FULL SCALE MANUFACTURING OF STEEL FIBRE REINFORCED CONCRETE PIPE

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ABSTRACT

A research project titled “Development of Fibre-Reinforced Concrete Pipes” funded by Con Cast Pipe and Natural Sciences and Engineering Research Council of Canada (NSERC) was conducted between 2011 and 2014 by Professor Moncef Nehdi and his research team at Western University to study the structural behaviour of steel fibre reinforced concrete pipe (SFRCP). 142 pieces of SFRCP, and 58 pieces of conventional reinforced concrete pipe (RCP) and non-reinforced concrete pipe with 300 mm, 450 mm, 600 mm inner diameters were manufactured using existing fully-automated equipment. These SFRCP specimens contain various fibre contents and two fibre types. During the manufacturing week, full production and quality crews were deployed to accomplish the planned activities. Over 300 testing cylinders and 60 testing beams were collected. A portion of the pipes were sent to the university for laboratory work and full scale testing. Another portion was tested in the precast plant using conventional testing equipment. This report presents the manufacturing and testing activities in order to demonstrate the practicality of SFRCP manufacturing. The challenges are discussed and concluded at the end of this report providing insights for any future development of SFRCP.

Keywords: Manufacturing, Steel, Fibre, Reinforced, Concrete, Pipe

1. INTRODUCTION

1.1 Background

Steel fibre reinforced concrete (SFRC) was first introduced in 1960s and was commonly used for crack control. Primary application can be found in non-structural elements such as slabs on grade and curtain wall construction. Although the use of steel fibre in concrete is a technological advancement in civil engineering, the design guideline for structural use was not clear and not included in many design standards.

When steel fibres are mixed with concrete, the combined matrix creates a uniform and balanced mechanical characteristic which compensates for the weak tensile property of concrete. In order to use SFRC in structural elements, it requires significant research effort to develop a full understanding of material behaviour, structural behaviour and design guidelines. The manufacturing process of SFRCP from dosing, mixing, casting, stripping and curing also needs to be examined. In fact, steel fibre has a high potential to be used to supplement or even replace conventional reinforcing steel especially in precast drainage products. Dr. Abolmaali mentioned in University of Taxis Arlington News Centre dated April 1, 2011 that the elimination of cages will make the pipe manufacturing process less expensive and less labour intensive. Subsequently, ASTM C1765-13 “Standard Specification for Steel Fibre Reinforced Concrete Culvert, Storm Drain, and Sewer Pipe” was published in late 2013.

In Canada, there is no industrial standard published for SFRCP. The conventional reinforced concrete pipe is governed by CSA A257.2. Unlike the equivalent American standard ASTM C76, it is performance based. In 2012, a 3-year SFRCP research project was sponsored by a major precast concrete fabricator in Ontario Canada, and funded by NSERC to study the behaviour of SFRCP using full scale experiments, testing, and numerical modeling. To support this project, the first step is to validate that the existing manufacturing technology is capable of fabricating the full scale quality SFRCP. Over a hundred of full scale pipe specimens were manufactured through a regular
production period. It was the first time that the precast fabricator, possibly the industry, introduced the steel fibre into its regular concrete pipe manufacturing process.

1.2 Research Scope

Some technological obstacles were expected during full scale production: the technique for dosing steel fibre into the mixer, the behaviour of the new concrete mix with the consolidation process, the moisture content of the new mix affecting the workability of concrete, the quality of the finished products, the performance tests on the finished products, and the impact in structural behaviour of using steel fibre in complete replacement of conventional reinforcement etc. This report documents the manufacturing experience and conventional performance tests including materials, process, sample collection, inspection, testing, and challenges. Additionally, it was also to explore if the use of SFRC in modern manufacturing equipment requires any additional capital investment and if the total cost of manufacturing is reduced. However, the latter two areas are excluded from this report.

2. MATERIALS AND PIPE SIZE SELECTION

2.1 Concrete

The concrete for all SFRCP specimens was made of a typical commercial mix using dry cast concrete with water-cement ratio between 0.3 and 0.4. The concrete was consolidated through vibration in the mould. The zero slump characteristic allows concrete to be stripped from the formwork immediately after sufficient vibration. The concrete mix properties were reported in the research report by Nehdi (2014).

2.2 Steel Fiber

The first phase of the research project considered various types of fibres. Two kinds of steel fibres were selected to be used in the full-scale test: Dramix RC-65/35-CN and Dramix RC-80/60-CN. The aspect ratio of the fibre (length : diameter) are 65 and 80, and the length of fibre are 35 mm and 60 mm respectively. These fibres are collated with hooked ends (See Figure 1), and are commercially available. It was found that the dosage of 20 kg/m$^3$ was too low to achieve adequate post crack behaviour; therefore, the full scale pipe specimens were prepared with the above mentioned types and their combined hybrid mixture in 20, 30, 40, 60 kg/m$^3$ steel fibre contents.

![Figure 1: 35mm long collated steel fibers with hooked ends (aspect ratio = 65)](image)

2.3 Pipe Size Selection

Nominal size of 300, 450 and 600mm inner diameter pipes were selected. The decision was to consider the quantity of the pipe specimens required for full scale testing and the associated duration of production. However, based on experience, for small diameter pipes 600 mm or smaller, the pipe strength is depends on the concrete strength rather than the reinforcing steel content and its position. Pipe size between 900 mm to 1800 mm depend more on the flexure strength where the strength of inner cage plays an important role. Large diameter pipes, 2100 mm and up, rely on the shear capacity of the reinforcing steel. The total area of steel and its orientation at the upper and lower haunch dictates the ultimate load that the pipe can withstand. That being said, it is more economical to use steel fibre in smaller diameter pipe than larger pipe. Moreover, steel fibres are expected to be evenly distributed (see Figure 2), which enhance the tensile strength overall hence the concrete is less sensitive to the location of steel for flexure strength. Therefore the mixture of concrete and steel fibre provides a more cost effective result in smaller diameter pipes.
3. MANUFACTURING

3.1 Facility

A total of 200 full scale pipe specimens were produced by Con Cast Pipe in their plant located in Oakville, Ontario. The manufacturing system, named EXACT 2500, from Schlusselbauer, Austria, is a fully automated system. The facility, opened in 2002, was the first of its kind in North America. The system was designed to manufacture RCP ranged between 300 mm and 1500 mm diameter, as well as 1200 mm and 1500 mm diameter maintenance hole components.

3.2 Production Plan

Five consecutive production days in the manufacturing facility were scheduled for this project in February 2012. It was to accommodate three full production runs after few trial runs on the first day. During the production, a total of 200 pipes including the three selected size of pipe with no reinforcement, conventional reinforcement and steel fibre reinforcement were produced. Table 1 shows the breakdown quantities of each type. In addition, 330 of 100 mm diameter x 200 mm tall concrete cylinders and 66 of 533 mm x 152 mm x 152 mm testing beams were also scheduled to be cast during this period.

Figure 3 shows the SFRC produced for this research.
### Table 1 Total Produced Quantity of each type of pipe specimen

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Total</th>
<th>Plain</th>
<th>Convention</th>
<th>65/35</th>
<th>80/60</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>96</td>
<td>22</td>
<td>4</td>
<td>25</td>
<td>23</td>
<td>22</td>
</tr>
<tr>
<td>450</td>
<td>50</td>
<td>6</td>
<td>8</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>600</td>
<td>54</td>
<td>14</td>
<td>4</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>200</strong></td>
<td><strong>42</strong></td>
<td><strong>16</strong></td>
<td><strong>49</strong></td>
<td><strong>47</strong></td>
<td><strong>46</strong></td>
</tr>
</tbody>
</table>

**Figure 3**: (a) Left - Fresh SFRCP; (b) Right – Testing pipe specimens, cylinders and beams

### 3.3 Production Process

The process started with weighing the fibres. Because the steel fibre dosing was a manual process, the prescribed fibre was weighed on the scale in several pails. Aggregates were first mixed by the mixer. The fibres were then manually poured into the mixer when the batch was called by the operator. Cement and slag were added after and mixed without water for few minutes. The collated steel fibres were expected to be broken down into pieces during the dry mix period. Water and admixture were introduced last to the mixing cycle. The glue between the steel fibres was further dissolved. When the mixing was completed, the batch was transported through flying bucket into the hopper, where the mix was visually inspected for consistency to ensure the fibres were evenly distributed. The distribution of fibres was also further inspected from the sample collected at this stage using a wash-out test. In this test, a set amount of the mix was randomly collected, weighed and washed. The number of fibres were counted and compared to the expected amount.

In a normal production process, a traditional cold drawn wire cage is fed into the core of the mould. The jacket is placed from the top. Two sets of knives engage from the jacket hold the cage in a pre-determined location inside the mould before concrete enters. This step was completely eliminated in manufacturing SFRCP, as was the cage fabrication. The SFRC was introduced into the mould at a steady rate. Vibration began as soon as the concrete reached a certain level. Until the mould was full, the header machined with the joint profile was pressed into the mould with a twisting motion to form the pipe spigot. The jacket of the mould and the pipe was then removed from the core and placed on the conveyor. The jacket then was stripped from the pipe. Due to the nature of dry cast concrete, the shape of the pipe was completely formed at this stage. To achieve the desired result, moisture content of the concrete is extremely sensitive to the final shape of the product. After the operator visually inspected the pipe, the pipe was moved by the conveyor into the staging area. When enough pipes were waiting along the conveyor, a fully computerized crane transported the pipe into a kiln for accelerated moisture curing. The heat and moisture are fully controlled in the curing chamber by an integrated system. After an 8-to-10-hour curing cycle, cured pipes were taken to the depalletization process, a process to remove the pallet. The pallet which forms the bell end of the pipe was removed by an impact hammer. Pallets were then taken to the cleaning and oiling station for reuse, the pipe was then rotated from a stand-up position to an installed position. Conveyer tracks send the pipe through an inspection station to tip out area. To this point, there is no operator involvement. Finally, pipes were taken by
the forklift in groups to the yard for storage. The process was illustrated in

Figure 4.

In addition to the pipe samples, a group of research assistants and fabricator staff assisted in making testing cylinders and beams. This process was an addition to the normal production process and solely for research purposes. Two vibrating tables were staged to accomplish this activity. Half of the cylinders were reserved for the university to examine and other half were tested on site for 1 or 4-day compressive strength.

4. INSPECTION AND TESTING

4.1 Visual Inspection

Each pipe specimen manufactured was visually inspected. The purpose of this inspection was to examine the quality of the concrete surface, the bell and spigot. In addition, dimensional checks were also conducted to ensure that the pipe met the dimensional tolerance specified in CSA A257.2. Table 2 exhibits the quantity of pipes from visual inspections showing voids or cracks in pipe spigot, bell, inside and outside barrel faces. Quantity of pipe failed Go-no-go measurement, which measures the inner diameter of the pipe, is listed.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Total</th>
<th>Plain</th>
<th>Convention</th>
<th>65/35</th>
<th>80/60</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spigot</td>
<td>88</td>
<td>20</td>
<td>0</td>
<td>25</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>Bell</td>
<td>7</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Outside barrel face</td>
<td>16</td>
<td>8</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Inside barrel Face</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Go-no-go</td>
<td>20</td>
<td>7</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Total Inspected*</td>
<td>200</td>
<td>42</td>
<td>16</td>
<td>49</td>
<td>47</td>
<td>46</td>
</tr>
</tbody>
</table>

*Total inspected quantities do not equal to the sum of the quantity under the described conditions. A pipe may exhibit more than one condition when visually inspected.

4.2 Three-edge Bearing Test

Three edge bearing (3EB) tests were conducted on the pipe specimens as per CSA A257.2. In this test, the pipe specimen is supported by two rubber strips and loaded by a loading beam (Figure 5(a)). The pipe is loaded until a 0.3mm wide by 300 mm long (design) crack appears. The crack usually starts at the invert of the pipe. The pipe is continuously loaded to ultimate failure. The maximum load recorded by the loading machine is called the ultimate load. The class of the pipe is then calculated using the load in kilo-newtons divided by the length of the pipe in metres and the inner diameter of the pipe in millimeters. The class labeled in “D” is a normalized value and is
interpreted as the amount of load can be taken per metre length of pipe and per millimeter inner diameter (N / m / mm). The pipe also required to have a safety factor of 1.5 between the design and ultimate load for 100-D or less, and 1.25 for 140-D or higher. Typical pipe classes commercially available for 300 mm, 450 mm, and 600 mm are 65-D, 100-D, and 140-D.

In this research project, specimens including non-reinforced, traditionally reinforced, and each dosage and type of fibre reinforced pipes were tested. The strength of the pipe was targeted to 140-D. The failure mode of SFRCP begins at the hairline crack similar to those in the conventional RCP. As the crack opens up, the stress is transferred to the steel fibre until the pipe cannot withstand any additional load. It was clear that the steel fibre failed in pull-out or rupture, see shown in Figure 5(b). The test results shown in

Figure 6 and Table 1 are normalized to equivalent pipe classes (N/m/mm). 300 mm pipe reached approximately 290-D, 390-D, and 500-D for fibre contents of 20kg, 40 kg and 60 kg/m³ respectively which showed that higher steel fibre content will produce a higher class of pipe. However with the same fibre content, increase in pipe size reduces the class. For example, SFRC reached 290-D, 190-D and 150-D for 300mm, 450 mm, and 600 mm at 20 kg/m³. At 600mm pipe, SFRC reached 290-D, 190-D and 150-D for 300mm, 450 mm, and 600 mm at 20 kg/m³. At 600mm pipe, SFRC with 20 kg/m³ fibre content was tested to 148-D which was less than the conventional cage design of 179-D, but will still meet the 140-D requirement. Conversely, the 300mm and 450 mm non-reinforced pipe and conventional RCP had very close D-load results (280-D and 284-D for 300 mm, 156-D and 157-D for 450 mm respectively), but far less (114D and 179-D) in 600 mm diameter. This also explains that smaller diameter pipes rely on concrete strength more than the steel content.
Figure 6: Three edge bearing test results

<table>
<thead>
<tr>
<th>Pipe Class (N/m/mm)</th>
<th>300</th>
<th>450</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Size (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>450</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF Dosage (kg/m³)</td>
<td>20</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>80/60</td>
<td>300</td>
<td>396</td>
<td>536</td>
</tr>
<tr>
<td>60/35</td>
<td>292</td>
<td>394</td>
<td>497</td>
</tr>
<tr>
<td>Hybrid</td>
<td>303</td>
<td>388</td>
<td>523</td>
</tr>
<tr>
<td>Cage (140-D)</td>
<td>284</td>
<td>157</td>
<td></td>
</tr>
<tr>
<td>No Steel</td>
<td>280</td>
<td>156</td>
<td></td>
</tr>
<tr>
<td>Requirement</td>
<td>140</td>
<td>140</td>
<td></td>
</tr>
</tbody>
</table>

4.3 Hydrostatic Test

Although the hydrostatic performance was not part of the scope of the research, it was part of the performance requirements according to CSA A257.2. Two hydro tests were conducted using 300 mm and 450 mm specimens respectively with 20 kg / m³ or 40 kg / m³ fiber dosage. The tests mainly examines the ability of the concrete pipe and its joint to withstand an internal hydrostatic pressure of 103 kPa for 10 minutes in proper alignment. The test specimens are also required to withstand an internal hydrostatic pressure of 90 kPa and 35 kPa for 10 minutes in maximum deflected position and under differential load respectively. Unfortunately, none of the specimen passed the required hydrostatic performance. The specimens showed leakage at the joint as well as the barrel of the pipe (See Figure 7). It was believed that the quality of the joint and the consolidation of SFRCP both contribute in providing the required hydrostatic performance. More discussion can be found in Section 5.
Figure 7: Leakage through barrel of the SFRCP in hydrostatic test

4.4 Compressive Test

The compressive strength of concrete was examined on site at 1-day or 4-days old in accordance with CSA A23.2-3C. The cylinder was cast on the day of pipe manufacturing and cured with pipe specimens in the kiln. The compressive test results are summarized in Figure 8. Few cylinders with steel fibres exhibited voids to a certain extent (see Figure 9). The compressive strength results of those cylinders were found to be significantly lower than others; thus they are excluded from the data points. The voids resulted from the ability of the consolidating steel fiber dry cast concrete using the vibrating table. No sign of similar voids showed in any of the pipe specimens. This also explained that the vibrating table may not be adequate in consolidating the concrete cylinder with steel fibres.

In Figure 8, the compressive strength in MPa are plotted against the fiber dosage in kg/m³. The range of strengths are 22 – 64 MPa, 23 – 52 MPa, 24 MPa – 51 MPa, 22 – 38 MPa for 20, 30, 40 and 60 kg/m³ fibre content. The large variance in the result attributes to the different efforts of consolidation and compaction. The higher the dosage, the lower the strength may also be attributed to the same reason.

![Compressive Strength Distribution](image)

Figure 8: Compressive Strength Distribution

![SFR Concrete Cylinder Compressive Test](image)

Figure 9: SFR Concrete Cylinder Compressive Test
5. CHALLENGES

Although all test specimens exceeded the structural requirement, many challenges and obstacles were faced. Pressure was generated in the first two days of production when only 15% of the planned specimens were produced. First of four non-reinforced pipes collapsed few minutes after being stripped on the manufacturing line. Some pipes were observed slumping to one side causing them to be curved. It was discovered that the moisture content was a partial factor in the non-reinforced pipe and SRRCP. The impacts of the core vibration intensity and conveyor speed were also studied. It was concluded that the SFRCP is less tolerable to the moisture content and vibration intensity than conventional RCP. The conventional cage provides better support and ductility to the fresh concrete. It was also determined that the fibre distribution improves with a longer mixing time.

As mentioned in the compressive test section, the team experienced a challenge in casting test cylinders with steel fibres. The vibrating table available for the conventional cylinder testing was believed to have insufficient strength. Lifting anchors and hammers were used to assist in compaction. Despite this effort, those cylinders that exhibited excessive voids with low compressive strength were removed from the analysis. A number of pipes were found to have either broken or cracked spigots, or spigots with excessive voids, see Figure 10. This is attributed to the moisture content at the time of the pressing operation, the insufficient energy being transmitted to the top of the pipe during the vibration process, or the excessive energy being transmitted to the pipe during the depalletization process. This also play a role in failing the hydrostatic test. More trial with different vibration setting and possibly the location of the vibrators may improve the quality of the spigot.

During the visual inspection, steel fibres were found to be exposed on the surface of the concrete (Figure 11). Signs of fibre corrosion were found in aged pipes. The corrosion may not be a major concern due to the fact that the steel fibre matrix was not continuously connected. However, the exposed fibre was a concern to the workforce in terms of safety, and those found in the inner surface of the pipe may also catch debris in the sewage or storm water causing a reduction of flow rate. Hence, the increased risk of turbulence in the open channel flow will affect its serviceability. Nonetheless, failing the hydrostatic test was the major road block to SFRCP research. In order for the SFRCP to be commercialized, the pressure rating in CSA A257.2 must be achieved.

(a) Left – Borken spigot caused by depalletization; (b) Right – voids in spigot due to inadequate consolidation

Figure 10: Pipe Quality
6. CONCLUSION

The scope of manufacturing of pipe specimens for this research project was completed using a fully automated manufacturing system. The system was capable of handling the steel fibres throughout the manufacturing process. The conclusion of this report can be summarized as follow:

1. The evaluation of the impact of using steel fibres to the production facility concluded that the equipment and internal production process are compatible with selected steel fibres and that this could be a complete replacement of the conventional reinforcing cage.

2. With assistance from the steel fibre supplier, the preliminary formula was determined. It was found that the idea dosage shall be maintained below 30 kg / m³. Exceeding this dosage may increase the difficulty in the mixing and consolidating process which leads to a longer production cycle. Within the recommended dosage rate, a consistent distribution of selected fibre was achieved through the normal concrete mixing and batching process.

3. The quality of the product needs further investigation which includes: (a) concrete porosity, (b) excessive voids near joint, (c) fiber exposure on the inner face of the pipe, ext. These areas of research will enhance the pipe surface appearance, and more importantly the ability to withstand hydrostatic pressure.

4. The three edge bearing test showed that SFRCP effectively provides adequate reinforcement in the pipe which allows the pipe to exceed the required design load. The ideal fiber types and contents for each pipe size can be studied. There is room to reduce the fibre contents in 300 mm and 450 mm pipe sizes.

5. There is no major capital investment necessary other than a steel fibre dispenser. The dispenser is readily available in the market to eliminate the manual weighing and dosing operation, and provide an efficient dispensing process. It is highly recommended if the production of SFRCP is to be commercialized.

Future work is required to better understand SFRCP behaviour. This research project proved that the steel fibre is capable to be used as an alternative reinforcing method for structural performance. Design guidelines are required to relate the equivalent dosage rate to the structural behaviour. It may be also possible to combine conventional reinforcing steel and steel fibre to achieve optimum structural behaviour in larger diameter pipes.
ACKNOWLEDGEMENT

1. Con Cast Pipe: SFRCP manufacturer and project sponsor
2. Bekaert: steel fibre supplier and material donor
3. University of Western Ontario: primary researcher
4. NSERC: project sponsor

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