1.0 INTRODUCTION
This paper describes the research, development and design of the ground anchor tendon protected against corrosion and damage by a double plastic layer.

2.0 HISTORY OF DEVELOPMENT AND REQUIREMENTS
In 1976 the British Standards Institute with the support of designated Chairman, Dr G S Littlejohn, selected a committee of UK specialists to produce a Code of Practice for Ground Anchorages.

The potential degradation of steel tendons when placed in the ground was a major consideration owing to the vulnerability of exposed steel to corrosive action and the consequential effect of anchor failure on the stability of an anchored structure. The Committee proposed that all permanent ground anchors be provided with "double corrosion protection". This term, of continental origin, was clarified in that in the event of perforation of one of the two barriers during installation or loading, the remaining barrier must remain intact. A study of published data on exhumed anchors and direct research work, lead the Committee to conclude in 1978 that, within the fixed length, cement grout could not, without qualification, be considered a corrosion protective barrier for permanent anchors. Thus, for anchor systems then available to comply with the requirements of the imminent Code, the double corrosion protection within the fixed anchor would require a single corrugated plastic duct supplemented internally either by a 5mm thickness of crack-controlled cementitious grout in which crack widths should not exceed 0.1mm, or by the provision of a 5mm thickness of "elastic" resin, which would "stretch" with the tendons without the presence of any cracks (Fig 1). Both of these protection systems are referenced in the current UK Code BS8081 (Ref 1), whilst only the former is approved in the European Standard EN1537:1996 (Ref 2).

Both the initial UK Code of Practice (DD81) produced in 1982 (Ref 3) and the subsequent document BS8081 (1989), require that “The suitability of all materials, components and method of construction should be demonstrated to the designer before
acceptance of any anchorage scheme". Such proving tests, part of which are to demonstrate the suitability of the corrosion protection components under load, are also required in the European Code, but an entire section is incorporated therein making the intent of the requirements more onerous and specific.

Full effectiveness of these two double corrosion protection systems was, in 1978, considered by the writer to be difficult to prove. Demonstration of crack-free deformation of the resin could be complex and costly, while demonstration of controllability of the crack spacing and restriction of crack width within cementitious grout around a multi-strand tendon is still in question, albeit controllability was believed to have been demonstrated around a deformed bar tendon. An alternative system conceived in 1978 involved the encapsulation of the bond length of the multi-strand tendon within two concentrically positioned plastic corrugated ducts and the complete filling of the inner core and the annulus between the ducts with an appropriate grout (Fig 2). Over the free length the provision of double plastic as corrosion protection is relatively simple, by single sheathing of individual strands and group sheathing of the multiple strand tendon. This double plastic corrosion protection system research work has continued from 1978 to 1996, and the system is approved in both the current BS8081 document and the European Standard.

3.0 PRINCIPLES OF THE ENCAPSULATION DESIGN AND THE PROTECTION PROVIDED

It was clear from the outset that any encapsulation system which provided effective protection against corrosion and transfer of the entire load capacity would, without careful design, require a particularly large diameter borehole to allow installation and would rarely be acceptable to the industry due to the high cost of the necessary drilling and installation operations.

Clearly, a small diameter encapsulation efficient in both corrosion protection and transfer of the entire load capacity of the incorporated tendon to the ground, would be the generally preferred option. Accordingly, the following principles were applied to the design and performance of the double plastic system:-

a. The multistrand tendon incorporates the maximum number of high capacity strands in as small an outer diameter as possible but ensures the transfer of full tendon load to the grout body which contains it, and across the outer interface to the adjacent material. Adequate spacing of strands must exist to allow full penetration of grout between and outside the strands.

Fig 2. The double plastic corrosion protection system developed from 1978 onwards and acceptable in BS8081 and the European Standard EN1537:1996
b. The inner corrugated plastic duct must contain the multistrand tendon, must not crack during loading, and must have the bond capacity with the grout at both the inner and outer interfaces to ensure the transfer of the full load capacity of the tendon. Surface contact between strands and inner duct wall is acceptable providing no ungrouted voids exist.

c. The outer corrugated plastic duct must be large enough to allow full annular grouting between the inner and outer ducts. It must not crack during loading and must have the bond capacity with the grout at both the inner and outer interfaces to ensure the transfer of the full load capacity of the tendon.

d. The gap between the outer corrugated duct and the borehole wall must be adequate to allow full grouting of the annulus in the borehole. Although 5mm is more than adequate for grout penetration, Codes of Practice generally require a minimum of 10mm in order to prevent encapsulation smearing during installation. Furthermore, the actual bore diameter in weak rocks and in soils is frequently controlled by design of the grout/ground interface and greater cover may be available.

Installation of the prefabricated double plastic system into the grouted borehole provides four actual barriers which contribute to protection of the steel strands against corrosion. Two layers of cementitious grout, one in the annulus between the concentric ducts and one in the annulus between the encapsulation and borehole wall, exist around the strands. However it is likely, during proof loading of the anchor, that cracks with widths in excess of 0.1mm will be formed in either or both of these layers owing to the necessary elastic extension of the strands and encapsulation components in relation to the lower strain in stiffer surrounding soils or rock. The presence of such cracks has been confirmed by inspection of encapsulations and surrounding grout after the full loading of encapsulations in gun barrel tests (Ref.4). Despite the presence of such cracks, the alkalinity of the cementitious medium provides a resistance to the corrosion of the steel and thus the two cracked barriers do contribute to the protection. In similar circumstances, a cracked resinous medium may be considerably less effective.

Clearly, the major barriers provided consist of two corrugated plastic ducts which during loading have the flexibility to deform as necessary and yet maintain their ability to prevent penetration of fluid or moisture. Although in the majority of cases the two barriers would each remain impregnable during proof loading conditions and during the full lifespan of the anchors, the requirement of the Code is that this condition must be maintained by inner duct only which would then accommodate any possible damage to the outer duct during installation. However, such damage is never an intent nor a criterion made known to site personnel. All efforts must be made to maintain the integrity of both plastic barriers.

4.0 ENCAPSULATION MATERIALS

4.1 Encapsulation Grout and Grouting

Very early investigation of the encapsulation of multistrand tendons generated a prefabricated resin filled encapsulation containing four 20mm diameter ducts each to accommodate an individual strand. However, during progressive placement of strands, each individually resin bonded, problems arose stemming from the exotherm associated with resin mixing. The heat generated accelerated resin setting in adjacent ducts and prevented installation of the third and fourth strands. Joint research between Universal Anchorage Company and Chemical Building Products Ltd during the mid-1970s advanced prefabricated encapsulation construction techniques with a preference for a polyester resin with fine grained filler and an appropriate setting time. Resin was poured into the double walled encapsulation, consisting of galvanised corrugated steel, which contained an air bleed hole, and strands were thrust into this resin. Such multistrand tendon encapsulations were fabricated on site and used on the Thames Bank Raising Scheme, at Woolwich (Ref 5), Grays and Greenhithe. Similarly
protected single bar anchors were marketed under the commercial name of HD1 from the mid 1970s. However, investigation into the use of a single plastic corrugated duct, as used in continental practice, continued and established a simple and thorough method of grouting a group of preplaced strands within the duct by placing the duct on a vertical or steeply inclined frame and pumping grout upward from the duct base. The use of a "pumping shoe" fitted to the base was found preferable to the incorporation of a tremie within the duct itself.

Throughout this period other similar anchor encapsulation systems incorporating single corrugated ducts with resin or cement grout were becoming available in the ground anchor market.

When development of double plastic duct encapsulation commenced in 1978, the design of a polyester resin offering ease of injection and a setting period which did not jeopardise fabrication but allowed removal of encapsulations from the frame within hours, benefited from the previous research. In 1980, double plastic encapsulations with resin grout were introduced to the UK anchor market. However, resin material was costly and demanded considerable attention to cleaning of mixing and pumping plant after usage. Proprietary cementitious grouts, complete with fine grained filler and plasticisers to ensure good flow characteristics and expansion properties within specified times of mixing and provision of guaranteed early strengths, were available. A number of cementitious grouts were investigated over an 18 months period to establish that the narrow annulus between the concentric ducts could be repeatedly fully grouted. Early in this period a double pumping shoe system was developed to allow independent grouting of the encapsulation core containing the strands, from the grouting of the annulus between the ducts. Order of grouting, confirmation of grout completion, spacing and centralising of strands, centralising of inner duct etc., were all essential controls which were established to ensure quality of the finished product.

Usage has now been made of the same material and proven grouting system for some 15 years. The efficiency of grouting of each encapsulation size is finally confirmed by lateral and longitudinal dissection of completed encapsulation after setting. The quality of the grout is established from cube tests, bleed and shrinkage tests. The performance of each encapsulation size is demonstrated by full-scale load tests within gunbarrels which themselves can be opened after use to inspect the integrity of the tested product.

4.2 Plastic Corrugated Ducting

The main performance requirements of the ducting are twofold in that the ducts must allow transfer of the full capacity of the anchor tendon from the inner grout to the outer grout without cracking, and the ducts must provide an impermeable barrier to fluid and moisture for the lifespan of the anchor without any material changes that may influence the bond mechanism.

Owing to the extremely high bond requirements between ducts and grout, the use of smooth non-corrugated ducting or surface roughened ducting is generally excluded. Furthermore, the actual shear capacity of the plastic medium within the duct wall is rarely adequate to allow transfer of a high load, thus the corrugated profile of the duct wall must be adequate to allow the majority of load to be transferred through the plastic medium whilst in compression. This concept is most easily explained by considering the corrugated plastic duct as a former which separates the inner grout from the outer grout, but ensures that the two grouts have an interlocked profile which allows transfer of load (Fig 3). The grout is subjected to high direct shear stress across the base of the interlock and the plastic duct wall is subjected to high compression stress. From this research work it is generally considered appropriate to ignore any adhesion bond capacity between the smooth, often "shiny", face of the plastic with the grout. From the figure it can be seen that the flat face of the corrugations
Fig 3. Simplified load transfer mechanism across corrugated plastic duct wall

along the outer duct wall considerably reduces the shear area of the grout, whilst that along the curved inner wall only nominally reduces the grout shear area. Hence, when utilising this commonly available profile, failure occurs along the outside of the duct and not the inside. The transfer of load from the tendon across the duct interface is carried by the shear area of the grout and the capacity can be calculated:

\[ \text{Shear capacity along outer interface} = \left( \frac{L}{2} - N t \right) \pi d_1 \tau_{ag} \]  

where \( L = \) encapsulation length, \( N = \) number of corrugation in encapsulation, \( t = \) duct wall thickness, \( d_1 = \) diameter of encapsulation (outer duct) \( \tau_{ag} = \) anchor grout shear stress

It follows that the actual shear stress mobilised within the grout body at an encapsulation interface is several times greater than the bond stress mobilised at the grout/ground interface on a larger surface diameter. Furthermore, associated with this encapsulation/grout load transfer (and also the tendon/grout load transfer) there are considerable bursting forces within the body of the outer grout. If these are not constrained by the surrounding ground, then the encapsulation may fail at a load lower than that calculated by summation of grout shear stresses (Ref 6 and 7).

Returning to the plastic duct properties, it is clear from the above that the corrugation profile in relation to the duct wall thickness is critical. Hence definitive shape values must be specified. BS8081 states that the minimum amplitude of the duct corrugation profile should not be less than 3 x the wall thickness (t) and the corrugation pitch (which controls the grout interlock width) not less than 6 x the wall thickness. It must be fully appreciated that the preference for increasing wall thickness can seriously jeopardise the load transfer mechanism by inducing unnecessary shear stresses in the plastic itself.

The minimum thickness of the duct wall is that necessary to ensure that the entire duct is adequately rigid to maintain its shape during tendon installation and during internal grouting whilst located on a rigid support frame. Nominal deviation from a circular section (ovality) can generally be tolerated.

Minimum wall thickness is, however, frequently specified; 0.8mm to 1.0mm not being uncommon. Realistically, the wall thickness requirements of single or outer ducts should be influenced by the abrasion resistivity of the plastic, and the weight of tendons to be installed, i.e. to prevent damage or perforation during installation in the borehole. In the case of the double plastic system, there is little or no risk of damage to the inner duct after encapsulation fabrication and thus the only essential thickness requirement is to satisfy the shape maintenance.

Outer ducts (or single ducts) are susceptible to handling damage and choice should be influenced by abrasion resistance. The vast majority of plastic corrugated ducts used for
encapsulations are manufactured for the ground drainage industry and, although they generally consist of high density polyethylene, there is a marked difference in texture. Most ducts are provided in coils, albeit one particularly strong semi-rigid duct is delivered in 3 to 6m in lengths complete with end threads. It is tougher and more abrasion resistant and, where possible, is preferred for use as the outer duct in the double plastic system.

Standard diameter corrugated ducts in the 35mm to 125mm diameter range are readily available, albeit the availability of inner ducts to provide a 5mm annulus thickness within 50, 65, 80, 100, 125mm diameter Drossbach outer ducts required considerable investigation and has necessitated the use of ducts from a number of international sources. Each size of encapsulation system has been extensively tested for "groutability" and, after exhumation, from the gunbarrel test, the integrity of the previously loaded ducting has been checked. The corrugated shape of the ducting allows considerable duct elongation prior to cracking, certainly much greater than the extension associated with tendon loading. No duct cracking has been observed in any full scale, full length encapsulation tests except for that caused inadvertently during dissection of the grout. However, where full scale short length encapsulations have been loaded beyond their ultimate load to identify failure mode, inevitably tensile failure of the ducts has been observed at critical sections where encapsulation failure translates to tendon failure in a composite mode.

5.0 STRAND ARRANGEMENTS AND PULL-OUT CAPACITY

This is a field in which an enormous amount of published data generally exists now, but information on particular strand arrangements with positive information on either strand noding or tendon noding characteristics is limited. (Strand "noding" is the deformation of the peripheral six wires from the original "lay"; tendon "noding" is the deformation of the peripheral strands from a constant pitch circle to provide a longitudinal wave like effect). In the very early days of anchoring (pre-1970) the benefits of strand noding or strand "bushing" or "caging", and of tendon noding, all to supplement simple adhesion bond by the presence of a mechanical lock, were realised. In 1975 Fuller and Cox (Ref 8) concluded their short wire and short strand pull-out tests by stating "load transfer between steel tendons and cement grout is critically dependent on both the shape and condition of the tendon surface. Generally any protrusions in the surface significantly enhance the load transfer whereas indentations produce only marginal improvement". Current knowledge that direct bearing capacity of confined grouts, which act on protrusions, grossly exceed the shear capacity of confined grouts, which translate across indentations, fully explains this phenomenon (Ref 7). The statement was further supported by results of research programmes sponsored by Universal Anchorage Company and carried out by Bruce (Ref 9) and Barley (Ref 10) just prior to the development of the double plastics systems in 1978. Bruce investigated pull out capacity of parallel deformed and non-deformed strands, either in contact, or at 5mm or 10mm spacing, over 1 to 3m fixed lengths in rock. He established values of ultimate bond stress for non-deformed strand in a group, ranging from 1.3 to 1.5 N/mm² with a preferred spacing of 10mm but an optimum of 5mm. For noded tendons he achieved 1.57 to 1.75N/mm² and for noded strands as much as 2.0N/mm² without failure. Barley's work, investigating capacity of underreamed rock anchors, required greater tendon bond capacity and his work established that noded strands in a group achieved bond stresses ranging from 3.0 to 4.5N/mm² over 1.5m fixed length without failure. Furthermore local bond stresses as high as 12N/mm² were identified by strain gauging in the area of the node. This supported the previous use of noded strands within prefabricated or single duct encapsulation and the noded strand system has now been used successfully for over 25 years. (It has in more recent years been successfully and extensively introduced into strands used for roof bolting in the mining industry).
Photo 1 (left) indicates individual strand pull-out at base of gun-barrel. Photo 2 (right) shows group strand pull-out with grout sheared between peripheral strands.

Although the principle of maintenance of an optimum strand spacing of approximately 5mm may, with adequate fixed lengths, allow full mobilisation of strand capacity with up to approximately 7 strands, as strand numbers increase a group strand failure mode becomes prevalent over that of a multiple of individual strand pull-outs (photo’s 1 and 2). When a high density of strands is contained within a circle diameter as defined by the external strands, a high concentration of bond stress exists at that circular interface. Figure 4 illustrates the actual failure plane exhibited, where encapsulation failure translates to group strand failure and then to strand pull-out. Group strand failure (Photo 2) involves a combination of direct shear of the grout between strands and a bond failure at the steel to grout interface over the external semi-circle of each peripheral strand:-

\[
\text{Total shear area} = \text{grout/grout shear area} + \text{grout/steel bond area} = (\pi D - n \times d_s)L + (n \times \pi d_s/2)L
\]

where
\begin{align*}
    n & = \text{number of strands on outer periphery} \\
    D & = \text{pitch circle diameter of outer strands} \\
    d_s & = \text{strand diameter} \\
    L & = \text{encapsulation length}
\end{align*}

Fig 4. Encapsulation, group strand and individual strand failure interfaces
It should be noted that the actual shear capacity of cement grout is approximately one order of magnitude greater than the actual bond capacity between non-deformed strand steel and cement grout. Research by Barley (Ref 10), has indicated the direct shear strength of anchor grout along an induced failure plane ranges from 13 to 20N/mm², whilst Bruce’s work indicated non-deformed steel/grout bond of 1.3 to 1.5N/mm². This suggests that pull-out capacity of strand groups from grout, either within a simple grouted borehole or within an encapsulation system, is strongly influenced by the spacing of strands on the outer periphery and:

\[
\text{Load capacity} = \tau_{ag} (\pi D - n x d_s)L + \delta_s(n x \pi d_s/2)L
\]

where

- \(\tau_{ag}\) = anchor grout shear stress
- \(\delta_s\) = grout/steel bond stress

For example: considering 16 strands of 15.2mm diameter on 100mm P C D which provides a 4.5mm spacing. Using ultimate grout shear and grout/steel bond stresses of 15 and 1.5N/mm² respectively, the load transfer capacity per metre of encapsulation is:

\[
(314 - 243)15 + 16 x \pi x 15/2 x 1.5 = 1638kN
\]

The composite bond stress on the external periphery (115mm diameter) is 4.5N/mm². Alternatively, considering 13 strands on a 100mm P C D, which provides a 9mm spacing, the load transfer capacity is 2206kN per metre of encapsulation and the composite bond stress is 6.1N/mm². The latter strand distribution allows a 36% increase in composite bond stress and hence provides a 35% increase in load capacity per metre. Clearly, the strand distribution on the outer periphery is the most critical but the distribution of strands contained within that periphery and the general density of steel within a grouted body are all relevant when designing a tendon arrangement or an encapsulation system. Situations have occurred where a high density of strands has been encapsulated for trial anchors and, in the belief that the prefabricated encapsulation is a "designed" system, the failure at the ground to grout interface has been mistakenly assumed.

It is acknowledged that strand noding increases the bond capacity of individual and of a multiple of individual strand pull-out mechanisms, but has a considerably smaller enhancement on the load capacity on the peripheral circle than an increase in strand spacing. Group strand capacity enhancement by noding may range from 5 to 10%, depending on strand spacing. The use of tendon noding, which produces a wave effect on the peripheral surface, and may vary the outer diameter by up to 25%, has a supplementary beneficial effect on load transfer due to the diametrical inconsistency. However, it increases the bursting stresses in the grout body around the tendon and where inadequate confinement is provided, may in fact reduce overall pull-out capacity.

There is a further consideration in the design of a system to mobilise the full capacity of each individual strand component that has rarely been considered. Richardson and Wycliffe Jones (Ref 11) observed that the ultimate pull-out capacity of individual non-deformed strand appeared to be in the order of six sevenths of the strand capacity. This drew attention to the load carrying and load transfer characteristics of the seventh strand wire, the central king wire. A brief study of the working mode of this wire, which is of larger area than the six peripheral wires, and is of shorter length than the spiral wound peripheral wires, provides a simple explanation for behaviour which may be inconsistent with that of other wires. Instances of protruding or withdrawn king wires at the strand head are not unusual during cyclic load operations, particularly where regripping is necessary.

Analysis would suggest that at wedge-locked ends at both live and dead ends of a prestressing system, the king wire is stressed by extremely high friction loading from the tightly gripped peripheral wires within the wedges of the normal lock-off system. This is also true at the stressing end of a ground anchor. However, in a non-deformed strand system, the
Photo 3. Unusual phenomenon after lock off of strand pull-in and king wire protrusion (Barley collection).

Fig 5. Centre king wire carries greater load than average peripheral wires until king wire slip occurs (after Richardson)

only mechanism to provide resistance to pull-out of the king wire is friction load from the peripheral wires over a fixed length where no mechanical enhancement of friction on the smooth king wire exists. In the case of noded strands, where peripheral wires are splayed or bushed to make a cage effect, the grout has direct access to bond to the king wire. Furthermore, the mechanical interlocking at such a location results in a concentration of lateral confinement of the strand and hence an increase in friction load on the king wire.

In the case of tendon noding, the intended deviation of individual strands in the bore may result in an increase in friction loading on the king wire (on the inside of the shallow "bends") and increased resistance to pull-out.

Richardson's research established that during initial loading of a grout anchored strand the actual load in the king wire was generally considerably higher than that in the peripheral wire (Fig 5). Whilst load was in the range of 60 to 80% of strand capacity, load in the king wire rapidly fell to a value lower than the peripheral wire. This would suggest that, at some stage of loading, static friction grip in the overloaded king wire may be exceeded and sliding friction results in maintenance of a much lower load. The presence of grease on the free length strand wires used for permanent anchor works may accentuate this occurrence.

This view is supported by the unusual phenomenon observed in permanent rock anchors in which parallel non-deformed encapsulated strands were installed. After proof loading, locking off and strand cropping of an anchor incorporating a multi-strand head, no change in protruding strand length is normally thought possible. Twenty-one strands of over 100 anchors (4 to 5 strands per anchor) exhibited remarkable individual occurrences of explosive movement, in which the protruding strand length reduced (Ref 12). Initially, it was considered that rock blasting some distance from the anchors was the sole contributory factor, but the phenomenon persisted for six months after blasting works were completed. The prestressing components were thoroughly tested, detecting no non-compliance with gripping or quality requirements. It was concluded that, with time, a sudden relaxation of king wire friction occurred, the tension in the king wire being released in an explosive manner causing the entire strand at the head to be momentarily ejected outwards thereby releasing the wedges. The loaded peripheral wires, still anchored, would immediately pull back inwards,
regripping the wedges and achieving a low load lock-off situation, but exhibiting shorter protruding strands. In all these cases, strand protrusion above the anchor head reduced and several inches of king wire upstand was evident (Photo 3). There were, however, cases of no change in strand length where the king wire pulled in several inches.

From the extensive data above and referenced documents, it is clear that the design of the strand distribution and modes of load transfer of the entire tendon components are complex, and, consistent with the recommendation of British Code and the European Standard, the full demonstration of the performance of each encapsulation system size is essential prior to use.

6.0 STRAND PULL-OUT ENCAPSULATION TEST RESULTS

During the 18 years of ongoing research and development of double plastic systems, all strand group arrangements have been subject to short encapsulation length tests to establish failure mechanisms and ultimate bond/shear capacities at the failure interface. Following satisfactory short test performance, full length encapsulations have been tested generally to 90% characteristic strength of tendon prior to usage on production anchor works.

Results of short encapsulation tests (generally 600 to 1000mm) in which failure has been attained, are presented in Table 1.

<table>
<thead>
<tr>
<th>Strand Detail</th>
<th>Encapsulation Diameter</th>
<th>Bond Stress on group-strand periphery</th>
<th>Tendon Bond Length (mm)</th>
<th>Load kN</th>
<th>Average Bond Stress N/mm²</th>
<th>Strain %</th>
<th>Comments on Failure</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bond Strength Group/Steel</td>
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<tr>
<td>1 x 15.2</td>
<td>5</td>
<td>9.1</td>
<td>600</td>
<td>270</td>
<td>9.4</td>
<td>2.9</td>
<td>At wedges</td>
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<td>1 x 18.0</td>
<td>5</td>
<td>9.1</td>
<td>700</td>
<td>360</td>
<td>9.1</td>
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<td>470</td>
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<td>4.2</td>
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Table 1: Short encapsulation test results - all strand contain strand nodes and group arrangements varied to obtain optimum

The strands tested were generally of dyform type from Bridon Wire, either 15.2mm or 18mm diameter, with characteristic strengths of 300 and 380kN respectively. Value of strand density represents the percentage area of steel within the outside encapsulation diameter. All tests incorporated a double corrugated plastic duct, and all strands contained one or more nodes, generally of 25 to 30mm outside diameter.
Bond stresses exhibited on the periphery of a group of strands are strongly influenced by strand arrangement and thus the values vary considerably. Investigation by Raison (Ref 13) involving six 15.2mm dyform strands within a single duct determined an ultimate bond on the strand periphery of 5.7N/mm².

Acknowledging that the normal duct profile favours failure along the outer surface, four pure individual failure modes can occur in a double plastic encapsulation. With consideration of uniform stress distribution, the load capacity of each can be calculated:

i. Multiple pull-out of individual strands;
Load capacity = \( n \times \pi \times d_s \times L \times \delta_s \) (4)

ii. Group pull-out of strands complete with interstrand encapsulation grout;
Load capacity = \( \tau_{eg} (\pi D - n \times d_s) L + \delta_s (\pi x nd/2)L \) (5)

iii. Failure along outer face of inner corrugated duct;
Load capacity = (L/2 - Nt) \( \times \pi \times d_3 \times \tau_{eg} \) (6)

iv. Failure along outer face of outer corrugated duct (encapsulation pull-out).
Load capacity = (L/2 - Nt) \( \times \pi \times d_1 \times \tau_{ag} \) (7)

where \( d_1 \) = outside diameter of outer duct  \( d_2 \) = inside diameter of outer duct
\( d_3 \) = outside diameter of inner duct  \( d_4 \) = inside diameter of inner duct
\( \tau_{eg} \) = encapsulation grout shear stress  \( \tau_{ag} \) = anchor grout shear stress

In the short encapsulation tests none failed by a simple failure mode along one interface. There were generally two composite failure modes which were exhibited on exhumation and dissection of the test samples:

vii. Group strand failure over a proximal length translating to multiple individual strand pull-out of the distal component.

viii. Failure along the outer duct face (usually of the outer duct) over a proximal length translating to group strand failure and thence to multiple individual strand pull-out of the distal component.

The results observed on dissection fully supported the necessity to inspect internally, since both mechanisms exhibited data at the stressing end and observations on the base that would suggest a pure type 1 failure mechanism had occurred throughout the entire encapsulation length.

Clearly failure of an encapsulation will progress from the proximal end along the circular plane or planes which provide the least resistance to pull-out.

Strand nodes cannot be efficiently located within 300mm of the base of a strand since, during loading, the peripheral wires will unwind below it and the benefits of the mechanical interlocking are lost. Furthermore, in a group strand anchor, nodes are located at staggered positions such that load concentration is distributed. Thus, in a one metre encapsulation strand, nodes may be distributed from 0.3 to 0.7m from the top with the "average" depth location at 0.5m. Failure over the proximal length of the short encapsulation test would take place along the group strand interface or the inner face of the inner duct, which have capacities of a similar order, whilst over the distal 500mm of the test, the strands would be predominantly non-noded which would in effect reduce the pull-out capacity of the multiple strands by a factor of 3 (reduced bond stress from 4.5 to 1.5N/mm²). Thus the failure mechanism would translate from group failure to individual strand pull-out from the encapsulation grout (Photo 2). Hence, dissection of the short encapsulation test will reveal the occurrence of a composite failure mode which is also experienced in short length site trials (Ref 14).
In full length encapsulation tests, the strand nodes would be distributed over the entire length, again to within 300mm of the base. The weaker interface over the proximal 500mm of the short test would extend over 4 to 5 metres to within about 500mm of the distal end. However, debonding would only take place over the first metre or so, as is common in anchor tendons. Such debonding is acceptable providing the apparent tendon free length does not exceed free length plus 50% fixed length - BS8081 acceptance criterion.

In situations where the bond capacity at the outer duct interfaces is critical, dissection of the grout can easily identify the failure plane. The grout will have sheared along a surface flush with the top of the duct corrugations, hence the "interlocks" of grout within the corrugations will either have separated from the anchor grout mass and remain in the duct corrugations (Photo 4) or, in the event of no failure, have remained with the grout mass.

Photo 4 (left) Grout remains in duct corrugation  
(right) Grout remains as part of grout mass (upper left)

7.0 PROGRESSIVE DEBONDING

The occurrence of progressive debonding at the steel grout and other load transfer interface is commonly accepted in the industry and is demonstrated in all encapsulation tests. This means, in effect, that ultimate bond stresses exhibited in short encapsulation tests cannot be fully reproduced in full length encapsulations. Thus in design, consideration should be given to application of a reduction factor or use should be made of bond stresses exhibited by identical strand groups over similar tested lengths.

8.0 SUMMARY

The double plastics encapsulation system ensures total insulation of the load carrying steel strands from the corrosive conditions of the geotechnical environment. Even in the event of damage or perforation of the outer plastic during carriage or installation, the protection against corrosion is still fully provided by the inner duct.

Load transfer across several interfaces within the encapsulation is complex, but the entire range of double plastics encapsulations has been extensively investigated over an 18 year period by gunbarrel testing to ensure satisfactory loading performance. These tests have provided a wealth of information on failure mechanisms and a much better understanding of load transfer from a high density of deformed strands across a number of critical interfaces mobilising component bond capacities.

Inspection of both inner and outer plastic ducts has been carried out after testing, and no evidence of cracking or other deterioration of the plastic has been observed in full scale encapsulation tests.
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