compared the crack controlling performance of WWF and fibers in controlling drying shrinkage cracks in restrained concrete rings. The ring test seemed suitable since it simulated the uniaxial state of stress that was typically assumed for temperature and shrinkage stress analysis. The comparison involved concrete specimens reinforced with hooked-end-steel fibers and fibrillated-polypropylene fibers at dosages of 0.25% and 0.5% by volume of concrete as well as two types of welded wire fabric: 150mm x 150mm with a diameter of 4.76mm and a similar 75mm x 150mm. The specimens were subjected to a drying environment after four hours of moist curing and cracking was observed between four hours and forty-two days. The age of first crack, number of cracks, maximum crack width and the average crack width were recorded. Fibers at higher dosages clearly outperformed the WWF in prolonging the time of first crack. However, with respect to reducing the crack width, both WWF and fibers compared favorably and similarly, reducing the maximum crack widths by about 70%. The researchers however did acknowledge that the effectiveness of the WWF was overestimated in this study due to the small thickness of the specimens.

Another study by Voigt et al. [8] confirmed the results above by testing specimens reinforced using a myriad of six different types of steel fibers, three different polypropylene fibers, WWF (W1.4 x W1.4 – 6 x 6 in.), and a control specimen. The specimens included single fiber type specimens as well as two-fiber blend specimens. All specimens were checked for visible cracks every 24 hours and the width of each crack was measured at forty-two days after casting. The results again clearly showed that the age of first visible crack increases with increasing fiber volume in all cases while the WWF in comparison has no effect on the cracking age. In terms of maximum crack width, the crack width decreases with increasing fiber volume for any of the individual fiber types. The WWF also proved effective, reducing the crack width to about 16% of that of plain concrete – a performance similar to that of the tested steel fibers in the fiber volume of 0.25%. This result was also reached in the study discussed above by Shah et al. [7], raising the question as to whether steel fibers at a dosage of 0.25% could be a viable replacement for WWF. Overall, however, the study deduced that the flat end 30mm steel fiber is the best-performing reinforcement, concerning age of first crack and maximum crack width and for all investigated fiber volumes.

Furthermore, researchers also determined that steel fiber reinforced concrete (SFRC) with fiber dosages typically used in construction (10 – 30 kg/m^3) can provide load carrying capacity similar to properly positioned WWF. Fibrillated polypropylene reinforced concrete, however, is not an effective replacement for WWF if crack control of hardened concrete is required. Although it is effective in reducing plastic shrinkage and hence increasing the overall durability of the concrete [9].

3 Research Significance

Restrained shrinkage cracking remains a considerable inconvenience for all types of concrete construction processes and failure of controlling these cracks results in, above all, reduced durability and efficiency. For the purpose of composite metal decks, the current ANSI/SDI C2011 standard permits the use of both, macro synthetic fibers as well as welded wire mesh, as a reinforcing material to control drying shrinkage. Comparative studies exploring the performance of these reinforcements however remains scarce. This paper investigates this comparison, providing short to intermediate term data on crack width development under restrained conditions of composite steel deck slabs – hence imparting some degree of confidence to the replacement of the welded wire mesh with fibers.

4 Experimental Program

Two sets of "dog-bone" shaped, relatively large concrete slab strip specimens, as shown in Fig. 1, were cast for this investigation. Each set consisted of 4 specimens (S1, S2, S3, S4) – each reinforced differently against drying shrinkage, either with a STRUX 90/40 fiber or WWF. All specimens however were subjected to restrained conditions similar to those occurring in elevated concrete slabs on steel corrugated sheets i.e. they were cast on corrugated steel decks, in rigid steel frames fitted with end anchors, which provided the bottom and end restraints respectively. Fig. 2 shows the details of the end restraint. All specimens were also exposed to normal indoor drying conditions.

The specimens had a cross-section of 200 mm width and 150 mm depth in the middle portion with the width gradually increased to 300 mm towards the ends. This enlargement of the specimen cross section reduced the stress concentration at the restrained ends.

In parallel to the two sets of restrained specimens, two sets of 75mm square-cross-section prisms were cast according to ASTM C-157 as well. Therefore, each restrained specimen had a corresponding square prism cast from the same concrete. The prisms were to be tested for free shrinkage data according to ASTM C-157.

The experiment sprouts from the provisions of the ANSI/SDI standards permitting the use of macro synthetic fibers to replace the conventional steel mesh used to control shrinkage cracking in composite metal decks. It examines the performance of WWF and compares it to that of macro fibers in different dosages of 2.4, 3.0, and 3.6 kg/m^3 (4.0, 5.0, and 6.0 lbs/yd^3). Table 1 outlines the specimen and its respective crack-inhibiting reinforcement. The effectiveness of each specimen was then determined from the maximum crack width measured over time.

4.1 Materials

The concrete used for this experiment was normal weight concrete with a 20 N/mm^2 (3000 psi) cylinder compressive strength as is commonly used for such topping applications. The concrete mixture is composed of:

- Ordinary Portland cement type I conforming to ASTM C150;

Fig. 2. One set of restrained specimens

Fig. 1. Details of end restraint.

Table 1. Specimen Reinforcments

Specimen	Reinforcement	Type/Rate
S1	WWF	W1.4 x W1.4 – 6” x 6”
S2	Strux 90/40	2.4 kg/m^3 (4 lbs/yd^3)
S3	Strux 90/40	3 kg/m^3 (5 lbs/yd^3)
S4	Strux 90/40	3.6 kg/m^3 (6 lbs/yd^3)

- Crushed washed aggregate with 10 mm (3/8”) maximum size, specific gravity of 2.83 and water absorption of 0.7%;
- 5mm washed sand with specific gravity of 2.67 and water absorption of 1.3%;
- Dune sand with specific gravity of 2.63 and water absorption of 1.2%.

Further, an unusually high w/c ratio of 0.64 was chosen to instigate higher drying shrinkage and increase shrinkage strain and cracking. Table 2 shows the mix proportions for the experimental slabs.

The fiber reinforcement used (Fig. 3) were made of polypropylene and polyethylene and with a rectangular cross section. The dimensions were a nominal length of 40 mm (1.75”), an average width of 1.4 mm (0.55”), an average thickness of 0.105 mm (0.04”), and an aspect ratio of 90. The specified tensile strength of the fibers is 620 MPa (90 ksi) and the modulus of elasticity 9.5 GPa (1378 ksi). The fibers were used with dosages of 2.4, 3.0, and 3.6 kg/m^3 (4.0, 5.0, and 6.0 lb/yd^3), corresponding to fiber volume fractions of 0.26 %, 0.33 %, and 0.39% respectively. The minimum dosage of 2.4 kg/m^3 (4 lbs/yd^3) coincides with the minimum requirement of ANSI/SDI –C 2011 standard and ASTM subcommittee C09.42.

Table 2. Concrete mix proportions.

Material	kg/m^3	lb/yd^3
Cement OPC	320	540
10 mm Aggregate	920	1550
5 mm Sand	670	1130
Dune sand	300	505
Free water (L)	206	347
Free W/C	0.64	0.64

The welded wire mesh used in slab S1 was a 6" x 6"-W1.4 x W1.4 (152 x 152 mm - MW9 x MW9) welded wire fabric (Fig. 4) placed on the bottom of the upper third of the slab, 50 mm (2”) from the slab top surface. It also coincides with the minimum allowed by the ANSI/SDI –C 2011 standard, which is equal to 59.8 mm^2/m (0.028 in^2/ft.).

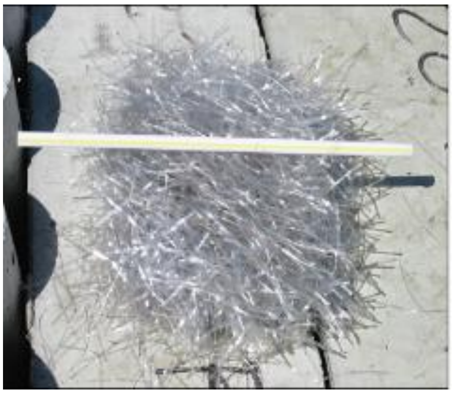

Fig. 3. Macro synthetic fiber used.

Fig. 4. WWF used.

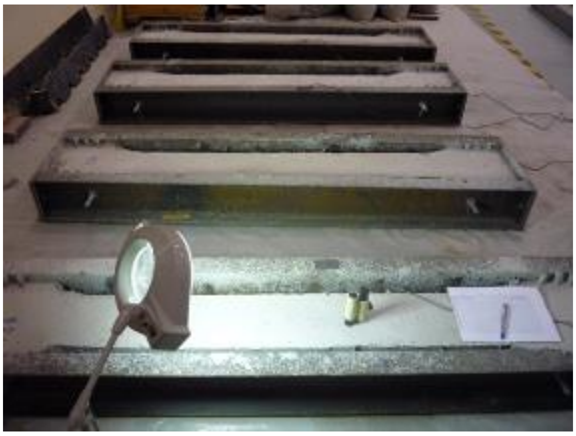

Fig. 5. Crack observation.

4.2 Observation Strategy

The essence of the experiment lies in the ability to distinguish the specimens with respect to their crack composition. Any crack that forms on the surface therefore is immediately identified with a unique crack code, then measured, and tracked. For the first

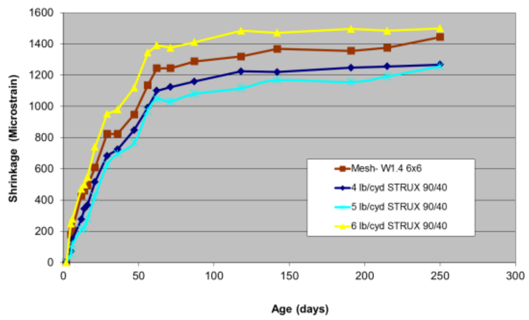

Fig. 6. Plot of free shrinkage strain versus time for set one.

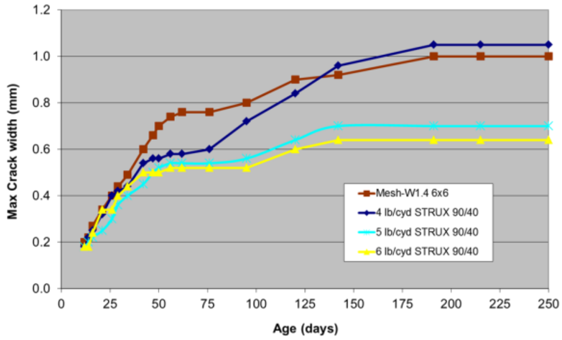

Fig. 8. Plot of maximum crack width versus time for set one.

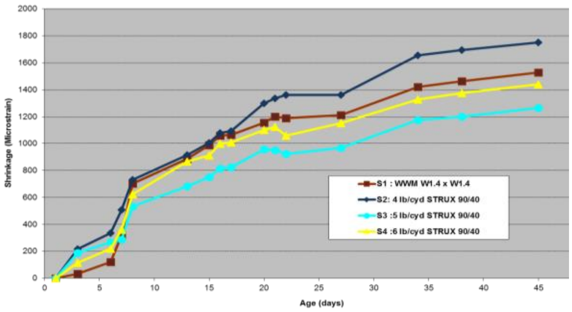

Fig. 6. Plot of free shrinkage strain versus time for set two.

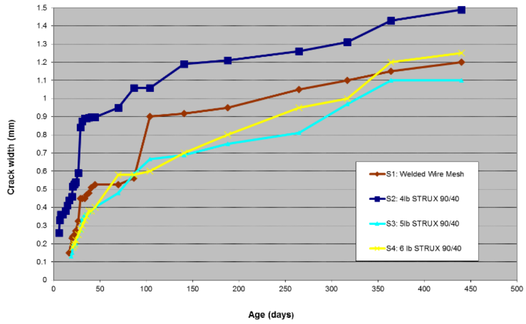

Fig. 9. Plot of maximum crack width versus time for set two.

two weeks after casting the specimens were inspected daily, in search of any cracks, and then every two days thereafter. The cracks were measured with a handheld graduated microscope with an accuracy of 0.02 mm (0.0007") and at several locations along its path. The crack width for that age then being the average of these measurements. Fig. 5 shows the hand-held microscope used.

The free shrinkage test also provided shrinkage data that exposed the potential for each concrete mix to contract and measurements were taken at appropriate intervals thus plotting the concrete's shrinkage with time.

5 Results and Discussion

Figs 6 and 7 show the plot of free shrinkage with time for sets one and two respectively. As shown, the shrinkage measurements are between 1200 and 1600 microstrain, with the anomaly of mix S2 in the second set that increased up to 1800 microstrain. All such measurements however have clearly exceeded practical acceptable levels and the behavior can be mainly attributed to the high w/c ratio of 0.64. Such a ratio was specifically chosen to aggravate the shrinkage, increase the crack width, and base the experiment on a "worst-case" situation. It can also be shown from the measurements of set number one which were recorded for a much longer period of up to 250 days that the shrinkage stabilizes between 75 to 100 days.

As for the restrained specimens, the formation of cracks were monitored and, for all specimens, the first hairline cracks were observed after 4 days with the first major crack developing at the earliest of 12 days. The major crack was then tracked and

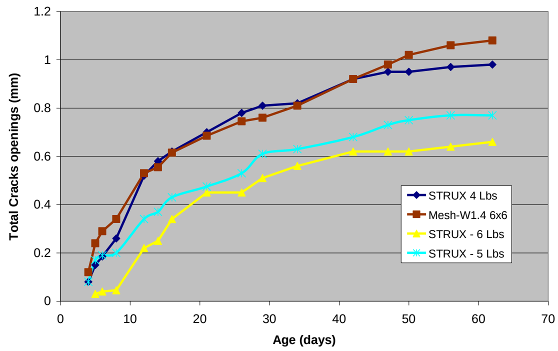

Fig. 10. Plot of total crack openings versus time for set one.

measured. Figs. 8 and 9 show the plot of maximum crack width (measured in mm) against drying time in days for sets one and two respectively. The maximum crack width for S2 (4 lbs/yd^3) of set 2 can be seen to be unusually high as compared to that of set 1, however this can be accounted for as a deviation in the mix that caused very high shrinkage strain as shown in fig. 7. Considering that, it can now be deduced from these results that specimens S1 and S2, although both couldn't control cracks to within acceptable limits, behaved similarly indicating comparable performance. Specimens S3 and S4 with fiber volume fractions of 3.0 and 3.6 kg/m^3 (5 and 6 lbs/yd^3) respectively also behaved similarly, however, considering the total openings as in fig. 10 confirms S4, with the higher fiber volume fraction, is superior. These results indicate that an increase in fiber volume fraction affects a decrease in average crack width and also that WWF and macro synthetic fibers in accordance with the minimum allowed reinforcement by the ANSI/SDI – C 2011 perform equally and can be used interchangeably.

6 Conclusion

In this experiment three dosages of fibers and a steel mesh were used in 4 restrained slab specimens cast on corrugated steel decks and exposed to normal laboratory drying conditions in order to evaluate the performance of each reinforcement option in controlling shrinkage cracks. The specimens were monitored for a period of up to 450 days and all appearing cracks were measured. Also separate standard prisms were cast and tested according to ASTM C-157 to determine free shrinkage strain for each concrete mix.

Considering that the WWF used in S1 (6" x 6"-W1.4 x W1.4) is the minimum secondary reinforcement allowed by the ANSI/SDI –C 2011 if WWF is to be used and the dosage used in S2 (2.4 kg/m^3 / 4 lbs/yd^3) is the minimum secondary reinforcement allowed by the same standard if macro synthetic fibers are to be used, then the results confirm that they can be used interchangeably with the fibers. The experimental program also confirms that an increase in fiber volume fraction provides better crack control causes a decrease in average crack width.

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