A Performance Comparison between FRC and WWM Reinforced Slabs on Grade

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ABSTRACT:

A comparative experimental study was conducted to investigate the effectiveness of fiber reinforcement as a non-corrosive alternative for welded-wire reinforcement in slabs on grade. Six full-scale slabs-on-grade, reinforced with various combinations of WWM (Welded Wire Mesh), polymeric macro-synthetic fibers (PMF) and cellulose fibers were tested under a centrally concentrated load. Their ductility and load carrying capacity were evaluated and compared.

Based on the results of this study, it seems that high dosages of polymeric macrofibers can be used to successfully reinforce concrete slabs. Given that the use of PMF eliminates the possibility of corrosion of reinforcement, this may be a superior option. Furthermore, it seems low dosages of fibers act as an ineffective replacement for WWM. Low dosages of PMF and cellulose fiber when added on their own, or in combination with each other were found to be insufficient in providing sufficient ductility or load carrying capacity compared to the control slab when subjected to the load test. Slabs reinforced with cellulose fiber had a poor mechanical response in comparison to WWM and therefore cellulose fiber on its own is not recommended.

1 INTRODUCTION

Slabs-on-grade, defined as concrete slab supported directly on foundation soil, are frequently used in sidewalks, industrial/commercial floors, parking lots, driveways, airport runways and pavements, and are therefore among the few structural elements where defects or cracks would be directly exposed to the public's eye. Concrete slabs-on-grade are subjected to different types of static and dynamic loads and loading conditions. The main performance issues associated with these structures are their ability to resist shrinkage cracking and curling and to effectively support various forms of concentrated and distributed loads. Traditionally, concrete slabs-on-grade have been reinforced with steel WWM grids. However, concrete slabs reinforced with WWM grids are susceptible to corrosion, which is why a considerable amount of research is carried out intending to find alternate ways of reinforcing concrete slabs-on-grade.

One of the potential ways of overcoming the problem of corrosion is by replacing conventional reinforcing materials with fiber reinforcement. The use of FRC in construction of slabs-on-grade has provided many advances such as improved resistance to shrinkage cracking, improved crack growth resistance and post-crack toughness, increases in the strength which can result in thinner, joint-less floor slabs (Knapton, 1999), (Hartmann et al, 1999), as well as easier construction and potential cost savings (Knapton, 1999), (Fitzpatrick, 1996).

This experimental study compared the performance and load carrying capacity of reinforced slabs-on-grade to try and determine optimal combinations of WWM, macro-synthetic fiber and cellulose fiber to best reinforce a slab-on-grade, keeping in mind potential corrosion issues.

2 PREVIOUS RESEARCH

Several studies have been carried out in order to evaluate the properties of the different types of reinforcing materials, and how they perform when they are used to reinforce concrete slabs:

Roesler et al (2006) did a structural response comparison between slabs-on-grade reinforced with a new synthetic macro-fiber and plain slabs-on-grade which revealed that that the added synthetic fibers improved the failure behavior of plain concrete slabs to a great extent. Although synthetic fibers did not increase the tensile capacity of the plain concrete slab, it was found that with the addition of synthetic fibers a larger proportion of the slab kept its contact with the sub-grade during the testing period and consequently higher flexural and ultimate cracking loads were obtained (Roesler et al, 2006). According to the authors, as cracking progressed, the synthetic fibers efficiently distributed the load all over the slab volume before flexural cracking, resulting in higher flexural and ultimate capacities than the plain slab-on-grade (Roesler et al, 2006).

Roesler et al (2004) also conducted another study on the fracture of plain and fiber reinforced concrete slabs under monotonic loading. It was found that fibers helped keep the slab in contact with the subgrade after flexural cracking was reached, enabling a better distribution of the load. The steel fibers showed the greatest improvement in ultimate load capacity, followed by the synthetic macrofibers.

In order to compare the load-carrying capacities of slabs reinforced with corresponding amounts of either welded-wire-mesh, fibrillated polypropylene fibers, or steel fibers, large scale load tests were carried out by Bischoff et al (2003) on all three kinds of slabs cast on grade in a test pit. An un-reinforced plain slab was also tested as a reference. Tests were performed on both loose and compacted sub-grades and the measured load-carrying capacity under a central load along with results from flexure beam tests were used to assess the performance of slabs reinforced with different materials (Bischoff et al, 2003). The results indicated that reinforcing the slabs with polypropylene fibers at a low dosage, which is common in the construction of slabs, provides little improvement in the load-carrying capacity when compared with the unreinforced reference slab and thus are not an effective substitute for welded wire reinforcement in slabs-on-grade particularly when the intention of the reinforcement is to control cracks in hardened concrete (Bischoff et al, 2003). It was also proven that a loose or poor sub-grade support can be simply compensated by reinforcing the slab with a reasonable amount of either WWM or steel fibers. This can be very useful in conditions where proper sub-grade preparation is not entirely feasible (Bischoff et al, 2003).

3 EXPERIMENTAL PROGRAM

3.1 Fibers

Two different types of fibers were used at different volume fractions: 40 mm Mono Fillament Synthetic Polymer Macrofiber, and 2.5 mm Natural Cellulose.

Synthetic Polymer Fibers are synthetic man made fibers resulting from research and development in the petrochemical and textile industries. Synthetic fibers can reduce plastic shrinkage and subsidence cracking and may help concrete after it is fractured (Kosmata et al, 2002). They are also able to increase toughness resistance of concrete. A major advantage compared to steel is that they are totally non corrosive.

The employed Cellulose fibers are easy to use due to their form, low cost, non corrosive, and is considered to be a 'green' building material. Their main function is to decrease cracking due to plastic and drying shrinkage. Other beneficial properties include increased durability of concrete and decreased porosity.

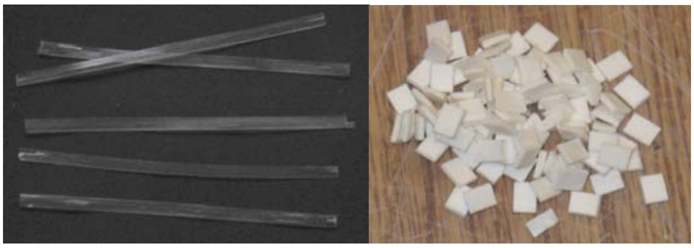

Figure 1: Fibers (Synthetic-L, Cellulose-R).

3.2 Specimen Preparation

Tests were completed on six full-scale (2.5m x 2.5m x 0.1m) concrete slabs; the slabs had been reinforced with various combinations of fibers and welded wire mesh. A summary of the types of slabs cast is given in Table 1:

Table 1: Slab Schedule

SLAB	FIBER TYPE	DOSAGE (kg/m^3)	WWM (Y/N)
A	None	N/A	Y
B	Macro Synthetic	2.4	N
C	Cellulose	1.2	N
D	Cellulose	2.4	N
E	Cellulose	1.2	Y
F	Macro Synthetic + Cellulose	1.2+1.2	N

Ready mixed concrete with an approximate compressive strength of 30 MPa, maximum aggregate size of 14 mm and 5% air content was used for all slabs at a 20°C room temperature. The fibers were added directly to the concrete in the mix truck just prior to casting. Slump for each pour was measured and recorded. Slump values ranged from 80mm-120mm after the addition of fiber. A number of beam (100mm x 100mm x 350mm) and cylinder (100mm x 200mm) specimens were also cast to determine the material properties of the FRC. Both slabs as well as the beam and cylinder specimens were cured for 28/35 days before testing. The slabs were then covered with polyurethane sheeting and wetted periodically.

3.3 Slab Test Procedure

28/35 days after casting, tests were conducted using the setup shown in Figure 3. Each slab was placed on a sub-base consisting of four sheets of rubber stacked on top of each other, providing a total thickness of 100 mm and a modulus of sub-grade reaction of 0.025 N/mm^3. Using a hydraulic jack, a centrally concentrated load was applied through a 100 mm x 100 mm steel plate and was measured by a load cell while lowering the loading arm at a constant displacement rate. The slab deformations were measured using three linear variable differential transducers (LVDTs) at different locations. Figure 4 schematically displays the layout of the LVDTs. The load and deflection readings were stored directly on a data logging system connected to a PC.

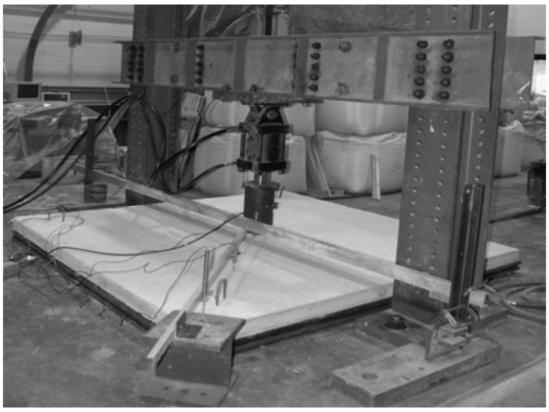

Figure 3: Test setup.

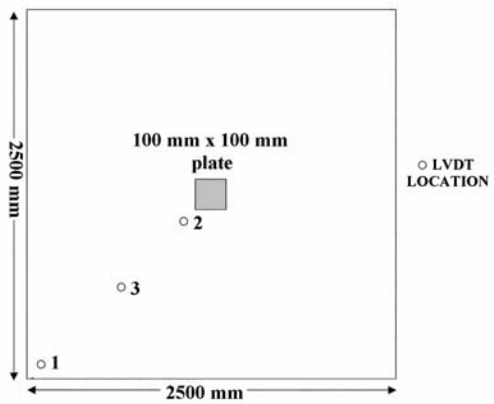

Figure 4: LVDT locations.

3.4 Beam Test Procedure

The fiber-reinforced concrete test beams were tested as per ASTM C1399 (2002) to obtain residual strength values. ASTM C1399, known as the residual strength test method (RSTM), is a technique employed to obtain the post-peak response of fiber-concrete composites. Details for the test procedure can be found in Banthia and Dubey, 1999, and ASTM C1399, 2002.

4 RESULTS

4.1 Slab Behavior

As load was applied, the first cracks to appear on all the slabs were located at the edges starting from underneath the slab and growing toward the top of the slabs. These cracks were very thin and happened prior to failure initiation. Beyond this point, depending on the type of reinforcement, the slabs tended to deform in different manners. In some cases, as load was incremented, a circular plug would form around the central loading plate, and cracks would then propagate outwards radially to the edges of the slab, joining the early edge cracks. Formation of a plug was typically associated with a more ductile failure. In other cases, the slab would fail in a more brittle manner, with failure being sudden and unexpected. No plug would be formed, and failure would be abrupt. Cracks generally formed extending outwards from the center of the slab perpendicular to the edges. In all cases, the slabs would deform by settling at the centre, where the load was applied, and rising towards the edges. In the cases where a plug was formed, after the peak load was reached, the edges of the slabs would settle back down and the slab would flatten back out. The failure types have been defined and shown in Table 2 and Figure 5.

Table 2: Failure Types

Failure Types	
α	Brittle Failure, No formation of plug
β	Ductile Failure, No formation of plug
γ	Ductile Failure, Formation of plug

Figure 5: L-Failure Type α, C-Failure Type β, R-Failure Type γ.

Analysis of deflection data revealed that the slabs reinforced with cellulose and polymer fibers keeps contact with the sub-grade for a much longer period than the slabs reinforced with WWM. The slabs reinforced with fibers did not undergo major displacements until approximately 80% of the peak load (PL), whereas for the WWM slab, the displacements started occurring at about 50% of the peak load (Figures 6+7).

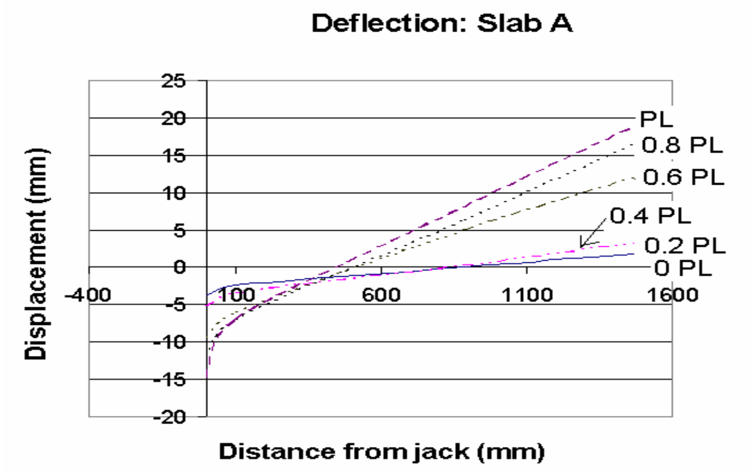

Figure 6: Deflection of Control Slab

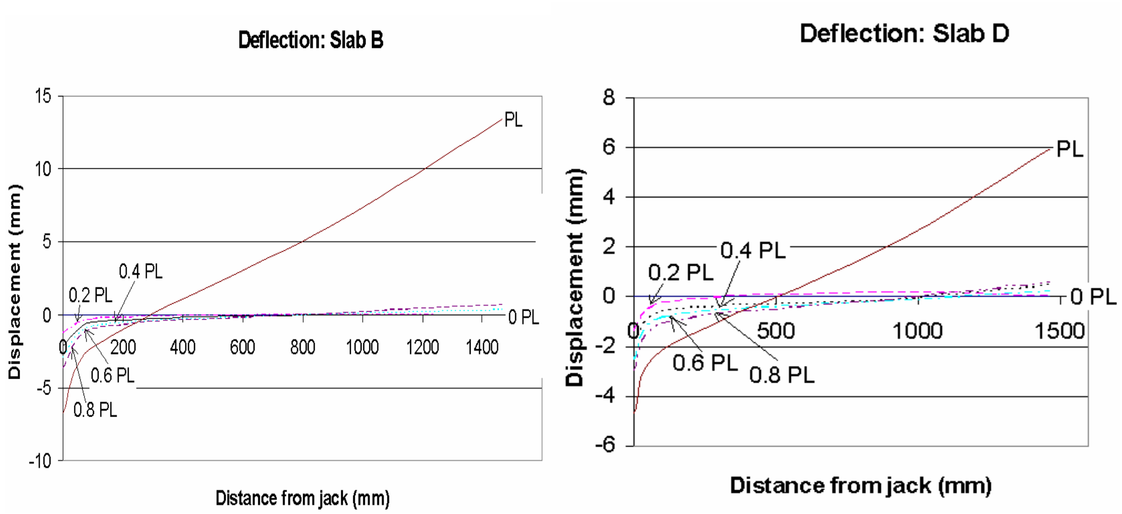

Figure 7: Deflection of Fiber Reinforced Slabs

This assertion can be confirmed by analyzing deflection data from Slab E (Figure 8). This slab was reinforced with WWM supplemented by cellulose fiber. The addition of the cellulose limited deflection of the slab until approximately 80% of the peak load.

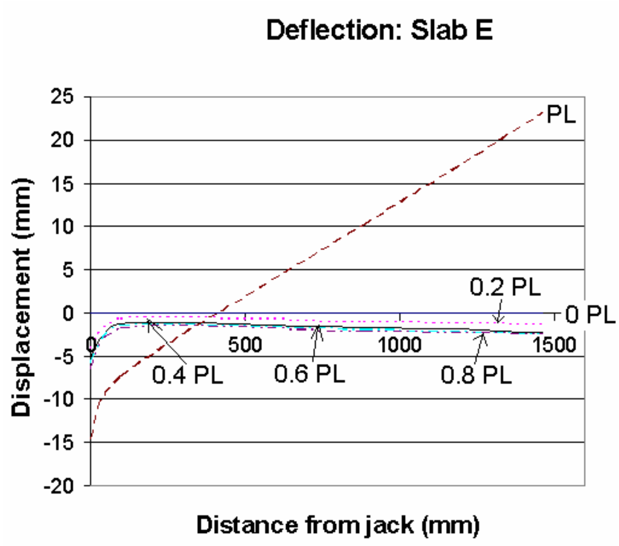

Figure 8: Deflection of WWM + Cellulose Fiber Reinforced Slab

4.2 General Results

Results from each of the tests are summarized in Table 3+4 below:

Table 3: Results

SLAB	AVERAGE COMP. STRENGTH (MPa)	PEAK LOAD (kN)	FAILURE MODE	% INCREASE
A	41.29	149.17	α	N/A
B	28.00	152.91	γ	2.51%
C	34.60	77.56	γ	-48.00%
D	38.04	136.66	γ	-8.39%
E	34.66	227.71	β	52.65%
F	29.64	116.90	γ	-21.63%

Table 4: Energy Absorbed by Slabs

SLAB	A	B	C	D	E	F
ENERGY ABSORBED (J)	1608	2764	500	331	4867	593
% INCREASE	-	71.89%	-68.90%	-79.42%	202.67%	-63.12%

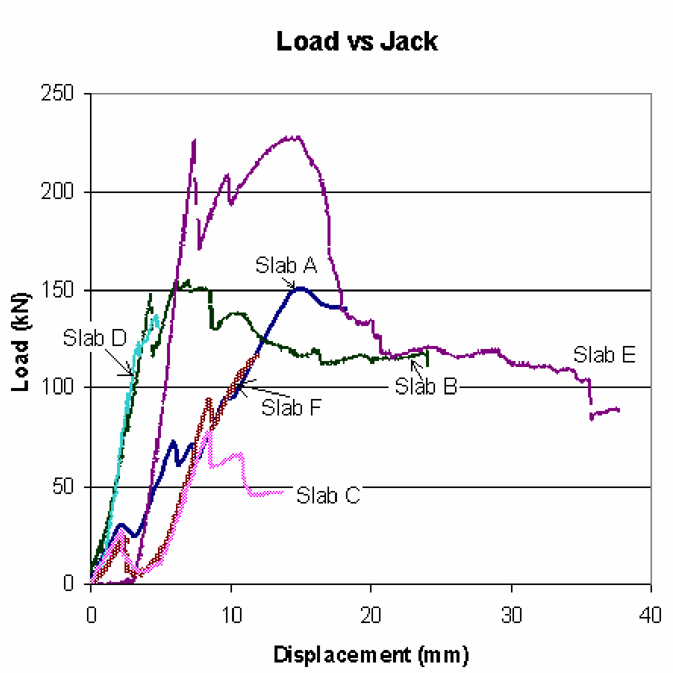

Figure 9: Load vs Displacement Curves of all Slabs

4.2.1 Macrosynthetic Fiber Reinforced Slabs

While the PMF reinforced slab (Slab B) showed a minimal increase in peak load supported (+2.61%) over the control slab reinforced with Welded Wire Mesh (WWM) only (Slab A), analysis of the deflection data showed that Slab B (2.4 kg/m^3 fiber) was more ductile than the control slab, showing an increase of +71.89% (Figure 9). This confirms the assertion made by Bischoff et al (2003) that PMF are effective in reinforcing concrete slabs at higher dosages.

4.2.2 Cellulose Fiber Reinforced Slabs

As there has been little to no research done on the effect of using cellulose fibers to reinforce concrete slabs, it is difficult to predict the type of structural response under loading. It was found that addition of cellulose fiber tends to decrease workability of the mix slightly, most likely due to the absorption of water by the natural cellulose fiber.

With regards to mechanical performance, it was found that on its own, addition of cellulose fiber is not an adequate replacement for WWM. At both low and high dosages, the cellulose fiber reinforced slabs sustained a lower peak load than the control (-48.00%/-8.39%), absorbed far less energy than the control (-68.90%/-79.42%) (Figure 9).

4.2.3 Hybrid Reinforced Slabs

A mixed response was obtained from the hybrid slabs which were reinforced with a combination of fibers or fiber/WWM. Slab F was reinforced with only low dosages of cellulose Fiber + PMF (1.2 kg/m^3 + 1.2 kg/m^3). This slab performed the most poorly of all the slabs tested, showing a decrease in peak load carried, and furthermore was not as ductile as the control slab (Figure 9).

In contrast, Slab E was reinforced with WWM supplemented with low dosage (1.2 kg/m^3) cellulose fiber. This particular combination of reinforcement appeared to perform particularly well when compared to the control slab. There was an increase in peak load capacity of 52.65% and analysis of the LVDT data showed significant increases in ductility/toughness as well (+202.67%). Given that use of cellulose fibers on their own did not perform particularly well, the reason for the sudden increase in performance is curious, and it may be worth performing more tests supplementing WWM slabs with different types of fibers to confirm the trend, and find out whether the performance increase would be worth the additional cost.

4.2.4 Beam Tests

The residual strength of a concrete specimen is a measure of its ability to bear a load even after it has been damaged or cracked. Fibers typically have the ability to increase the post cracking load carrying capacity by acting as bridges and transferring load between the cracks. Furthermore, this also allows the concrete to deform more under increased loading. Therefore, theoretically, the presence of fibers should increase ductility, and this would be reflected in a higher value of the ARS.

Results from the beam tests provide ARS values for different fiber reinforced concrete specimens. As shown in Table 5, concrete reinforced with cellulose fiber has almost no residual strength at all. The specimens containing polymeric macro fiber, on the other hand, demonstrate considerable residual strength, which explains the more ductile behavior of the slabs reinforced with these fibers.

Table 5: ARS Results

Slab	A	B	C	D	E	F
ARS	-	1.22	0.09	0.13	0.09	0.65

5 RECOMMENDATIONS FOR FUTURE RESEARCH

An interesting result from this study was observed from the hybrid WWM + cellulose fiber reinforced slab. Addition of cellulose fiber to the slab significantly increased the mechanical performance compared to the control slab. Given the poor performance of low dosages of cellulose fiber used to reinforce concrete on its own, or even when it is supplemented by PMF, the sudden increase in performance was totally unexpected, and the reason for the increase is unknown. It may be worth performing more tests supplementing WWM slabs with different types of fibers including cellulose fibers to confirm this finding, and find out whether the increase in structural performance would be worth the additional cost.

An important point of interest involves the testing procedure. Rubber mats were placed underneath the slabs to simulate the effect of a well compacted subgrade. However, it is quite possible that in practice, slabs on grade would be poured on subgrades which are not as well compacted and do not provide the same stiffness as the mats used in testing. Bischoff et al (2003) noted that addition of steel fiber or WWM may provide sufficient support for slabs resting on poorly compacted subgrade. The presence of a poorly compacted subgrade may effectively turn portions of a slab on grade into a suspended slab. Given the prevalence of poorly compacted subgrades, it may be well worthwhile to repeat the tests on a simulated poor subgrade to see how well the various forms of reinforcement perform then.

It was found that while the SHM instrumentation used to monitor the slab deformations was adequate for the purpose of this study, a more extensive sensing system may have provided more thorough and precise results. Use of fibre optic sensors (Tennyson et al, 2001) applied to, or embedded in the slab could have provided useful data related to strain distribution, deflections and general slab condition (Yang and Newhook, 2007) (Mufti et al, 2007). Also, it is known that RC and FRC slabs emit discrete bursts of Acoustic Emission (AE) energy when undergoing stress. Degala et al (2009) studied AE monitoring of CRFP reinforced slabs. In retrospect, it may have been useful to instrument the slabs in this study with AE sensors to monitor the difference in the AE signatures of the different types of FRC slabs so that AE sensors could possibly be used in the future for slab structural health monitoring (SHM).

6 CONCLUDING REMARKS

1) Based on the results of this study, it seems that high dosages of polymeric macrofibers can be used to successfully reinforce concrete slabs by increasing their toughness. Given that the use of PMF eliminates the possibility of corrosion of reinforcement, this may be a superior option.

2) Slabs reinforced with only cellulose fiber performed quite poorly. The addition of cellulose fiber tended to slightly decrease workability, but more importantly, the mechanical response

(peak load/toughness) of the slabs reinforced with cellulose fiber on its own was deficient compared to the control slab.

3) It seems that low dosages of either type of fiber act as an ineffective replacement for WWM. Low dosages of PMF and cellulose fiber when added on their own, or in combination together were found to be insufficient in providing sufficient ductility or load carrying capacity compared to the control slab when subjected to the load test, thereby confirming the assertion of Bischoff et al (2003).

4) Analysis of deflection data revealed that the slabs reinforced with either cellulose or polymeric fiber keep in contact with the sub-grade for a much longer period than the slabs reinforced with WWM. Therefore, it seems that the presence of fibers delays major deformation/crack opening of the slab until it is about to fail.

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