Considerable research has already been conducted on the mechanical response of fiber reinforced plastic (FRP) tendons for use in pretensioning and post-tensioning concrete structures. This research has been performed primarily outside of the United States and directly by tendon manufacturers. An experimental investigation was undertaken to provide a domestic evaluation of the mechanical performance of ten different aramid, glass, and carbon FRP tendons, with attention paid to the effects of the anchorage device recommended by the manufacturer. The first phase of the project herein reported consisted of the verification of some tendon-specific properties, namely: ultimate strength, modulus of elasticity, and ultimate strain. It was determined that, given the limitation of the experimental program, a reasonable correlation exists with data supplied by manufacturers. In most cases, the anchorage devices permitted the tensioning to failure of the FRP tendons. Ultimate load capacity was generally controlled by the anchor rather than the tendon itself, suggesting that anchor efficiency could be improved. It was determined that heating one anchor to 60°C (140°F) had no detrimental effect on the tensile performance of the tendon-anchor system.
Concrete is conventionally reinforced with steel bars and tendons. It is well known that the deterioration of concrete structures can mostly be attributed to corrosion of the reinforcing steel. This results from exposure to environments high in moisture and chlorides. Chlorides come from sources such as sea water or de-icing salts used in the wintertime on bridges and parking garages.

Coating the steel reinforce ment with a layer of epoxy has been the most common method of several practices used for controlling corrosion. Some recent failures have left doubts about the dependability of epoxy-coating protection.\(^1\)\(^2\)\(^3\) Galvanizing of steel reinforcement, another form of protective coating, is suspected of unsatisfactory protection in chloride-contaminated concrete, of impairing steel to concrete bonding, and of causing hydrogen embrittlement of prestressing tendons.\(^4\)

Instead of protecting steel with a coating that can be damaged and become ineffective, a solution to corrosion control of prestressed and non-prestressed concrete can be found by removing the steel altogether and replacing it with fiber-reinforced plastic (FRP) composites. Such a solution has to be proven valid in terms of economics, construction, and long-term performance.

FRP reinforcement can have advantages over steel in being lighter in weight, higher in tensile capacity, more resistant to corrosion, and electro-magnetically transparent. Several manufacturing methods are available for fabrication of FRP reinforcement for concrete. For rod- and grid-type reinforcement, pultrusion and braiding are the most commonly used manufacturing methods because of low cost, high quality, and efficient fiber orientation. Flat or round FRP rods come in a variety of surface shapes: dimpled, indented, or coated with sand in order to provide better bonding with concrete.

FRP composites have already been used in pedestrian and roadway bridges in Europe and Japan.\(^5\)\(^6\)\(^7\) They have been used to reinforce masonry walls, railway sleepers, pontoons, barges, and many special structures.\(^8\) They have also been used as a replacement for cables in new suspension structures or as ground anchors.\(^9\)

With regard to anchorage devices for FRP tensioned systems, several considerations must be taken into account, such as efficiency, effects on FRP materials, and corrosion resistance.\(^9\) Each available type of FRP reinforcement differs not only with respect to fiber and matrix types, but also with respect to manufacturing, geometry, and mechanical properties.

These differences make difficult the design of anchors with adequate grip that do not produce damage to the tendon. Low strain at failure and low transverse stiffness increase the tendency for FRP composites to fail at the anchors. The problem becomes even more critical in the case of permanent anchors (unbonded post-tensioned systems) where anchor performance must be assured for the entire life of the structure.

The scope of this paper is to provide an evaluation of some of the commercially available FRP tendon-anchor systems for application in prestressed concrete structures through the laboratory verification of anchor efficiency and tendon strength, stiffness, and ultimate elongation. Tension to failure tests were conducted using anchors suitable for prestressing operations in order to provide a meaningful database for field applications.

### PRODUCTS AND MATERIALS

Properties and characteristics of the tendon/anchor systems used in this project are discussed next and summarized in Table 1. The trade names of the products are used for clarity of reference. The list order is based on type of anchor system (i.e., wedge, molded, and spike anchors). Within each type of anchor system, the list has been arranged alphabetically by fiber type (i.e., aramid, carbon, glass) and product name.

**Arapree** — Arapree was a combined development of AKZO Chemicals and Hollandsche Beton Groep, the Netherlands. Recently, manufacturing rights have been transferred to Sireg S.P.A., an Italian industry. Arapree consists of aramid (Twaron) fibers embedded in epoxy resin. Two
types of cross section are available in the market place: rectangular and circular. The former may be easier to grip with a wedge anchor system. Two round rods of 7.5 and 10 mm (0.27 and 0.39 in.) were used in this study. Manufacturer’s data (based on gross cross section) for these rods are listed in Table 1.

The anchoring system developed for Arapree, both flat and round rod types, consists of a tapered metal sleeve into which the tendon is either grouted (post-tensioning application) or clamped between two wedges. The latter was used for this project (see Fig. 1). The wedge anchor, designed primarily for temporary use, is made up of a steel socket and two semicylindrical tapered wedges made of Polyamide PA6. The outer surface of the wedges and the inner surface of the metal socket are smooth and noncoated. The inner surface of the wedge trough that holds the tendon is similarly smooth and gripping of the tendon relies solely on the frictional resistance provided by the plastic.

**FiBRA** — Mitsui Construction Company of Japan produces an FRP rod known as FiBRA. The rod is formed by the braiding of fiber tows followed by epoxy resin impregnation and curing. Different types of fibers are used with aramid being the most common. Depending on small variations in the manufacturing process, two types of rod, rigid and flexible, are produced. Rigid rods are mainly used for concrete reinforcement whereas flexible rods, which can be coiled, are used as prestressing tendons. In this project, a 12.7 mm (0.50 in.) nominal diameter aramid-based tendon of the flexible type was used (see Table 1).

FiBRA has two different types of anchoring system: a resin-potted anchor used for single tendon anchoring and a wedge anchor for either single or multiple tendon anchoring. The latter was used in this project (see Fig. 2). This anchor is made of four steel wedges (held together by an O-ring) that slip inside a steel cylinder with a conical interior surface. Grit is applied to the inner surface of the wedges. The exterior surface of the wedges and the interior surface of the steel cylinder are coated with a dry lubricant to assist in seating and removal of the anchor.

**Carbon Stress** — Carbon Stress is the trade name of a prestressing tendon manufactured by Nederlandse Draad Industrie, a subsidiary of the Dutch steel producer Hoogovens. The original technology for this prestressing system was developed by AKZO Chemicals and is similar in manufacture to Arapree. Both flat and round bars are currently available. Both bar types are formed through pultrusion of epoxy-impregnated carbon fibers. The flat bar is dimpled with a hatched pattern to create a better bonding surface. The round bar is coated with sand. Both types of tendons were obtained for testing (see Table 1).

Carbon Stress employs anchoring devices similar to those of Arapree. One difference is in a dry lubricant coating on the exterior surface of the plastic wedges to assist in setting of the wedges. This also aids in removal of the wedges after use. In addition, wedges for flat tendons are prepared by the manufacturer with a sand-coated surface in the grip zone (see Fig. 3). The wedges for the round tendons come with instructions to apply a
layer of epoxy and sand into the groove that holds the tendon. In both cases, the function of the sand-coating is to increase the gripping capability of the anchor.

**Leadline** — Mitsubishi Kasei Corporation of Japan has developed a pitch-based carbon FRP rod called Leadline that is pultruded and epoxy-impregnated. There are several varieties of Leadline rods that differ in pattern and method of fabrication of their surface deformations. Smooth rods have no surface deformations. Indented rods have two shallow helical depressions in the surface that spiral in opposite directions. Ribbed rods have either raised helical windings similar to the indented pattern or a circumferential winding transverse to the longitudinal axis of the rod. An indented, 8 mm (0.31 in.) diameter tendon was used for this project (see Table 1).

Leadline utilizes a modified wedge system to anchor the tendons (see Fig. 4). The modification comes in the form of an aluminum sleeve that fits between the wedges and the tendon. The sleeve has four independent arms that extend along the length of the tendon. The wedges are placed around the sleeve such that the gap between adjacent wedges falls over the solid portion of the sleeve. The sleeve is intended to spread the stresses imposed on the tendon by the wedges. A plastic film is placed around the whole assembly to secure the multiple pieces together for insertion into the steel socket.

**Technora** — Technora rod is a product jointly developed by Sumitomo Construction Company and Teijin Corporation, both of Japan. Named for the brand of aramid fiber used in its manufacture, Technora is a spirally-wound pultruded rod impregnated with a vinyl ester resin. Manufacturing of a spirally-wound tendon begins with pultruding the impregnated straight bundles through an unheated die. Identical fiber bundles are wound spirally around the rod to produce a deformed surface. Longitudinal fiber bundles are added to the outer surface before a second spiral winding is added. The product is then cured in an oven.

Technora tendons employ either wedge type or potted type anchorages. Anchorages for a single rod or multiple rods numbering from 3 to 19 rods are available. The potted anchors used in this project were developed for use with the spiral wound rods and are constructed so that the rod is inserted into a housing and then fixed with injected grout (see Fig. 5). A screw thread is cut into the outer surface of the housing so that the anchor can be secured with a nut onto a bearing plate. An 8 mm (0.31 in.) diameter, spirally-wound rod with potted-type anchors installed by the manufacturer was used in this project (see Table 1).

**CFCC** — Carbon Fiber Composite Cable (CFCC) was developed by Tokyo Rope and Toho Rayon Co., both of Japan. The cable is formed by twisting a number of small-diameter rods (e.g., 7, 13) similarly to a conventional stranded steel tendon. Materials used for CFCC include PAN-based carbon fiber and epoxy resin developed by Tokyo Rope.

Multiple pieces of prepreg (i.e., semi-hardened tows with a resin precursor) are made into a bundle that is treated with a proprietary coating and formed into a small-diameter rod. A number of these rods are then stranded and formed into a composite cable that is heated and cured to form the finished product. The coating protects individual rods from ultra violet radiation and mechanical damage while increasing the bond characteristics with concrete. Table 1 shows the properties of the seven-wire tendon examined in this investigation.

CFCC anchoring methods are classified as resin filling and die-cast methods by the manufacturer. The anchoring systems are chosen based on the intended application. The resin
filling method bonds the cable to a steel cylinder utilizing a high performance epoxy. These cylinders can be threaded as necessary to allow anchoring with nuts. The die-cast method attaches the cable to a steel tube by means of a molten and die-molded alloy. Steel wedges are then utilized to clamp the steel tube similarly to steel tendon systems. For this project, resin filled sockets installed by the manufacturer were utilized (see Fig. 6). The length of the metal cylinder is dependent but the standard length is 13.5 times the rod diameter.

**Lightline** — The only domestically produced tendon examined in this project was the Lightline cable from Neptco, Inc. This FRP tendon is stranded from seven individual rods (one central rod surrounded by six others), mimicking a conventional seven-wire steel strand. The individual rods were simply twisted together and held in place by straps. The Lightline cable is a composite of E-glass fiber and epoxy resin with properties as given in Table 1.

At the time of testing, the manufacturer had not developed the anchoring system to be utilized with this particular tendon. A resin potted anchor with a parabolically tapered interior surface was chosen as the anchoring system. This steel anchor is threaded on the outside to receive a matching nut. The laboratory preparation of the anchor for use with the Lightline tendon involved several steps as described in the literature. Sikadur Hi-Mod 35LV epoxy was used for potting the anchors.

**Parafil** — Linear Composites of England is the producer of a parallel-lay rope composed of dry fibers contained within a protective polymeric sheath. Parafil was originally developed in the early 1960s to moor navigation platforms in the North Atlantic. A variety of fiber types may be used; those of primary interest for prestressing are the Type G ropes (Kevlar 49 aramid fibers) as considered in this investigation (see Table 1). The cross-sectional area of the rope used in this project is based on a 10.5 mm (0.41 in.) diameter, determined by subtracting the sheath thickness to the nominal diameter. Parafil has several features that distinguish it from other prestressing systems: it cannot be bonded to concrete; it contains no resin; and it was not initially developed for prestressing. Nevertheless, it has been used for prestressing concrete on a number of occasions.

Parafil ropes are anchored by means of a barrel and spike fitting, which grips the fibers between a central tapered spike and an external matching barrel (see Fig. 7). It has been suggested that aluminum alloy, galva-
nized mild steel, stainless steel and other materials can be used for the anchors because this scheme takes advantage of the fibers of the rope simply by being tightly packed in the protective outer sheathing.

TEST EQUIPMENT AND PROCEDURE

Test Equipment

The test equipment used to tension specimens to failure was a universal testing machine set in displacement control. Electronic equipment consisted of one load cell, one clip-on extensometer, and two potentiometers. The internal load cell and extensometer of the testing machine were used to double check the measurements of load and displacement of the moving cross-head. The equipment arrangement is shown in the sketch of Fig. 8.

Test Procedure

Each specimen was cut to a 1200 mm (74.2 in.) length and one anchor was installed at one end of the rod (except for Technora and CFCC, which had both anchors pre-installed by the manufacturer). This unit was then inserted into the test frame with the prepared anchor resting on top of the load cell that was sandwiched between two 12.7 mm (0.5 in.) thick plates. Another 12.7 mm (0.5 in.) thick plate and anchor were then attached to the lower end of the rod. The moving cross-head of the test machine was positioned so that the plate at the lower end was snug without stressing the tendon.

The length of the specimen from anchor to anchor was measured for calculations of the nominal strain. The clip-on, 25.4 mm (1.0 in.) gauge length extensometer was attached to the specimen at the onset of the test by means of built-in attachment springs. All tests were conducted at a loading rate of 0.635 mm/min. (0.025 in./min.). Safety precautions were taken to protect operators and equipment from brittle failures. The extensometer was removed prior to failure for protection of the device. Potentiometers were always in place to measure the displacement of the moving cross-head.

High Temperature Test

One of the anchor/tendon systems (i.e., FiBRA) was chosen to undergo a direct tension test when the anchor was elevated to high temperature. The same test setup as for the room temperature tests was used except one of the anchors was wrapped with a heating blanket and allowed to come to equilibrium at 60°C (140°F) for 2 hours before the tension testing was performed. The selected temperature level was chosen to represent the maximum value for a weather exposed system in hot climates.

TEST RESULTS

Data obtained from each test were plotted on sets of graphs similar to those shown in Figs. 9 to 11. These figures represent typical cases for wedge-type anchor systems such as FiBRA (see Fig. 9) and Leadline (see Fig. 10), and potted-type anchor systems such as CFCC (see Fig. 11). An explanation of the three graphs in each figure follows:

(a) The upper graph shows the load
vs. time relationship to display the overall tendon/anchor performance during the test. A period of lower slope at initial times is evidenced in the wedge anchor systems when the wedges are seating themselves into the terminals and the system is stiffening.

(b) The middle graph shows two strain vs. time relationships. The lighter line is based on the nominal strain, computed as the displacement of the cross-head divided by the tendon length between anchors. It is always a linear relationship corresponding to the constant increase in displacement over time. The heavy line is the extensometer record of strain on the tendon itself. For each system, it was expected to be nonlinear in the initial stage. Also, at any given time, the strain measured directly on the tendon is less than the strain derived from the cross-head displacement.

(c) The bottom graph shows two stress vs. strain relationships. The machine line (light line) is nonlinear as the changing slope is determined by the rigidity of the entire system (i.e., tendon, anchors, cross-heads, and cross-head supports). The tendon line (heavy line) is practically linear. The tendon line is continued after the removal of the extensometer until the ultimate capacity of the tendon is reached (shown by a black diamond on the graph). The slope of this portion of the line corresponds to the experimental modulus of elasticity ($E$) derived as the average of the last 200 data points recorded before removal of the extensometer. The abscissa of the maximum point was then used to estimate ultimate strain at failure.

Results for all specimens are summarized in Table 2. In this table, anchor/tendon system experimental data are compared with manufacturers’ data and results are reported below.

### Wedge Anchor Types

Arapree — Results of load to failure tests of Arapree tendons are not reported in Table 2 because the tendons could not be failed in tension using the manufacturer’s provided wedge anchors. The tendon/anchor system was only capable of attaining approximately 40 percent of the manufacturer’s reported ultimate load due to continuous slip between tendon and wedges during testing.

**FIBRA** — Specimen 1 exceeded nominal tensile strengths reported by the manufacturer by more than 10 percent. Based on experimental records in the load range 78 to 94 kN (17.5 to 21.1 kips), the computed $E$ value (as defined above) was 77.4 GPa (11.2 ksi). The computed ultimate strain was very close to the reported value of 2.0 percent.

Specimen 2 behaved almost identically to Specimen 1. Failure occurred in both specimens near the upper anchor (see Fig. 12). It is possible that this failure was influenced by the anchor given its proximity to it. Some local damage was visible in the portion of tendon surrounded by the wedges inside the anchor (see Fig. 13).

The FIBRA tendon was also used for the high temperature tension tests. For this tension test, a heat blanket was placed directly on the lower-end anchor. The tension test started approximately 2 hours after initial setting when a constant temperature of 60°C (140°F) was uniformly reached. The results for Specimen 1 compare closely with the reported strength limit but were relatively low in comparison...
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Table 2. Summary of experimental results.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th>Data source</th>
<th>Breaking stress (MPa)</th>
<th>Breaking load (kN)</th>
<th>Maximum elongation (percent)</th>
<th>Young's modulus (GPa)</th>
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<td>179.06</td>
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<td>188.40</td>
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Note: 1.0 in. = 25.4 mm; 1.0 kip = 4.48 kN; 1.0 Msi (ksi) = 0.145 GPa (MPa).

Table 2. Summary of experimental results.

The second specimen behaved similarly with the ultimate load 8 percent above the manufacturer's value. Failure strain was extrapolated to be 2.07 percent. The modulus of elasticity determined from these tests is comparable to that obtained with room temperature tests. Loading of both specimens was uneventful up to failure. Data curves compare closely with those for room temperature tests.

Carbon Stress — The first specimen of flat-strip Carbon Stress reached 76 percent of the manufacturer's breaking load value and only 68 percent of the corresponding strain. This first specimen demonstrated a partial failure resulting in 7 kN (1.6 kips) load loss just prior to complete failure. Initial location of failure could not be identified as the specimen shattered on failure.

The second specimen reached a stress level just over 70 percent of the manufacturer's strength and ultimate strain was recorded at 68 percent of the manufacturer's value. The computed average E value from these tests was approximately 85 percent of the manufacturer's value.

The first round Carbon Stress specimen failed at 61 percent of the manufacturer's breaking load. Ultimate strain was consistent with the load level, also reaching 58 percent of the manufacturer's value. As with the flat-strip specimen, failure resulted in complete destruction of the tendon, making it impossible to determine the location of the initial failure.

The second specimen behaved much like the first, though strength and strain levels were even further below the reported limits. The elastic moduli calculated for Specimens 1 and 2 were 88 and 104 percent of the manufacturer's reported value.

Leadline — The Leadline wedges required the largest displacement before proper seating of the tendon was achieved (see Fig. 10). Test results were in good agreement with the manufacturer's values, based on comparisons of strength and strain limits. The first specimen reached a stress level 15 percent greater than reported. Extrapolated failure strain was 1.48 percent.

The second specimen also surpassed reported ultimate strength (7 percent higher than the reported limit). Estimated maximum strain was approximately what the manufacturer reported. The modulus of elasticity of both specimens was found to be 177 GPa (25.6 ksi) and higher than reported.

Potted Anchor Types

Technora — Because Technora rods utilized a potted anchoring system, it was predicted and verified that load and strain increased linearly almost immediately from the onset of loading. For the first specimen, breaking load was recorded at 6 percent higher than reported and extrapolated ultimate strain was 15 percent above the reported ultimate value.

The second specimen behaved much the same, recording a failure load 3 percent higher than reported. There were several incidences of anchor/tendon slip observed during the test. The estimated maximum strain was 0.0355, which is lower than the reported ultimate strain by 4 percent. The values of the modulus of elasticity for Specimens 1 and 2 were, respectively, 20 and 10 percent below the reported values.

Slipping of the tendon through the anchor caused drops in stress levels and was common to both specimens. Popping and cracking noises could be heard from the early stage of each test. This behavior was recognized by researchers at the manufacturing company who acknowledge that it is not possible to attain 100 percent of the theoretical tendon capacity with the currently used potted anchors. Ultimate failure resulted from pull-out of the tendon from the grouted anchor (see Fig. 14). Damage to the tendon was essentially nonexistent except in the areas just in front of the anchors where the outer layer of the tendon was stripped.

CFCC — The first specimen failed at 109 percent of the reported strength value. The corresponding extrapolated
strain was 20 percent less than reported. The reason for this difference is clearly in the modulus of elasticity, because the experimental value is 16.5 percent higher than the reported value. The second specimen also reached a higher load (20 percent more than the reported value). The corresponding strain was slightly less than the manufacturer’s value. The $E$ value was 7.8 percent higher than expected. Post-test inspection of these tendons showed that both specimens failed at a location near the anchors.

Lightline — For the first specimen, failure occurred at a level significantly below the reported failure limit (40 percent less than reported). The maximum strain was only 0.0109, only 44 percent of the reported ultimate strain. Failure resulted from the rupture of two of the seven stranded rods. The second specimen reached a load 73 percent of the reported ultimate load. Extrapolated maximum strain was 0.0124 for this specimen and in agreement with the previous test.

In both specimens, the elastic modulus was much higher than the reported value. This might have been the result of the relative movement of the individual rods and its effect on the extensometer reading. Failure of the second specimen was pull-out from the upper anchor with no damage to the tendon itself.

Spike Anchor Types

Parafil — The first specimen failed at 94.1 kN (21.2 kips), short of the manufacturer’s value by 10 percent. The second tendon failed at 87 percent of the reported ultimate capacity. Strain measurements were obtained directly from the external sheath and may not be representative of the strain in the fiber. It is suspected that failure initiated by slipping within the anchors, possibly due to improper installation of the spikes.

DISCUSSION OF TEST RESULTS

When considering ultimate load capacity, four tendon/anchor systems (in addition to the one tested at high temperature) showed higher values than reported. The remaining six systems that correspond to four different manufacturers showed a load capacity lower than reported. It could be mentioned that two of the manufacturers of tendons with lower than reported results have only recently considered commercial production and a third one is still in the development stage. The point being made is that the data base is still very limited.

Manufacturers usually report strength, ultimate strain, and elastic modulus. In several cases, the value reported for $E$ is different from that obtained from the strength-to-ultimate strain ratio. It is, therefore, clear that some safety factors are built into the reported values. Variation between computed and reported values of the modulus of elasticity occurred for each tendon/anchor system. Based on the experimental average value for each system, half of the values were higher and half were lower than the reported moduli of elasticity.

Anchor types can be divided into three groups: wedge, resin/grout potted, and spike systems. The wedge systems can be further subdivided into direct contact (plastic and steel wedges), and systems utilizing a sleeve. The potted anchors group varied depending on the internal configuration of the socket: straight, linearly tapered, and parabolically tapered sockets. Only one spike anchor was considered. The following observations are made for the three anchor groups:

Wedge Anchors

Grit should be present on the wedge surfaces to ensure proper gripping of the tendons. This observation is drawn from comparisons between the Carbon Stress and Arapree tendons, both of
which utilize plastic wedges. The Carbon Stress system with applied grit did not show the slippage of the untreated Arapree wedges.

Some local damage to the tendon was induced by steel wedges even though there was no indication of loss of efficiency. Local damage to the tendon appears to be controllable through use of aluminum sleeves that prevent direct wedge-tendon contact. The drawback may require a more complex and time-consuming anchor assembly. Systems that have a dry-lubricated outer wedge surface were easier to take apart than other systems, though both required a use of force to free the wedges. For the tendon-anchor system tested at high temperature, there was no significant difference in behavior as compared to room temperature.

Resin/Grout Potted Anchors

Two of the three systems failed due to pull-out of the tendon from the resin/grout anchor without rupture of the tendon. The parabolic system showed splitting and cracking of the resin plugs in both tests. The potted anchors were by far the easiest to setup for testing when pre-installed. The practical drawbacks include pre-cutting the tendons to length, and curing time for the resin/grout.

Spike Anchors

The spike anchors used with the dry fiber ropes worked relatively well. This system required the longest setup time resulting from the combination of removal of the plastic sheath, combing and spreading of the individual fibers and proper placement of the spike with a uniform distribution of fibers all around it.

CONCLUSIONS

Ten commercially available FRP tendon/anchor systems for prestressing of concrete structures were evaluated in tension up to failure. Even though a limited number of test repetitions were performed, important experience was gained by installing the anchors and observing their performance during stressing.

Based on the results of this investigation, the following conclusions can be drawn:

1. In the case of four tendon-anchor systems, the manufacturers’ values of strength, modulus of elasticity, and ultimate strain appear to be in good agreement with experimentally derived values. For the remaining systems, experimental data were below expectation.

2. Ultimate load capacity is generally controlled by the anchor rather than the tendon itself, suggesting that anchor efficiency can be improved.

3. The three classes of anchor systems (i.e., wedge, resin potted, and spike) offer advantages and disadvantages. The degree of complexity in terms of installation procedure varies.

4. For wedge type anchors, dry lubrication and sand-coating on the two faces of the wedges are helpful. Protection of the tendon can be attained with a sleeve. High temperature did not adversely affect the performance of the system tested. Wedge anchor systems are suitable for pretensioning applications.

RECOMMENDATIONS

Precast concrete technology using FRP tendons has demonstrated a level of maturity that is sufficient for considering demonstration and verification in precast yards and job sites rather than the laboratory. It is unlikely that further refinement of the existing anchor-tendon systems will be undertaken without the direct participation of precast concrete fabricators or contractors. In contrast to Europe and Japan, the American construction industry has not shown any significant level of reaction to or interest in the introduction of advanced composites for reinforcement to concrete. The fundamental reason for this apathy has been cost. Even though this is an important issue, the attitude of the construction industry towards innovation is only lukewarm, and this may have negative consequences in the long term.

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