DEVELOPMENT OF TUBE FEEDING EQUIPMENT FOR
CONSTRUCTION OF CONTINUOUSLY REINFORCED CONCRETE
PAVEMENT

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Word count: 4,531 words text + 7 figures x 250 words (each) = 6,281 words

Submission Date: July 31, 2015
ABSTRACT

In South Korea, the performance of continuously reinforced concrete pavement (CRCP) has been better than that of jointed concrete pavement (JCP). However, most of the Portland cement concrete (PCC) pavements in South Korea have been JCP, primarily due to the difficulty in providing extra space along the edge of the pavement needed for concrete delivery in CRCP construction. About 80% of Korea is covered by mountains, and it is quite expensive to acquire and prepare land to provide space for concrete delivery. To build CRCP at a reasonable cost in South Korea, a CRCP construction method is needed that does not require extra space for concrete delivery. Several different methods have been tried that allowed the delivery of concrete to the front of a paver, including a pre-assembly method. Although the pre-assembly method did not require extra space for concrete delivery, it did require a high level of labor and its productivity was quite low. A more efficient method was needed. In a tube-feeding method (TFM), concrete can be supplied from the front of a paver with better productivity. Efforts were made to improve the capability of TFM in placing longitudinal steel at correct elevations. The ability and productivity of the newly developed TFM in placing reinforcing steel in correct elevations were quite satisfactory, and CRCP was constructed with the new TFM. Early age performance of CRCP built with TFM in terms of characteristics of transverse cracks has been satisfactory.

Keywords: Continuously reinforced concrete pavement: CRCP construction: Tube-feeding method
INTRODUCTION
In South Korea, about 60 percent of expressway lane miles of are Portland cement concrete (PCC) pavement, and the remaining 40 percent is asphalt pavement. The reason for a larger portion of PCC pavement in expressways is the ability of PCC pavements to provide better performance for heavy truck traffic with lower maintenance cost. At the early ages of PCC pavement usage in Korea, many miles of continuously reinforced concrete pavement (CRCP) were built; however, a higher initial cost and concerns about numerous transverse cracks resulted in discontinuation of the use of CRCP and more use of jointed concrete pavement (JCP). Another reason for the discontinued use of CRCP is the constructability issue. In South Korea, more than 80 percent of land is mountains, and extra space is needed in CRCP construction for concrete delivery; therefore, CRCP construction in mountainous areas when steel is placed with chairs is cost prohibitive. Meanwhile, the performance of CRCP built at early ages in Korea has been better than that of JCP built even at later ages (1, 2). Also, CRCP and JCP test sections built in 1985 by the same contractor - with the same pavement structure (slab thickness and base type/thickness), concrete materials, traffic, and environmental loading - clearly indicated better performance of CRCP than JCP. This finding has lately prompted a second look at the potential use of CRCP in Korea. However, the issue of extra space needed for CRCP construction to provide concrete still remained. Extra space is not needed for JCP construction, since concrete can be supplied in front of a paver onto a prepared base. For CRCP construction to be feasible in South Korea, concrete has to be supplied in front of a paver so that extra space is not needed.

There are several methods available that allow the delivery of concrete from the front of a paver, eliminating the need for extra space. Methods include the pre-assembly method and the tube feeding method (TFM). In the pre-assembly method, longitudinal and transverse steel are assembled at the jobsite and moved to the front of a paver. Concrete is supplied from the front of a paver, as shown in Figure 1(a). However, due to the weight of the steel assembly as well as the limited extension of the concrete delivery machine, the length of the steel assembly in the longitudinal direction is quite limited, which requires extensive moving and tying longitudinal steel operations, and accordingly, the productivity of this method is quite low. TFM, which allows the concrete delivery in front of a paver without needing extra side space, has been utilized in the US and Europe, with varying degrees of performance. It has been reported that the primary cause for poor performance of CRCP with TFM was the inability to ensure the steel is placed at a proper depth, and the use of TFM in CRCP construction is not recommended (3, 4). On the other hand, a detailed study conducted to compare the long-term performance of CRCP built with the traditional chair method and TFM indicated, from a practical standpoint, no difference between them, as shown in Figure 1(b) (5). It appears that, as long as longitudinal steel is placed at a proper depth within a given tolerance, CRCP construction with TFM can be a viable option in regions where providing extra space for concrete delivery is quite difficult and expensive, such as in South Korea. Compared to the pre-assembly method, the productivity of TFM will be much higher since no moving operations of assembled steel bars are needed and longitudinal steel can be tied together in advance. Efforts were made to develop a TFM that ensures placement of longitudinal steel at a proper depth within allowed tolerances.
CRCP used to be constructed with TFM in several states in the US and in Europe. Figure 2(a) illustrates CRCP construction with TFM in Virginia (6). It is noted that the space between a tube feeder and a paver is rather large, and concrete is placed between the tube feeder and a paver, which could make it quite difficult to control the elevations of steel. It was reported that distresses developed due to the variations in steel depth beyond a tolerance level. If the steel was placed too high in the concrete slab, corrosion of steel and spalling of concrete resulted, as shown in Figure 2(b). On the other hand, if steel is placed too low, crack widths at the top of the slab could be excessive (3). The same type of issue has been reported in South Carolina, where variations in steel depth were quite large in CRCP built with TFM, resulting in poor performance. On the other hand, an in-depth investigation conducted in Illinois showed comparable performances of CRCPs built with a chair method or TFM, as shown in Figure 1(b) (5). In Texas,
CRCP sections built with TFM performed satisfactorily, and the Texas Department of Transportation (TxDOT) specifications allow both a chair method and TFM for steel placement (7), even though the last time TFM was used in Texas was in the middle of 1980s. In Europe, CRCP sections built with TFM have provided satisfactory performance (8). Based on the past experience, it appears that the performance of CRCP built with TFM could be comparable to that of CRCP built with a chair method, as long as the elevations of longitudinal steel are maintained within a given tolerance.

FIGURE 2 (a) CRCP construction with TFM in Virginia and (b) Distress due to steel placed near the surface (6)
This section describes the efforts made to improve TFM in placing longitudinal steel at a correct depth with minimal variations. First, potential causes for a large variance in steel depths with TFM in the past were identified. Next, means to minimize variations in steel depth were devised, and tubes and other parts with proper characteristics were made and assembled.

**Factors Affecting Steel Elevation in TFM**

In manual steel placement method with chairs, the elevations of steel in areas between adjacent chairs are secured by transverse steel. On the other hand, in TFM, there are no chairs, and therefore no vertical support, so the steel elevations should be secured by other means. Since there is no vertical support for steel in TFM, it is essential that longitudinal steel elevation should be guided by tube elevation, and adequate tension is maintained in longitudinal steel during construction. Since concrete is supplied from the front of the tube feeding machine at a certain height, there will be concrete weight loading on longitudinal steel, which could impact the final elevation of longitudinal steel. The maximum steel deflection due to self-weight of steel and over-burden concrete weight is computed by the following equations:

\[
\frac{d^2y}{dx^2} = \frac{P}{E} \frac{y}{I} = \frac{wL}{2EI}x^2 - \frac{w}{2EI}x
\]  

\[
y = \frac{EIw}{P^2} e^{(L-x)\sqrt{\frac{P}{EI}}} + e^{\frac{x}{\sqrt{EI}}} - e^{L\sqrt{\frac{P}{EI}}} - 1 - \frac{w}{2P}x^2 + \frac{wL}{2P}x
\]

where,

- \( y \) = deflection of steel
- \( x \) = distance from the end of the tube
- \( P \) = tensile force in steel
- \( w \) = weights of steel and over-burden concrete
- \( L \) = distance between the end of tube and the front of the mold
- \( E \) = modulus of elasticity of steel
- \( I \) = moment of inertia

Equation 1 is the governing equation and, with the boundary condition of \( y=0 \) at \( x=0 \) and \( x=L/2 \), the Equation 2 is obtained. In the modeling of tube feeding equipment, it was assumed that the steel is fixed at the front of the mold and supported by roller at the end of the tube, which may not represent the real situation perfectly; however, it was considered that the assumptions were adequate for this work. Figure 3(a) illustrates the relationship between exposed steel length, defined here as the distance between the end of a tube and the start of the mold, and deflection of the steel for various tensile forces in the steel. The figure shows beneficial effects of tensile forces in the steel deflections while, with no tensile forces, the deflections increase exponentially with exposed length. For example, with the exposed length of 1,000 mm, the deflections could exceed the tolerance limit of 12.5 mm. It also shows that tensile forces in the range of 196 N and 589 N reduce steel deflections substantially, while no appreciable difference is observed in steel deflections for the range of tensile forces analyzed here. Based on this analysis, it was decided to provide tensile forces in steel of the values in the range analyzed here.
Choi et al.

Several methods to induce tensile forces in the steel were considered, and it was determined that frictional forces by the use of curved tubes would be the most efficient and practical. To determine the optimum radius of the curved tubes, experiments were conducted. Tubes with six radii were made – 5,000, 6,000, 7,000, 8,000, 9,000, and 10,000 mm – and pull-out testing conducted. The inside and outside diameters of the tubes were 50 mm and 60 mm, respectively. Figure 3(b) shows the testing results: the frictional force decreased rather quickly as the radius increased from 5,000 mm to 8,000 mm, while it changed little for the radius above 8,000 mm. Based on the analysis and test results, a radius of 9,500 mm for tubes and 1,300 mm for the distance between the end of tubes and the front of the mold were selected for tube feeding equipment.

FIGURE 3 (a) Exposed rebar length vs deflection and (b) Radius of tube vs pull-out force
Another factor influencing steel placement depths could be concrete consolidation under the paver. In general, a paver progresses at a rate of one meter per minute, with vibrators on at about 8,000 vibrations per minute. The concrete consolidation operation might affect the elevations of steel. To investigate the effects of concrete consolidation on the settlement of steel, an experiment was conducted. Forms for three concrete blocks, each 500 mm in width, 300 mm in height, and 10,000 mm in length, were fabricated and two #6 reinforcing steel (D=19 mm) with 9,000 mm long were placed at the mid-depth with tie wires at two blocks, as shown in Figure 4(a). Concrete was placed into all three forms, tie wires that were supporting the steel in two blocks were removed, and two #6 reinforcing bars (D=19 mm) were placed on top of the concrete in the third block, as shown in Figure 4(b). A slip-form paver proceeded with a speed of one meter per minute, with one vibrator in each concrete block running at about 8,000 vibrations per minute, which simulated actual concrete consolidation occurring during concrete paving with a slip-form paver. The depths of steel bars were evaluated after the slip-form paver completed consolidation of concrete. The settlements of steel bars placed at the mid-depth were in the range of 5 to 20 mm, while those of steel bars placed at the concrete surface varied from 3 mm to 18 mm. Most states limit the vertical variation of steel depth to ± 12.5 mm. The settlements observed at some locations in this experiment exceeded the maximum tolerance; however, the maximum settlements occurred at the end parts of the bars. The settlements in other parts of the bars were quite small, within 8 mm. This experiment indicated that, if steel bars are continuous, vibration operation by a slip-form paver would not cause settlements of steel bars greater than the afore-mentioned tolerance limits.
FIGURE 4 (a) Forms for steel settlement experiment and (b) Vibration of concrete

This experiment did not simulate the compression of concrete that occurs during concrete placement due to the weight of a slip-form paver. However, it is postulated that the compressive stresses on the steel due to the compression of concrete are equal in all directions, as concrete is liquefied by vibration, and the settlements of steel bars due to compressive stresses might be negligible. Based on the findings from analysis and testing results, it was decided that tubes with a radius of 9,500 mm would be used for the manufacture of a tube feeding equipment.

Structure of Tube Feeding Equipment (TFE)

TFE is self-propelled equipment with its own power system and consists of three components – concrete receiving module, tube module, and vibration module. The paving system using TFE developed in this study is shown in Figure 5(a). It shows that longitudinal steel was placed on the edges of the base layer, which provides a space in the middle portion for concrete trucks to have access to the concrete delivery equipment. Concrete is delivered to the TFE through a conveyor belt. Figure 5(b) illustrates the TFE, with concrete receiving and tube modules shown. Figure 5(c) shows the side view of the TFE. Tubes have flared ends, with 105 mm diameter. Also, tubes with various lengths were used, from 1,800 mm to 2,250 mm, to accommodate the various radii of longitudinal steel in front of the TFE. Figure 5(d) illustrates underside of the TFE, with tubes, vibrators and auger shown. Rubber plates were installed to protect the ends of tubes, so that concrete cannot get into the tubes. The vibrator module consolidates the concrete in order to reduce any stresses imposed on steel by concrete, with the goal of minimizing the variations of steel elevations.
FIGURE 5 (a) Paving system with TFE, (b) Front view of TFE, (c) Side view of TFE, and (d) Underside view of TFE

CRCP CONSTRUCTION WITH TFE

Once the TFE was assembled, its performance in placing steel in the right elevations within a given tolerance level was evaluated. The testing was conducted on September 26, 2013 in a section of freeway that was not in use due to re-alignment of the freeway. At the beginning of the test section, longitudinal steel was placed with chairs and transverse steel, quite similar to normal manual placement of steel. A paver was brought to the beginning of the test section, TFE was placed to the front of the paver and longitudinal steel was fed into the TFE. Concrete was supplied from the front of the TFE. While the TFE progressed, the elevations of longitudinal
Choi et al.

Steel were periodically checked by removing concrete and exposing longitudinal steel. They were all within the tolerance limits of ±12.5 mm of a target elevation, except at a pavement edge, where excessive mortar was accumulated at the edge due to super-elevation of the section. Figure 6(a) shows the concrete being placed by TFE and the tension in the steel being adequate to support about 70 kgf (686 N) weight. Once the concrete was hardened, two full-depth concrete saw cuts were made in a transverse direction at 300 mm apart. Concrete block was removed and steel depths were evaluated as shown in Figure 6(b). There were a total of 49 longitudinal bars, and all the bars were within ±12.5 mm tolerance limits, except at the pavement edge.

The ability of TFE in placing longitudinal steel at a correct elevation was confirmed in a trial with a test section, and TFE was used to construct CRCP as part of an expressway system in Korea. There was a jointed concrete pavement construction project in Goryeong, in the southern part of Korea, and a field change was made to place 400 meters of CRCP. The construction began on December 5, 2013 and was completed in the same day. Total width of the pavement was 8.4 meters. The construction of CRCP with TFE in this project is shown in Figure 5(a). Longitudinal steel bars of 9 m length were tied with couplers, and placed along the edge of the base one day prior to the concrete placement.
During the construction, the elevations of steel were checked at six different locations just after the TFE. The locations were identified as a distance from a string line as well as a marking at the string line. Concrete was removed to expose the steel, steel depth measured from the bottom of the slab, and concrete was put back. Once the paver passed, the depth of the steel was measured at the same location. These comparisons were made at six locations, and the difference in steel elevations at these six locations was almost negligible, ranging from 1 mm to a maximum of 6 mm, indicating that concrete consolidation operations by a paver do not alter the steel depth appreciably with the tension provided in TFE.

**Performance of CRCP constructed with TFE**

The CRCP section built with TFE is less than two years old, and it is too early to evaluate its performance. Instead, early age behavior in terms of transverse crack characteristics was evaluated. Three traits of transverse cracks are reported to be related to long-term performance: crack spacing, crack width, and meandering of cracks. Crack spacing and crack width are determined primarily by concrete placement temperature, the amount of longitudinal steel, and concrete properties such as coefficient of thermal expansion \((9, 10)\). These variables are independent of construction methods – either traditional chair method or TFE. Accordingly, field evaluation of CRCP built with TFE focused on the meandering characteristics of transverse cracks. One document recommends the placement of transverse steel primarily in order to achieve straighter transverse cracks \((11)\). Since no transverse steel was used in this test section, the probability of meandering cracks might increase. One method proposed to quantify the degree of meandering of cracks is to quantify the skewness of transverse cracks, called randomness index (RI) \((12)\). RI is a mathematical model for predicting the randomness rating using certain physical measurements of a crack. When a crack is straight and perpendicular to the pavement centerline, RI of the crack would be 5.5, while that with 45 degrees to the pavement centerline has an RI of 2.1. Cracks more deviant from straight and perpendicular to the pavement centerline will have a larger RI value of cracks. RI values evaluated in CRCP constructed with the chair method were in the range of 1.6 to 5.0 \((12)\). RI values were estimated on typical cracks.
observed in the section built with TFE and the results, shown in Figure 7, show RI values in the range of 2.4 to 5.5, which is well within the range of values reported for cracks in CRCP built with the chair method.

![Randomness Index (RI) Distribution](image)

**FIGURE 7 Randomness index (RI) distribution**

**Potential Issues Related to CRCP Constructed with TFE**

Transverse steel design has been based on subgrade drag theory, which requires more transverse steel (smaller spacing between transverse steel) as more lanes are tied together. The use of subgrade drag theory for the design of transverse steel implies keeping longitudinal cracks if they occur, reasonably close. However, longitudinal joints are provided at every 3.6 m spacing, and curling stresses for slabs with 3.6 m width are maintained quite small (13). Accordingly, longitudinal cracks are not likely, if longitudinal joint saw cuts are made early enough with a proper depth. Also, in practice, subgrade drag theory is not used, and transverse steel spacing is normally fixed regardless of how many lanes are tied together. For example, in Illinois DOT, #4 bars (D=12.7 mm) are placed at 1.2 m spacing (14), while in Texas DOT, #5 bars (D=16 mm) are placed at 1.2 m spacing (15). The amount of transverse steel used in practice when more than 4 lanes are tied together is smaller than the value from subgrade drag theory, which implies that, in current practice, the role of transverse steel is to provide support for longitudinal steel. In jointed concrete pavement, transverse steel is not placed. Since TFE developed in this study places and is able to keep longitudinal steel at correct elevation within a tolerance level, transverse steel may not be needed when placing CRCP with TFE.

**CONCLUSIONS AND RECOMMENDATIONS**

In South Korea, the performance of CRCP has been better than that of JCP. However, most of the Portland cement concrete pavements in South Korea have been JCP, primarily due to the difficulty in providing extra space needed for concrete delivery in CRCP construction, because 80% of South Korea is mountainous. To build CRCP at a reasonable cost in South Korea, a CRCP construction method is needed that does not require extra space for concrete delivery – a method that would allow the supply of concrete from the front of the paver. In a tube
feeding method (TFM) that was used in the past for longitudinal steel placement, concrete can be supplied from the front of a paver, eliminating the need for extra space on the side of the pavement for the delivery of concrete.

The use of TFM in CRCP construction has been banned by some states due to the difficulty in placing longitudinal steel at the right elevations, which resulted in performance issues. Even where TFM is allowed, its use in CRCP construction has almost disappeared due to the advent of more efficient and inexpensive chairs and contractors’ increasing familiarity with steel placement with chairs. However, there are places where TFM could be quite useful for CRCP construction if TFM could place longitudinal steel at correct elevations within a tolerance level. Efforts were made to improve the capability of TFM in placing longitudinal steel at correct elevations, and tube feeding equipment (TFE) was developed that enhanced the capability of placing longitudinal steel at correct elevations. CRCP was constructed with the newly developed TFE and early age performance was monitored. Based on the findings made so far, the following conclusions could be made:

1. TFE with a capability of placing longitudinal steel within ±12.5 mm of a specified elevation was developed.
   A. The key to ensuring steel placement at a correct elevation was to keep longitudinal steel in adequate tension.
   B. Structural analysis showed that 196 N of tensile force in steel was sufficient to limit the settlement of steel within 12.5 mm. The distance from the back of the tubes and the front of the mold, up to 1,500 mm, did not have substantial effects on the steel settlement.
   C. Several ways were identified for providing tensile force in steel while TFE progressed, and utilizing tubes with an adequate curvature was the simplest way. TFE developed in this study used tubes with 9,500 mm radius.

2. To evaluate the viability of CRCP construction with TFE, a 400 meter long CRCP section with 8.2 m wide and 300 mm slab thickness was constructed.
   A. Splicing of longitudinal steel, which is 9 m long, was made with couplers. Longitudinal steel bars thus pre-assembled at the jobsite were placed at a maximum about 30 degrees from the inset of the tubes to the edges of the pavement, at which point they were placed parallel to the centerline of the pavement at pavement edges. This setup allowed concrete placer in the middle of construction area and in front of the paver.
   B. The productivity of CRCP construction with a TFE developed in this study was quite satisfactory, only limited by the rate of concrete supply.
   C. To evaluate elevations of longitudinal steel in hardened concrete, a concrete slab was cut full-depth in a transverse direction at two locations with 300 mm spacing. Locations of longitudinal steel thus evaluated from the slice of the concrete slab were all within the tolerance limits (±12.5 mm from a target elevation) except at a pavement edge due to super-elevation.
   D. The elevations of longitudinal steel were evaluated during the construction, by removing fresh concrete at random locations. At almost all the locations, they were within the tolerance limits.
The characteristics of transverse cracks – meandering of cracks – were evaluated. Meandering of cracks in terms of randomness index was comparable to that of CRCP built by traditional manual steel placement method with chairs.

TFE allows CRCP construction in areas where securing extra space needed for concrete delivery from sides of the roadway is quite expensive. Also, TFE does not require transverse steel, which lowers initial construction cost slightly. Even though the early age behavior of CRCP built with TFE is comparable to that of CRCP built with manual steel placement method, long-term performance needs to be further monitored.

ACKNOWLEDGMENTS

This research was supported by a grant (14TBIP-C073609-01) from Technology Business Innovation Program (TBIP) funded by Ministry of Construction & Transportation of Korean government.
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