Expansive Cement Couplers

A Means of Pre-tensioning Fibre Reinforced Plastic Tendons

J.M. Lees, B. Gruffydd-Jones, C.J. Burgoyne

Structures Research Group
Department of Engineering
University of Cambridge
Trumpington Street
Cambridge, CB2 1PZ

Queries addressed to: Dr. C.J. Burgoyne
Structures Research Group
Department of Engineering
University of Cambridge
Trumpington Street
Cambridge, CB2 1PZ

Abstract

Fibre reinforced plastics, describes a group of materials composed of inorganic or organic fibres embedded in a resin matrix. FRPs are, strong, non-magnetic, light-weight and for the most part, non-corrodable.

There is great scope for the use of fibre reinforced plastics (FRPs) as concrete reinforcement and the high strength of the materials is conducive to prestressed applications. However, finding a suitable method of anchoring the tendons without inducing stress concentrations in the fibres has been identified as a problem.

The current paper investigates the potential for the use of expansive cement couplers as a means of pretensioning FRP tendons. An experimental study was carried out on couplers to join steel reinforcing bars and then extended to include the coupling of FRP materials to steel prestress wire.

Notation

L_1	=	Anchored length of steel (mm)
L_2	=	Anchored length of aramid tendon (mm)
L	=	Length of reinforcement embedded in expansive cement (mm)
P	=	Expansive pressure (MPa)
T	=	Pull out force (N)
t	=	Time (hrs)
UL	=	Nominal surface area of tendon/reinforcement (mm^2)
μ	=	Coefficient of friction between tendon and expanding cement
σ_u	=	Ultimate stress of composite (MPa)
σ_y	=	Yield stress of steel (MPa)
τ	=	Shear strength (MPa)

1 Introduction

The cost of repairing existing Canadian concrete parking structures was recently estimated to be between $4-6 billion CAN (£2-3 billion). The estimate for the repair of highway bridges in the United States was in the range of $50 billion US (£33 billion). The main cause of the deterioration of these structures was the corrosion of steel exacerbated by the use of road deicing salts [1].

The problems are not limited to North America. In the UK, the Department of Transportation has banned the use of grouted steel prestressing tendons because of fears of tendon corrosion. Within Europe, steel corrosion has been estimated to cost £1000 million per year [2]. The construction industry needs to seek alternatives to steel reinforcement; a potential solution is the use of fibre reinforced plastics (FRPs) as concrete reinforcement.

The term *fibre reinforced plastics* describes a group of materials composed of inorganic or organic fibres embedded in a resin matrix. FRPs are light-weight, strong, non-magnetic and for the most part, non-corrodable. The aerospace industry has used fibre reinforced composite sheets to form aircraft wings but, to date, FRPs have not been widely used in the construction industry, because of a high initial cost and a lack of confidence in new materials on the part of the designer.

The first concern can be easily addressed; although the material cost of FRPs is typically 3-4 times that of steel, when membranes, epoxy coating etc. are specified and added to the price of steel, the costs are comparable. In addition, FRPs fare well when lower long-term maintenance and construction costs are included [1].

The second concern is more difficult to quantify. Design codes for FRPs do not exist at the moment, although several draft codes are in various stages of completion. The Japanese are at the forefront of FRP research and have established draft guidelines for the design and construction of prestressed concrete bridges using FRPs. Several bridges using FRP tendons have already been constructed in Japan [3] and Japan's new material market is predicted to reach 5.4 trillion yen(£36 billion) in the year 2000 (compared to 500 billion yen (£3.3 billion) in 1980) [4].

In the construction industry, the most commonly used FRPs are glass fibre reinforced plastics (GFRPs), carbon fibre reinforced plastics (CFRPs) and aramid fibre reinforced plastics (AFRPs). Figure 1 shows typical stress - strain properties of these three materials and steel.

Unlike steel, FRPs are elastic materials and do not yield (see Figure 1) . In a beam prestressed with steel, as the load increases beyond a certain limit, the steel yields and the ensuing deflections provide ample warning of failure. In contrast, the failure of FRP materials is brittle and sudden. Research into the determination of how ductility can be achieved in beams which are reinforced with FRPs is ongoing.

Another area of concern is the method of stressing and anchoring FRP tendons. Traditional methods of gripping steel prestressing tendons have proved to be unsatisfactory. A potential solution to this problem is the use of expansive cement and a recent study in Japan highlighted the successful use of expansive cement in an anchorage system for FRP tendons [5]. The cement was poured into a metal sleeve surrounding the tendon and left to harden and expand. The pressure from the cement grips the tendon evenly and avoids stress concentrations.

Expansive cement could be used in a similar way to couple reinforcing bars together or to join FRP materials to steel. The latter case is particularly useful for pretensioning applications; the ends of a FRP tendon can be coupled to lengths of prestress wire which would enable the FRP tendon to be stressed and locked off using existing equipment.

2 Fibre Reinforced Plastics

Fibre reinforced plastic rods are made up of continuous lengths of fibres impregnated with resin. The fibres are linearly elastic and have a high strength and stiffness in the longitudinal direction [6]. In any group of fibres, the properties and the diameters of individual fibres will vary; there will also be flaws and defects on some of the fibre surfaces. The combination of these factors leads to the strength of a bundle of fibres being lower than the average fibre strength.

The fibres are characterised by a very low shear strength, a deterioration of strength at sustained high load levels due to stress rupture [7] and a low compression capacity as a result of fibre buckling.

Matrix materials include epoxy, vinylester and polyester resins. Fillers and additives can also be included in the matrix to reduce cost and/or to improve specific physical properties. It is important that the matrix is durable since one of its primary roles is to protect the fibres against lateral pressure, abrasion and chemical attack [8].

The fibres and matrix are combined to form composite rods which are usually manufactured by a pultrusion process in which the fibres are drawn from their spools, dried and pulled through a resin die. The resulting composite rods are then cured and cut to length [9].

The strength of the composite is not as high as that of the individual fibres but, because of the matrix, is greater than the lowest possible fibre strength. The matrix evens out the variability of fibre strength by bond transfer from broken to unbroken fibres and hence the fibre-matrix bond is important [8].

FRP composites are characterised by large Poisson's ratios (between 0.35 and 0.62) which reflect the properties of the matrix and the anisotropy of the fibres, and low coefficients of thermal expansion (in some cases negative). In general, the tensile strength of FRP rods drops sharply when exposed to temperatures in the range of 150-250 ° [10]; greater attention will thus have to be given to fire protection.

3 Anchoring of FRPs

The prestressing of FRP tendons is very different from that prestressing of steel. A recent paper [11] documented tendon breakages during prestressing which were due either to bond failure at the anchorage sleeve or rupture of the strand at the anchorage.

When tensioning FRPs there is a difficulty associated with finding a suitable method of gripping the tendon. The fibres are susceptible to damage and have a low shear strength. Simultaneous shear and compressive stresses on the surface of the FRP element are expected to reduce the axial strength and little is known about the multiaxial strength of FRP [12]. The anchors must be designed so that no detrimental stresses are induced in the tendons. A summary of the principal available methods follows:

3.1 Resin Systems

The tendon can be placed in a tube and resin injected into the void between the tendon and the tube. The advantage is that stress is distributed evenly over the tendon surface but there are difficultues in finding an appropriate resin.

Resins have contradictory design requirements. A resin with a low modulus of elasticity limits the peak shear stress during transfer whereas a resin with a high modulus of elasticity is better for long term creep control. Additional considerations are deterioration of the resin, bond failure between the resin and the tendon and loss of strength at elevated temperatures [13].

3.2 Wedges

Steel wedges in a tube with an inner conical profile and an outer cylindrical surface have been used as a means to grip tendons and are easy to install. Either the wedges themselves or the bars can be treated to make a rough surface and improve the grip. Unfortunately, the grips induce axial tensile stresses, lateral compressive stresses and shear stress which lead to premature failure in the anchor [14]. The need to reduce lateral stresses means that the wedges are much larger and shallower than those that would be needed for steel tendons.

3.3 Expanding Cements

Harada [5] has worked on the use of expanding cements as a means of anchoring CFRP tendons. The end of the tendon was placed in a steel tube and an expanding cement slurry was poured in the void between the tendon and the tube. Expansive pressures of 39.2 MPa were achieved after 48 hours.

Tests have shown that over a period of two years the prestress losses are less than 6% and that the expansive pressure increases with time and is stable. Harada predicts the capacity of expanding cement anchors from a combination of residual shear strength τ and frictional resistance induced by the expansive pressure P. Thus,

$$T = UL * (\tau + \mu * P) : \tag{1}$$

A particular advantage of this anchorage system is that it can be used with any type of continuous fibre reinforcing bar, regardless of shape and diameter of the continuous fibre.

4 Expansive Cements

The first expansive cement was developed in the 1940's by Henri Lossier, a French engineer [15] who used it to make self-stressing concrete. Expansive cement is a hydraulic cement that expands during the early hardening period after setting. Various types of expansive cement exist but they all consist of three basic components: portland cement, an expanding agent, and a stabiliser.

The expanding agents react in the presence of water to form ettringite (calcium sulphoaluminate hydrate) with an accompanying expansion of the paste [16]. The stabiliser slowly takes up the excess calcium sulphate and so arrests expansion. Careful proportioning of the cement ingredients is necessary to achieve the desired expansion.

The main use is for expansive cement concrete, of which there are two basic classes, which differ in the magnitude of expansion, and hence application.

1. Shrinkage-compensating concrete. The restrained expansion caused by the cement induces compressive stresses which offset the tensile stresses resulting from shrinkage. The use of expansive cement does not prevent the concrete from shrinking, which takes place after moist curing has ceased. The magnitude of expansion due to the cement is controlled to exactly cancel out the subsequent shrinkage of the concrete. However the two effects occur over different time scales, so differential strains and stresses still occur.

2. Self-stressing Concrete. The compressive stresses induced by the cement are large enough to result in significant residual compressive stress in the concrete

after drying shrinkage has occurred.

The principal difference between the two classes of expansive cements is the amount of expansive component provided.

The type of expansive cement available differs from place to place in the world. In the U.K., only one type (a shrinkage compensating cement) is manufactured, while in America three types are available with considerable development of one (type K) in progress [17], [18], [19], [20], [21], [22]).

In Japan there are at least five different types of expansive component available, with differing chemical composition and expansion mechanisms. They include Bristar cement, manufactured by Onoda Cement Company Ltd. which is used in the work reported here. The chemical formula of Bristar cements is proprietary, but they have been reported to be a combination of an organic expansive agent with cement [23].

Expansive cement concrete has been successfully used in a wide variety of applications in America, Japan and Russia; for example prefabricated self-stressed concrete slabs and walls; self-stressed concrete pipe; concrete paving, especially for airport taxiways; hydraulic structures where shrinkage-compensating concrete is advantageous in preventing cracks which cause leaks; underground structures; grouted concrete.

To date, Bristar cement has primarily been used as a demolition agent. It is a highly expansive material when reacting with water and under conditions of restraint can develop pressures of more than 50MPa within 48 hours. However, if unrestrained, the expansion causes the cement paste to crumble. Typically, the cement slurry is poured into holes drilled into rock or concrete; as the cement hardens it undergoes a large volume expansion and cracks the surrounding material. A controlled pattern of cracks can be achieved by engineering the size and geometry of the hole pattern, allowing precise fracture control. Research has been carried out to refine the method, investigating the stresses caused by the cement [23],[24],[25].

The reaction between water and the cement powder is highly exothermic, and the rate of pressure development is a function of temperature. To account for this there are four types of Bristar cement, suitable for different ranges of ambient temperature. A certain amount of care is required when using the expansive cement to prevent run-away chemical reactions.

5 Experimental Work

The aim was provide a full strength joint between FRP and steel by enclosing the ends of the bars in a sleeve of steel tube, and filling the annulus with expansive cement. The constrained expansion would exert pressure on the bars, thus gripping them without local stress concentrations. Initial experiments were carried out on a coupler for joining reinforcing steel (see Figure 2) and the results were later extended to include the coupling of prestress wire and FRP materials. The properties of the reinforcing steel, the prestress wire and the two types of AFRP used in the experiments can be found in Table 1.

5.1 Modes of Failure

There are four possible modes of failure:

1. Failure of the bar when the joint is at full strength, as intended.

2. Failure of the steel tube.

3. Failure of the cement at the joint between the cement and the bar, characterised by a pull-out failure of the bar.

4. Failure of the cement at the joint between the cement and the steel tube characterised by pull-out of bar and a plug of cement.

There are several parameters which influence a failure mode which results in the failure of the cement (items 3,4). They include:

- The expansive pressure P: a function of the water/cement ratio, time from casting, and cement type.
- The surface area: determined by the length L of reinforcement inserted in the cement.
- The coefficient of friction μ: determined by the surface condition of the tube and reinforcement.
- The shear strength τ: determined by the surface condition of the tube and reinforcement.

5.2 Steel Reinforcement Couplers

The properties of steel are well known and it was felt that by performing an initial series of tests to join two steel reinforcement bars, a better understanding of the behaviour of expansive cement couplers would be gained. The results could then be applied to FRP materials.

The test series was modelled on an experimental programme previously carried out on adhesive couplers [26].

5.2.1 Plan of test

Initial calculations determined the required tube dimensions (thickness, length) to couple 12 mm deformed high yield reinforcement bar (nominally, $\sigma_y = 490$MPa). The calculations, based on equation (1) and Harada's data ($\tau = 4.46$ MPa, $\mu = 0.244$), suggested the use of the following:

- Tube

The standard test specimens were cast using a steel tube 200mm long ($L = 100$mm), 3.25 mm thickness, and 31.75 mm outer diameter. This was referred to as 'thick' (see Table 2). Several tests were also carried out using thinner diameter tubes; test *c* used a tube of the same outer diameter but thinner wall thickness (1.63 mm) and probably different steel, while tests *l* and *m* were carried out on thick tubes whose outer diameters were machined down to give wall thicknesses of 2.31 mm and 2.17 mm respectively. Other tests were carried out on tubes where L varied from 40-90mm.

- Cement type and water/cement ratio

Most tests used Bristar 100 (suitable for temperatures in the range 15 - 35°C), with 27.5% water (55ml/200g) although other water/cement ratios varying between 25% and 30% were also tested. Test *g* used pure Portland cement, for comparison purposes.

Tests *o*-*t* were set up to measure the pressures generated. The effects of plasticiser was also investigated by adding a small amount of 'Supaflo' plasticiser to the water in test *t* in order to increase fluidity.

5.2.2 Test Procedure

The steel tubes were initially cleaned in a chemical cleaning bath. The joints were assembled in batches of up to six, supported firmly in a wooden frame on a bench. This jig was designed to align the bars vertically and centrally in the tube while the cement hardened. Vaseline was applied to the base of the tubes to prevent leakage. The cement was mixed by hand according to the manufacturer's instructions, and spooned into the top of the tube while striking the bars and tube to expel all the air from the cement. The tubes were filled one at a time; fresh cement was mixed for each tube. The joints were left in the jig until the cement had set. All joints were tested after three days, except for tests *h* and *i*, which were tested after 24 and 48 hrs respectively; and tests *o* and *p*, which were tested after 33 days.

The pull-out tests were carried out in a tension testing machine at a loading rate of 5kN/s and joints *a*-*p* were tested to failure.

Tests *o*-*t* were performed to monitor the pressure generated over time and demonstrated the effects of different water/cement ratios and the addition of plasticiser; some tests used the thinner tube. Joints were set up with a strain gauge glued circumferentially in the centre of the tube to measure the hoop strain. Pull-out tests were later performed on tests *o* and *p*, after a period of 33 days.

One test was performed using a bar greased with oil, to simulate site contamination (test *k*).

5.2.3 Results

The pressure rise in the tubes was estimated by using the measured hoop strain and thin walled tube theory. At 24 hours, the pressure was about 18 MPa, at 48 hours was about 25 MPa, while after 72 hours the pressure remained more or less constant at about 30 MPa. These values will be used in the subsequent analysis of the test data.

It is accepted that measuring the strain on the outer surface of the steel tube is an indirect way of determining the pressure acting on the reinforcement. In a study by Harada [27] an *"outer pipe method"* of predicting expansive pressures was compared with an *"inner pipe method"*. In the outer pipe method strain gauges were attached to the outer tube surface whereas in the latter method, gauges were set on an inner steel pipe located inside a larger diameter tube with expansive cement in the annulus between the tubes (the inner pipe is analogous to reinforcement). The resulting pressures calculated for the different methods did not differ significantly.

Tests *l* and *m* show that the ultimate strength of the tube is about 330 MPa (test *c* was a different batch of steel), while the actual strength of the bar is about 600 MPa.

In order to get an estimate of the values of μ and τ, the tests that failed at the bar/cement interface (*d,e,f* and *h*) can be considered.

Equation (1) can be rearranged to give:

$$\tau + \mu P = \mathrm{T/UL}$$

The values of T/UL can be plotted against P as shown in Figure 3. The graph suggests a value of τ = 1.6 MPa, and μ = 0.7. For comparison purposes, Harada's predicted values (τ = 4.46 MPa, and μ = 0.244) are also shown, but it must be noted that these are based on the use of CFRP bars, rather than steel. The present results are very sensitive to the pressure generated in the cement in test h, and a small change in P would make a significant difference to the predicted value of τ. Although it is hard to draw any conclusions based on such limited results the implication is that a higher value of μ has been observed than was done by Harada. However, the working pressure of 30 MPa is lower than he measured (50 MPa). Clearly further testing needs to be carried out to confirm these results.

- Water/cement ratio

The fluidity of the cement/water mix was found to be very sensitive to water/cement ratio. At 25% H_20 the mixture was only just sufficiently fluid to fill tube, and then with difficulty. It was necessary to stir cement to expel trapped air. At 27.5% H_20 it was adequately pourable in laboratory conditions but was probably too stiff to be practical on site. At 28.5% H_20 the mixture was easily pourable.

Both the 27.5% and 28.5% mixes (tests *b* and *j*) reached full strength after 3 days.

Test *t* used 25% H_20 with 2ml of plasticiser, which was intended to increase the fluidity (and hence ease of filling joint) without reducing the pressure generated. The effect, however, was to reduce the setting time of the cement, thereby making it more difficult to pour, instead of easier. The strain gauge results showed also that the plasticiser reduced the rate of gain of pressure, although the pressure was still increasing after 500 hours.

- Long term behaviour of expansive pressure

Cement with 27.5% water in the thick tube generated a pressure of 25MPa in 48 hours. The pressure continued to rise, at a decreasing rate, reaching 34MPa after 9 days.

The pressure generated in test *q* started to fall slightly, after 9 days. Similar tests carried out in Japan showed no decrease in pressure even after 6 months; all curves of expansive pressure continued to increase gradually with time. Further tests should be performed to determine the extent of any decrease in pressure over a long period of time. Another area of interest is the long term effects of the expansive cement and corresponding expansive pressure on the FRP bar itself.

No fatigue tests on the joints have been carried out. The Japanese report [5] describes fatigue tests carried out during the research into the FRP tendon anchorage system. The results showed that the fatigue cycling had little effect on the tensile strength of the specimens.

5.3 FRP Couplers

As part of an ongoing research project, pretensioned beams using Aramid Fibre Reinforced Plastic (AFRP) rods are being cast. Temporary anchorages are not yet available economically for AFRP, so a means is required to couple each end of the AFRP to short lengths of conventional steel wire. It is proposed to couple the aramid tendons to steel prestressing wire (steel/aramid/steel) using expansive cement anchors, and the tendon specimen can then be stressed and anchored using standard collets and wedges for steel prestressing tendons. The couplers can be fitted away from the stressing bed, and if necessary, proof-loaded before stressing.

Once the steel/aramid/steel tendon is anchored, the concrete beam is cast around the free length of aramid tendon located between the couplers. After the concrete has reached a sufficient strength, the tendons are detensioned and prestress is transferred to the beams, after which the expansive cement couplers can be discarded.

The motivation was not necessarily to develop an optimum joint in terms of critical pressures and lengths but to determine a suitable coupler that would be stronger than the coupled materials and that did not result in excessive slip and loss in prestress during pretensioning.

The experimental results from the steel reinforcement couplers gave insight into the nature of such a coupler.

5.3.1 Tendon Couplers

Initial tests were performed in a manner similar to the reinforcement steel tests to ensure the integrity of a coupler using prestress wire alone (see Figure 2). Two pieces of smooth prestress wire were embedded in 25mm o.d. mild steel tubes with 3.25mm wall thickness. The expanding cement was mixed with 27% water. The first tests all failed due to the prestress pulling out. In the second series of tests, the end of the prestress wire was deformed using a diamond knurler to improve the bond between the expanding cement and the prestress wire. There was a major improvement and tests 2.1 and 2.2 resulted in failure due to the prestress wire reaching its ultimate load (see Table 3).

Once the details for a coupler for the prestress wire had been determined, the results were extended to include two FRP materials. The materials tested were a braided AFRP (FiBRA, made by Mitsui) and a deformed AFRP (Technora, manufactured by Teijin).

The surface characteristics of the two materials are very different. The profile of FiBRA is formed by braiding the fibres during the pultrusion process prior to resin impregnation. The deformed surface of the Technora is a result of winding a fibre around the rod after the longitudinal fibres have been pulled through the resin die. The winding fibre is held in place by a longitudinal securing fibre and a circumferential securing fibre which are fixed with resin. Studies [28] suggest that the bond of a braided AFRP is less than that of a similar deformed bar and that a reduction is also required to account for the reduced bond of the AFRP due to the outer coating of resin.

Specimens were cast which were composed of steel/AFRP/steel (see Figure 4). The casting jig was constructed by aligning vertically two single specimen frames (as in section 5.2.2) a set distance apart. The lengths of embedded braided AFRP were 150mm and 175mm with free lengths between couplers of 200mm and 150mm respectively. The embedded lengths for the deformed AFRP were increased to 175mm and 200mm to reflect the higher breaking strength of this type of rod. Both deformed AFRP specimens had free lengths of 150mm.

A mix with 27% H_2O with Bristar 100 was used and from the results of series 2, an embedded length of 150mm was used for the knurled prestress wire. After 3 days the specimens were tested in tension and in all cases failure occurred in the AFRP at the loads indicated in Table 4.

During the testing of specimen 3.1, a clicking noise was noted at approximately 10kN ($\approx$ 0.64 of the manufacturer's published ultimate capacity), the load stabilised at this value then increased to 12.2kN ($\approx 0.78\ \sigma_u$) at which point the clicking noise was again apparent. The load increased to 16.6kN and then dropped drastically. At this point the decision was taken to unload the specimen and measure the length. The length of the original 200mm section had increased to 204mm which suggested that slip had occurred in the couplers. The specimen was then reloaded and failure occurred due to the tendon breaking at 18.4kN.

In both specimens 3.1 and 3.2, the section which failed had a fibrous appearance. At the ends close to the coupler, buckling in the FRP was apparent, probably caused by a compression wave generated when the AFRP failed.

Because of the rather erratic behaviour of the tendon with 150mm embeddment, a coupler with 175mm embedded length will be used for stressing the braided AFRP tendons.

A clicking noise was also noted in test 4.1 (deformed AFRP) although only a small slip occurred and the failure of specimens 4.1 and 4.2 did not occur as explosively as that of 3.1 and 3.2. Failure occurred in the section close to the end of the steel tube and it appeared that the fibres had pulled apart, breaking the winding fibre. A coupler with 200mm embedded length will be used for stressing the deformed AFRP tendons.

Since failure was a result of the FRP breaking, the tests highlight the potential for the use of expansive cement couplers in tensile tests. The system may be suitable for laboratory testing, and for comparisons between different systems, but it is not practical for day-to-day testing since preparatory work is needed and full strength is not achieved for a few days.

5.3.2 Pretensioned Specimens

Tests were also carried out to ensure that the coupler maintained its integrity from the time of tensioning to the time of prestress transfer. Anchors with an embedded length of knurled steel of 150mm and a length of braided AFRP of 175mm were used. The free length of the braided AFRP was 1000mm.

Two days after casting, the specimen was set in a tensioning bed. A load cell, located at the dead end, was attached between the steel collet and the anchor plate and was used to monitor the load in the tendon. Strain hoops, used to monitor slip in the coupler, were connected at either end of the steel tubes to the steel tendon at one end and the aramid tendon at the other. The steel/aramid/steel specimen was prestressed to $0.65\sigma_u$ using a hand powered jack. After tensioning, the specimen was left for a period of two weeks and both the slip in the anchors and the loss of prestress was monitored using a datalogger.

The majority of the prestress loss was a result of relaxation in the tendon and there was no significant reduction as a result of slip in the coupler. Because of the low modulus of elasticity of the aramid tendons, small slips will not result in a significant loss in prestress.

5.3.3 Expansive Pressures

Since a 27% H_2O water content was not considered in the deformed steel tests, a coupler using this water content was set up to monitor the change in pressure over time. In this case, both longitudinal and circumferential strain gauges were attached to the tube and connected to a data logger. A set of longitudinal and circumferential temperature compensating gauges were also attached to the system. Dial gauges at either end of the specimen measured overall changes in length.

The pressures in the tube were calculated using a thick walled analysis and a graph of the change in pressure with time can be seen in Figure 5. The values of pressure were higher than those obtained from tests p, q for 27.5% water. The use of the pressures from Figure 5 in the analysis of the reinforcement steel tests would result in a lower calculated value for the coefficient of friction between the deformed steel and the expansive cement.

In this test, where there were no externally applied axial forces, the longitudinal gauges were in compression. This indicates that the Poisson's ratio effects due to the large circumferential expansion is more significant than the longitudinal expansion of the tube.

5.3.4 Horizontal Casting

Various attempts have been made to cast joints horizontally, but none was entirely satisfactory.

6 Discussion

6.1 Bond of Reinforcement

The surfaces of the materials used in this project; deformed steel bars, smooth and knurled prestress wire and a braided and deformed AFRP rod all have different bond characteristics. The bond between the material and the cement is important in determining the capacity of the expending cement anchors.

Mechanical interlock, adhesion and friction have been identified as mechanisms by which force is transferred from the reinforcement to concrete. At small slips, bond occurs as a result of the mechanical interlock of the hardened cement paste at surface irregularities. With increasing displacement, adhesion is destroyed and the transfer of load takes place by friction between the concrete and the bar surface [29]. These mechanisms would be similar in the case of expansive cements but modified by an increase in the friction component due to lateral pressure.

For deformed steel bars, bearing is thought to be the most significant transfer mechanism. The adhesion of FRPs is expected to be weak so the bond of these materials will rely on friction and mechanical interlock. Treece et al. [30] carried out a series of beam tests on both uncoated and epoxy coated steel reinforcement bars. In the epoxy coated specimens which failed, there was no evidence of adhesion between the epoxy coating and the concrete and no sign of the concrete crushing. The lack of adhesion results in diminished friction capacity. In contrast, the uncoated bars showed good adhesion and failure was due to the crushing of concrete as a result of the bearing against the lugs. For the flexural specimens they found that the coated bars resulted in a 35% reduction in bond strength.

The discrepancy between the values of τ and μ quoted by Harada and those found here must also reflect the difference between steel and CFRP. The CFRP has a rough surface and is twisted, but the surface layer consists of resin, which may be expected to have a lower value of μ. Clearly, more tests are needed to determine μ and τ for each combination of cement and bonded material, preferably on specimens where the internal pressure is measured at the time of testing rather than relying on similar specimens at the same age.

The prestress wire is effectively smooth and the small indentations on the surface provide very little bearing or frictional resistance. The results for the prestress wire predict that the coefficient of friction for the wire is close to zero since the pullout load did not change with increasing pressure. The values of τ and μ for the knurled prestress wire can be estimated if it is assumed that after 3 days the anchor is just strong enough to break the bar. It is found that $\tau <$ 9.47 MPa and $\mu > 0.203$.

Since none of the AFRP specimens pulled out, the values of τ and μ for the AFRP material cannot be calculated. It is expected that the values for the AFRP would be closer to those of the CFRP than those of deformed steel. Both the braided and deformed profiles of the rods would provide greater frictional resistance than the twisted profile of the CFRP but the adhesive resistance would be similar.

It can be argued that, Harada's formulae are not necessarily applicable in the case of the deformed type AFRP. If the outer spiral winding fibre detaches from the longitudinal fibres, then the pull out load would also depend on the bond strength between the longitudinal and spiral winding fibres. Hence an additional failure mode could exist.

6.2 Expansive Cement

The tests have shown that a reinforcement steel joint using 27.5% water/cement reached full strength within 48 hrs. This has potential use as a method of jointing reinforcing bars on site without the need for mechanical processes such as swaging or threading. For the purpose of practical design of the joint, it would be desirable to achieve full strength with:

- sufficient fluidity for quick joint assembly on site
- full strength achieved in a minimum time after casting.

Cement made with 28.5% water/cement is considerably easier to pour than the 27.5% mix, and so would be more practical. Test j showed that a joint made with the 28.5% mix reached full strength within 3 days. However, a period of 3 days is an improvement on a similar joint made with adhesive, which requires 6 days for the adhesive to reach full strength [26].

The amount of water in the cement is critical; a few drops more or less make a significant difference to the fluidity, and also affect the rate of expansion and the pressure reached. In a practical site application even rain water on the bars would alter the water/cement ratio; it might be necessary to specify that the bars be dried before being joined.

The ambient temperature and water temperature also affect the expansion of the cement, and these effects have not been studied here. Further tests may need to be carried out on the other types. In a site setting, clear instructions should be supplied in the joint package explaining which cement type to use.

Other points that need to be stressed in a site application would be:

- the cement packet should not be opened until the moment of joint assembly (to prevent the cement from absorbing moisture).

- the cement should be poured as soon as it is mixed (within ten minutes).
- a means of aligning and holding the bars centrally within the tube should be provided.

The long term stability of expansive cement in fluctuating moisture and temperature conditions is also an unanswered question. Another area of concern is a deterioration of the cement over time, although Harada's work on anchors that remained stable after a period of two years is encouraging [5].

7 Conclusions

Steel Reinforcement Coupling

1. Expansive cement couplers can be used effectively to join reinforcing bars together.

2. As a result of the tests the following assumptions can be made;

- τ = 1.6 MPa, μ = 0.7 (based on limited results)
- Use 28.5% water/cement ratio.
- The joint will reach full strength within three days.

To join bars of other sizes, use the relationship:

- T = UL(τ + μP)

to calculate the required tube length. The tube thickness will depend on the diameter of bar.

3. A practical method of joint assembly on site needs to be developed.

AFRP/Prestress Wire Coupling

4. For the stressing of FRP materials, the use of expanding cement couplers is likely to be viable in laboratory controlled conditions but not in terms of large scale production.

5. The anchors can be used as a means of stressing FRP tendons without inducing stress concentrations.

6. A means of casting the anchors horizontally should be investigated.

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LIST OF TABLES

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Material	**Young's Modulus (GPa)**	**Max Elong (%)**	**Yield (MPa)**	**Ultimate (MPa)**
12mm Deformed Steel	200	10	460	590
5mm Steel Prestress Wire	220	6	1500	1760
3.7mm Braided AFRP	64	2	N/A	1430
4mm Deformed AFRP	56	3.7	N/A	1810

Table 1: Material Properties

Test No.	Cem Type	%H_20	Tube	L (mm)	Bar Cond	Time (days)	Fail (kN)	Fail Mode
a	J	25	Thick	100	norm	3	65.7	bar
b	J	27.5	Thick	100	norm	3	66.8	bar
c	J	27.5	Thin	100	norm	3	62.5	tube
d	J	27.5	Thick	40	norm	3	35	cem1
e	J	27.5	Thick	60	norm	3	54	cem1
f	J	27.5	Thick	80	norm	3	64.5	cem1
g	PL	29.5	Thick	100	norm	3	5.5	cem2
h	J	27.5	Thick	100	norm	1	54	cem1
i	J	27.5	Thick	100	norm	2	67.5	bar
j	J	28.5	Thick	100	norm	3	66	bar
k	J	27.5	Thick	100	oil	3	67	bar
l	J	27.5	Thin1	100	norm	3	66.5	tube
m	J	27.5	Thin2	100	norm	3	61.5	tube
n	J	27.5	Thick	90	norm	3	67.5	bar
o	J	25	Thick	100	norm	33	68	bar
p	J	27.5	Thick	100	norm	33	66	bar

SPECIMENS USED TO MONITOR EXPANSIVE PRESSURE

Test No.	Cem Type	%H_20	Tube	L (mm)	Bar Cond
o	J	25	Thick	100	norm
p	J	27.5	Thick	100	norm
q	J	27.5	Thick	100	norm
r	J	27.5	Thin	100	norm
s	J	30	Thin	100	norm
t	Jpl	25	Thin	100	norm

KEY:

J	Bristar 100	J(O)	Bristar 100, old
PL	Portland Cement	cem1	failure at cement/bar interface
pl	Plasticiser	cem2	failure at cement/tube interface
L	Length of bar in cement		

Table 2: Results of tests on 12mm Reinforcement Couplers

SERIES 1 AND 2

- Mild Steel Tube: 25.4mm external diameter, 3.25mm wall thickness
- 5mm Diameter Prestress Wire: Ultimate strength 34.5kN

Test	% H_2O	L (mm)	Knurled (y/n)	Time (hrs)	Fail (kN)	Fail Mode
1.1	27	150	n	24	22	cem1
1.2	27	150	n	73	20	cem1
1.3	27	175	n	73	22.4	cem1
2.1	27	150	y	24	31.3	cem1
2.2	27	150	y	73	35.5	bar
2.3	27	175	y	73	36	bar

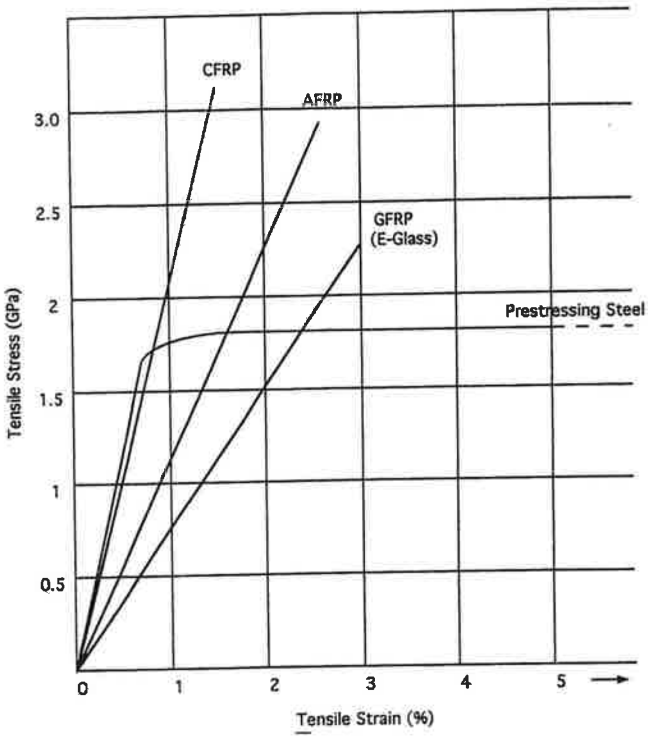
Table 3: Axial Tension Capacity of Anchors with 5mm Prestress Wire

SERIES 3 AND 4

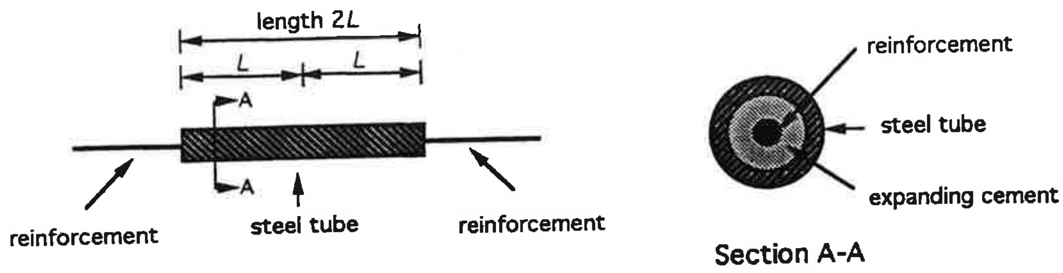
- Mild Steel Tube: 25.4mm external diameter, 3.25mm wall thickness
- Knurled 5mm Diameter Prestress Wire: Ultimate strength 34.5kN
- 3.7mm AFRP braided rod (untreated): Manufacturers Assured Load 15.7 kN
- 4mm AFRP deformed rod (untreated): Manufactures Assured Load 22.7 kN

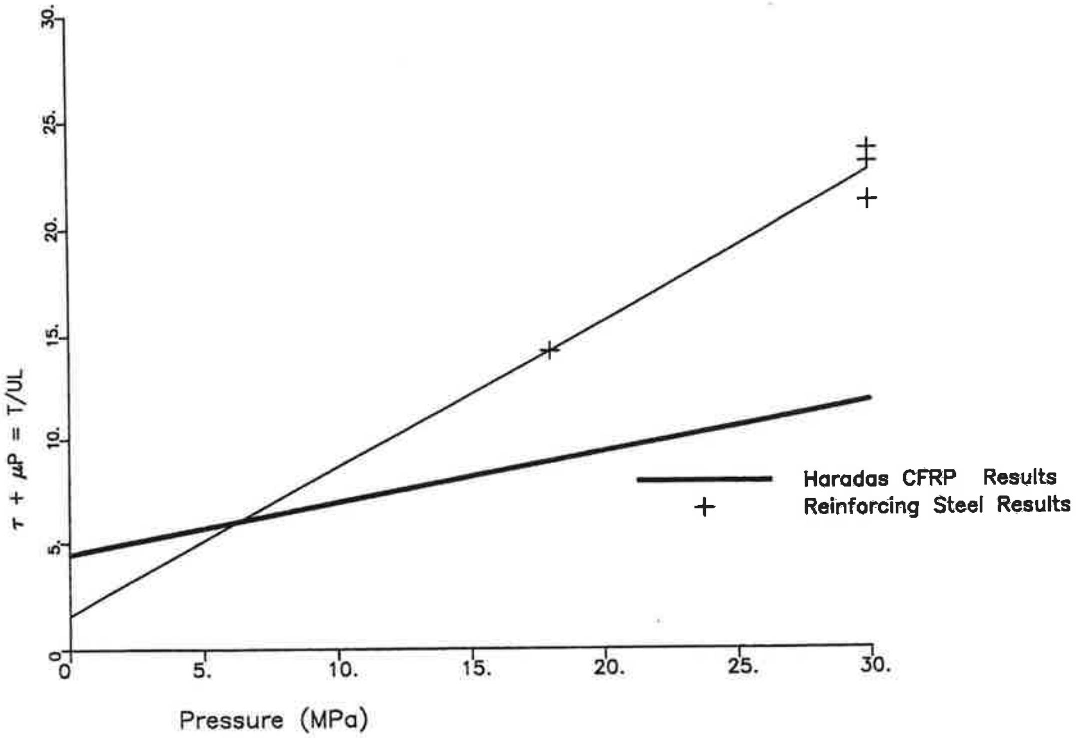
Test	**AFRP Surface**	**%H$_2$0**	**Steel** L_1	**AFRP** L_2	**Time hrs**	**Fail (kN)**	**Fail Mode**
3.1	braided	27	150	150	74	18.4	AFRP
3.2	braided	27	150	175	74	19.4	AFRP
4.1	deformed	27	150	175	72	25.2	AFRP
4.2	deformed	27	150	200	72	26	AFRP

Table 4: Axial Tension Capacity of Steel/Aramid/Steel Specimens

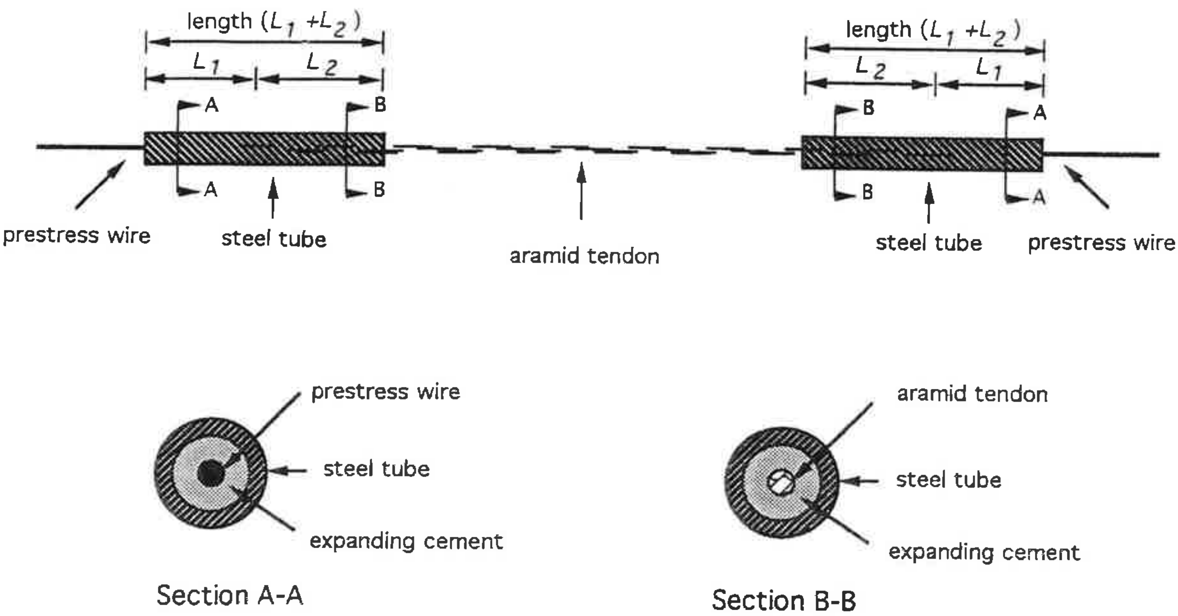


CFRP
AFRP
GFRP
(E-Glass)
Prestressing Steel
3.0
2.5
2
1.5
1
0.5
0
1
2
3
4
5
Tensile Stress (GPa)
Tensile Strain (%)

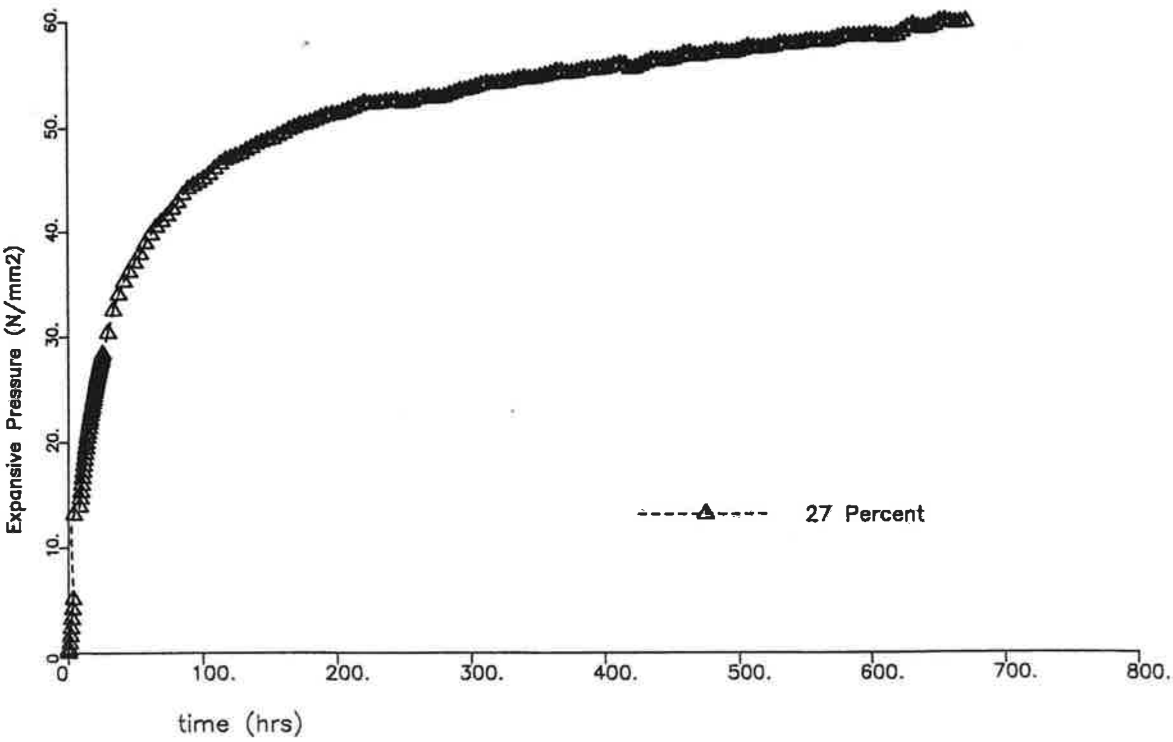

length 2L
L
L
A
A
reinforcement
steel tube
reinforcement
reinforcement
steel tube
expanding cement
Section A-A



τ + μP = T/UL
0
5.
10.
15.
20.
25.
30.
Pressure (MPa)
Haradas CFRP Results
Reinforcing Steel Results



length (L_1 +L_2)
L_1
L_2
A
B
prestress wire
steel tube
aramid tendon
length (L_1 +L_2)
L_2
L_1
B
A
steel tube
prestress wire
prestress wire
steel tube
expanding cement
Section A-A
aramid tendon
steel tube
expanding cement
Section B-B



Expansive Pressure (N/mm2)
0.
10.
20.
30.
40.
50.
60.
0
100.
200.
300.
400.
500.
600.
700.
800.
time (hrs)
27 Percent