GROUNDS AND GROUTING

The most common and lowest basic cost material used for fixing and protecting rock anchors is neat cement grout. The influence of certain grout parameters on bond development has already been noted (Littlejohn and Bruce, 1975) and information on grout mixes and grouting procedures as used in rock anchor practice is now reviewed, and recommended quality controls are discussed.

Grout composition
Cement
The type of cement used will obviously vary from contract to contract as dictated by ground conditions and the installation programme. Thus, while Ordinary Portland Cement (Type I) may suffice in many cases, a sulphate-resisting (Type II), or a rapid hardening variety (Type III) may be required. In Britain, Ordinary and Rapid Hardening Cements must comply with BS 12 and High Alumina Cement with the relevant clauses of BS 12 and 195. It is recommended that high alumina cement be restricted to short term test anchors, in view of the use of high water cement ratios often necessary for pumpability.

Since cement surface areas (and therefore particle sizes) are normally controlled by specification, the most likely deterioration in cement quality may be due to age or poor storage, when partial dehydration or carbonation may lead to particle agglomeration and reduction in post-mix hydration. Although large sizes may be removed by sieving, it is likely that better control may be exercised by insisting on fresh cement, and by careful storage. Ideally cement should not be stored on site for more than one month, and must be kept below 40 deg. C, under cool storage. Cement should be used in order of delivery.

Water
Water which is suitable for drinking (except for the presence of bacteria) is generally considered suitable for cement grout formulation. Water containing sulphates (> 0.1 per cent), chlorides (> 0.5 per cent), sugars or suspended matter e.g. algae must be considered technically dangerous. High chloride content should be particularly avoided where the steel tendon is in contact with the grout.

Where there is some doubt as to the quality of the water, a test on the lines of BS 3148 "Tests for water for making concrete" may be carried out.

The proportion of water to cement in a grout rather than the quality of water is the most important determinant of grout properties. Excess water causes bleed, low strength, increased shrinkage and poor durability. The extent to which these (and also fluidity) are related to the w/c ratio of an OPC grout is shown in Fig. 4.

Table VII has been prepared to illustrate a range of w/c values recently used or recommended throughout the world, for neat cement grouts. Most ratios are between 0.40 and 0.45 which gives a grout with sufficient fluidity to be pumped and placed easily in small diameter boreholes, and yet retains sufficient continuity and strength after injection to act as a waterproofing and/or strengthening medium.

Admixtures
The use of inert "fillers" such as ground quartz, limestone dust, fine sand, clay, and even sawdust, has long been common, particularly in Europe. The resultant mixes have been used primarily to waterproof

### TABLE VII. RANGE OF W/C RATIOS RECENTLY USED OR RECOMMENDED

<table>
<thead>
<tr>
<th>W/C ratio</th>
<th>Ordinary Portland</th>
<th>Rapid Hardening</th>
<th>High Alumina</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>0.45</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>0.4</td>
<td>0.45</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>0.4-0.45</td>
<td>0.40-0.45</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>&lt;0.45</td>
<td>&lt;0.45</td>
<td>&lt;0.45</td>
<td></td>
</tr>
<tr>
<td>0.35-0.4</td>
<td></td>
<td>&lt;0.45</td>
<td></td>
</tr>
<tr>
<td>&lt;0.45</td>
<td></td>
<td>&lt;0.45</td>
<td>&lt;0.45</td>
</tr>
<tr>
<td>0.36-0.44</td>
<td>0.34-0.04</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>&lt;0.45</td>
<td></td>
<td>&lt;0.45</td>
<td>&lt;0.45</td>
</tr>
<tr>
<td>0.4-0.5</td>
<td></td>
<td>&lt;0.5</td>
<td></td>
</tr>
<tr>
<td>0.4-0.45</td>
<td>0.4-0.45</td>
<td>0.4-0.45</td>
<td></td>
</tr>
</tbody>
</table>

*Source

- Anti-bleed admixture permitted: Maddox et al (1967)
- U.A.C. anchors: Anon (1969)
- Fluidifier permitted: Buro (1970)
- "Intrusion" admixture permitted: Thompson (1970)
- Admixtures permitted: Gosschalk and Taylor (1970)
- Expanding agent recommended: Barron et al (1971)
- Recommendation: Conte (1971)
- Recommendation: Littlejohn (1972)
- Recommendation: C.P. 110 (1972)
- Recommendation: Bureau Securitas (1972)
- Recommendation: Mascardi (1972)
- Recommendation: Manitoba Hydro (1972)
- Recommendation: South African Code (1972)
- Recommendation: Stocker (1973)
- Recommendation: Hill (1973)
- Recommendation: White (1973)
- Recommendation: Golder Brawner (1973)

### TABLE VIII. COMMON CEMENT ADMIXTURES FOR ANCHOR GROUTS

<table>
<thead>
<tr>
<th>Admixture</th>
<th>Chemical</th>
<th>Optimum dosage (%) of cement by weight</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator</td>
<td>Calcium Chloride</td>
<td>1—2%</td>
<td>Accelerates set and hardening</td>
</tr>
<tr>
<td>Retarder</td>
<td>Calcium Lignosulphonate</td>
<td>0.2—0.5%</td>
<td>Also increases fluidity</td>
</tr>
<tr>
<td></td>
<td>Tartaric acid</td>
<td>0.1—0.5%</td>
<td>May affect set strengths</td>
</tr>
<tr>
<td></td>
<td>Sugar</td>
<td>0.1—0.5%</td>
<td></td>
</tr>
<tr>
<td>Fluidifier</td>
<td>Calcium Lignosulphonate</td>
<td>0.2—0.3%</td>
<td>Entains air</td>
</tr>
<tr>
<td></td>
<td>Detergent</td>
<td>0.5%</td>
<td></td>
</tr>
<tr>
<td>Expander</td>
<td>Aluminium powder</td>
<td>0.06—0.02%</td>
<td>Up to 15% expansion</td>
</tr>
<tr>
<td>Anti-bleed</td>
<td>Cellulose Ether</td>
<td>0.2—0.2%</td>
<td>Equivalent to 0.5% mixing water</td>
</tr>
<tr>
<td></td>
<td>Aluminium Sulphate</td>
<td>up to 20%</td>
<td>Entains air</td>
</tr>
</tbody>
</table>

*Geotechnics Research Group, Engineering Dept., Heriott’s College, University of Aberdeen.

**This is the second section of this article on rock anchors and rock anchor construction; the first, which appeared in our September issue, pp. 34-45, dealt with drilling, water testing and waterproofing, and tendon work. These articles together form the second part of a three-part series on rock anchors: the first also split into two sections that were published in May, pp. 25-32 and July, pp. 41-48, covered design aspects. The third will deal with testing and stressing.
or consolidate boreholes prior to redrilling—a role in which neat cement grouts may be uneconomic. Such fillers are seldom employed however in grouts used for tendon bonding.

With respect to anchor grouts, chemical admixtures have often been employed particularly those to prevent shrinkage, to permit a reduction of the w/c ratio while ensuring fluidity, to accelerate or retard setting, and to prevent bleeding which in turn discourages corrosion. Table VIII lists common types of admixtures employed in grouts. Care should be taken however to ensure that the basic grout materials are compatible and except under carefully considered and controlled conditions, different types of admixture should not be included in the same grout. For example, admixtures such as calcium chloride should not be used with sulphate resisting, super-sulphate or high alumina cement. Calcium chloride can also corrode steel in contact with the grout and to avoid this potential hazard the authors recommend that use of this admixture should be banned in anchor grouting.

Geddes and Soroka [1964] conclude that aluminium-based expanding agents improve grout workability while increasing the "confined" compressive strength (i.e. where expansion has been restrained on setting). This latter effect increases the bond capacity of the grout which has been illustrated experimentally by a reduction in bond transmission length. Leech and Pender [1961] have also favoured the use of aluminium powder in an amount of 0.006 per cent by weight of cement and they stipulate that bleeding was also inhibited. Pender et al [1963] advocate that a 2 per cent expansion of grout volume is desirable; this figure can be attained by using 0.002-0.005 per cent aluminium powder. However, a warning on the use of aluminium powder has been sounded by Moy [1973]: While confirming the findings of Leech and Pender, he emphasises the great sensitivity of grout mix properties to the amount of aluminium powder added—and its efficiency of dispersion and mixing. For example, slightly larger dosages of powder can give a markedly spongy and crumbly grout.

In Britain, some success has been achieved with calcium lignosulphonate as a grout fluidifier, when used at a concentration of 0.03 per cent by weight of cement. In this way a pumpable low w/c grout—0.3—can be satisfactorily produced for anchors, installed in water sensitive marls and shales.

In rock anchoring, grout bleed seldom receives consideration despite its great importance in corrosion protection. Anti-bleed additives based on cellulose ethers have been successfully employed (e.g. Maddox et al, 1967: 0.2 per cent by weight of cement), although slightly lower grout crushing strengths and higher initial grout viscosities result. They found from field tests that the final mix gave negligible settlement at the top of the tendon, and complete grout cover free from fissures or water filled lenses. Commercial products are readily available and Celacol M5000DS and Methocel 65HG4000 are recommended for consideration. Dosages are normally expressed as a percentage of the mixing water, rather than the cement, and vary according to the viscosity grade of the material. For example Celacol M5000DS and equivalent grades are normally added at a rate of 0.4-0.5 per cent by weight of water.

In general, considerable international agreement on the use of admixtures is apparent. For instance, the use of chloride bearing compounds is banned in Britain, Germany, France, Switzerland, Italy and the United States. CP 110 stipulates that admixtures may be permitted only when "experience has shown that their use improves the quality of the grout". Nitrites, sulphides, and sulphates are also banned, and total expansion should not exceed 10 per cent.

In Germany, the use of any additive is rare, and only those which increase workability of the grout are employed. Mascardi [1973] states that in Italy moderately expanding additives are used but air entraining or metallic expanding types are banned, as are rapid hardening agents.

Hill [1973] considers that sand, and tibleed and expansion agents are acceptable in the United States, whereas White [1973] discourages the use of anything other than cement grouts. A very comprehensive survey of grout admixtures has been prepared by the American Concrete Institute [1971], and is recommended to the interested reader.

In summary, it may be concluded that the use of admixtures for grouts is still very much an art. Even the manufacturers have relatively little practical experience of their use for rock anchoring. Consequently, whenever a new mix is designed or adopted, the following must be recorded:

(i) water/cement ratio,
(ii) admixture concentration,
(iii) flow reading (through flowmeter, flow cone or viscometer),
(iv) crushing strengths (two cubes each) at 3, 7, 14 and 28 days, and
(v) notes on amount of free expansion or shrinkage, bleed and final setting time.

Even if the design is satisfactory, unless the cement and admixture is delivered on site ready mixed, very careful supervision of the grout mixing personnel is essential. Hence the general indication is that admixtures should be used only where absolutely necessary.
Grout crushing strength

Some grout properties have already been referred to—pumpability, slight expansion on setting, a minimum w/c, and resistance to bleeding. In addition, the crushing strength requirements are of fundamental importance.

CP-110 steel reinforcing bar is the grout used for prestressed concrete work must have a compressive strength in excess of 17N/mm² at 7 days. Normally higher strengths are specified for anchoring, and Littlejohn [1972] recommends a minimum value of 24N/mm² for grouts used in tendons in Britain. A survey of world practice reveals that this figure is in fact common in many countries, although Mascaré (Italy) feels that 35N/mm² is necessary (w/c < 0.45) whilst PCI (1974) recommends a minimum of 40N/mm².

It is noteworthy that Thompson (1970) describes how satisfactory anchorages were installed at the John Hollis Bankhead Dam, Alabama, with a grout of 28 day strength of 17N/mm². This serves as a reminder that low strength grouts are only acceptable in rigid, competent rocks where "arching" mechanisms of the particulate grout can be mobilised, whereas high strength cement grouts are necessary in soft, yielding rocks.

In general a major disadvantage of cement grouts, even when admixtures are used, is the time required for the grout to develop full operational strength (see Fig. 5). Other problems are associated with its low tensile strength, brittle nature, and installation in adverse conditions. However, where time and bond length are not restricting factors—especially where large anchor volumes are involved—no economic substitute to cement grout is available.

Mixing

The authors recommend that to ensure good practice, the following fundamental points should be observed.

1. The cement (and fillers where applicable) must be measured by weight.
2. Water should be added to the mixer before the cement, and the admixtures added with great care usually during the latter half of the mixing time.
3. Although the mixing time depends on the type of mixer, the total time should not be less than 2 minutes according to CP 110.
4. Mixing by hand is to be strongly discouraged.

The equipment must be able to produce grout of uniform consistency, and should have two drums or tanks: one for mixing, the other for storage and delivery. In order to avoid heating of the grout, slow agitation only is permissible in the storage tank.

Rate of shear during mixing is particularly important, and it is noteworthy that the most common type of grout mixer, comprising an impeller in a tank, combines two major effects which influence the efficiency of mixing—circulation and fluid shearing. Circulation is usually incapable, since a large slowly rotating impeller will produce a high circulating capacity and low shear rate, while a small rapidly rotating impeller will yield a high shear rate and poor circulativity. For cement grouts of low w/c ratio shear rate is a critical factor in mixing and ideally impeller speeds of 1500-2000 rpm are required. In this connection an ideal type of mixer is the Colcrete double drum mixer which circulates the grout through a centrifugal pump. The grout is recirculated through a zone of high shear with sufficient impact and turbulence to break up clusters or agglomerates, and provide maximum interdispersion of water and cement.

Where conventional paddle mixers are employed, field analysis indicates that the best results are obtained when the paddles are cut with slots, and where slotted baffle plates are fitted around the perimeter of the tank or drum.

Experience suggests that the actual mixing in the field is generally satisfactory, but that often the strainer between the two tanks is too small or easily clogged. In such cases, unstrained and lumpy grout overflows into the delivery tank and subsequent mixing is incomplete. In addition exit points should be fitted at the base of tanks to avoid formation of cement cake at the bottom.

The use of rapid "snap-off" couplings permits the grout to be quickly changed, which tend to form in bends of flexible pipes or at constrictions. It is noteworthy that rigid steel pipes do not allow the position of the obstruction to be quickly ascertained.

Finally it is an elementary yet important observation that a high standard of cleanliness of grout mixing and pumping equipment is usually associated with simpler and more efficient grouting operations.

Grouting methods

There are basically two distinct modes of anchor grouting, namely by two-stage or single-stage injection.

Two-stage grouting involves first injecting a "primary" mix to effect the bond between the tendon and rock. After final stressing, a "secondary" phase is introduced, largely for the corrosion protection of the free length. In the one-stage system, both functions of the grout are simultaneous.

In two-stage injections the primary grout may be preplaced or postplaced with respect to the introduction of the tendon. Postplacing can be advantageous when dealing with a "sluggish" or "slabby" rock, and is the only choice for very shallow or upwards-inclined anchors.

It is good practice to ensure that the primary grout extends for at least 2m above the designed fixed anchor length. This inhibits crack formation in the proximal end of the anchorage during stressing. Where the primary grout is preplaced, the tendon should be hosed within 20 minutes of the injection. Even after the tendon has been correctly hosed, problems have been experienced with grout/ tendon bond development and opinions currently differ as to whether the tendon should be left static after hosing (FIP, 1973) or vibrated (Standards Association, Australia, 1974).

Secondary grouting is usually accomplished with a mix of the primary composition although Mitchell [1974] recommends a grout mix with the exact quantity and quality of the vital primary batch is difficult to judge without careful checking and (c) a two-stage method is inherently more time-consuming and laborious.

Single-stage methods are free from these problems. However it must be noted that unless the free tendon length is meticulously greased before sheathing all the load applied at the head will not be transmitted to the intended anchorage zone due to friction in the free anchor length.

On the practical side, before grouting commences, it is advisable to check the airtightness of all pipes involved, and the tremie pipe—flexible and usually 12-25mm in diameter—should be blown and flushed with water.

Both hole and tendon should be thoroughly water-flushed from the bottom upwards for at least 10 minutes prior to grouting. If the grout is to be postplaced the tremie pipe may be conveniently incorporated in the tendon, but terminating at least 150mm from the foot.

Grout should be tremied at a steady rate and the pipe, once incorporated in the tendon, may be withdrawn slowly during the operation. At no time must either the end of the tube be lifted above the surface of the grout or the level of grout in the pump storage tank be allowed to drop below that of the exit pipe, otherwise air may be drawn into the grout placed.

In the single-stage method or during the secondary phase of a two-stage injection, grouting should continue until grout of the same composition as that mixed has been emerging from the hole for at least 1 minute.

The Australian Code recommends that it is preferable to provide a standpipe during grouting so that grout shrinkage will occur in this pipe and not in the hole. In any case it is traditionally regarded as good practice, particularly in relation to dams, to "top up" anchor holes where necessary, a few days after the major grouting operation.

Grouting pressures

The general conclusion amongst specialist contractors is that high grout pressures are completely unnecessary for successful anchorages in intact rock but useful for anchors in badly fissured rock. Analysis of the data received suggests that grouting
pressures normally lie in the range 0.28—0.70N/mm².

A.T.C. Ltd. (1973) experimented with different injection pressures when grouting anchors in chalk and concluded that there is no real benefit in employing grouting pressures levelling off at 4N/mm². Practical and economic considerations often set the maximum grouting pressure at 3N/mm², and for the subsequent contract anchors, a pressure of 2N/mm² was used. Fig. 6 illustrates the relation of grout pressure to average anchor capacity, claimed for Solelone's "Tamanchor" (I.R.P.) system anchors. Others grouting pressures which have been used in practice are shown in Table IX.

It can be summarised that permissible grouting pressures are largely a matter of conjecture. They depend on the circumstances and geology of the site and "rules of thumb" should be proven at each site by site work, or grout pumping tests, before being put into general use. As a starting point the most common rule for permissible pressure appears to be 0.023 N/mm² per metre of overburden.

### Quality control

Variations in grout properties arise from three principal causes:

(a) inadequate mixing,
(b) variations in grout materials quantities and quality, and
(c) apparent variations arising from the testing procedure.

In order to obtain a satisfactory basis for grout mix design it is essential, prior to any anchor contract, that methods of storing, batching, mixing and testing of materials be rigidly defined and adhered to.

### Mixing of cement grouts

Contact between cement and water leads to a prolonged sequence of exothermic reactions leading to complete hydration and ultimately final setting of the cement-water paste. There are normally four stages to this reaction:

(i) an initial highly exothermic reaction lasting 5—15 minutes,
(ii) a dormant period lasting up to 2 hours during which there is a low rate of heat evolution,
(iii) an increasing rate of reaction leading to full setting after 6 or more hours, and
(iv) a continuing decreasing rate of reaction after setting.

During the dormant period, a cement grout should maintain a consistent physical state when its properties can be measured and predicted. In order to obtain this consistent physical state when the cement is added to the water, sufficient mechanical agitation must be induced to fully disperse the cement grains. To achieve this and at the same time avoid false sets, mixing for a period of 5-10 minutes is normally required. Under most field applications this should be achieved by agitation during storage, and pumping and placement after mixing.

### Variation in grout quality

Variations of material quantities and qualities from those specified in the grout design are largely a reflection of the standards of site organisation, equipment and supervision and as such are difficult to quantify. Neville (1963) has attempted however to define the quality of concrete mixes by relating the coefficient of variation of cube strength to the degree of site control, and it is considered that these standards (Table X) apply to cement grouts.

<table>
<thead>
<tr>
<th>TABLE IX. VARIATION OF CONCRETE STRENGTHS</th>
<th>Coefficient of variation (mean strength)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degree of site control</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>Best laboratory control</td>
<td>5</td>
</tr>
<tr>
<td>Best site control</td>
<td>10</td>
</tr>
<tr>
<td>Excellent</td>
<td>12</td>
</tr>
<tr>
<td>Good</td>
<td>15</td>
</tr>
<tr>
<td>Fair</td>
<td>18</td>
</tr>
<tr>
<td>Bad</td>
<td>25</td>
</tr>
</tbody>
</table>

The best possible results obtainable when site control approaches laboratory precision should have a coefficient of variation of 10. This will require:

(a) Obtaining cement, fillers and chemical admixtures from a reliable source,
(b) Storage of cementitious materials under dry and constant conditions,
(c) Accurate determination and monitoring of moisture content of fillers,
(d) Use of cement in fresh condition,
(e) Weigh batching of all materials (meter for water is acceptable),
(f) Controlled water/cement ratio,
(g) Adequate mixing rate and time of mixing,
(h) Immediate pumping and injection of grout after mixing, and
(i) Rigid supervision of all operations.

In practice the cement grout is expected to fulfil the dual role of fixing the anchor to the rock and protecting it against corrosion, often in "aggressive" environments. It is surprising, therefore, that the only common method of checking quality is by crushing a nominal number of cubes after the anchors have been constructed. Furthermore, samples are often carelessly taken, or not taken for every anchor.

Additional measurements are therefore recommended which permit the quality of the grout to be assessed before the grout is injected, thereby pre-empting the possibility of potentially expensive and/or dangerous errors occurring.

### Measurement of important grout properties

Accuracy of measurement of grout properties is an important factor in determining the variability of grout properties in the field. Some property measurements, such as bleed, have been developed principally as laboratory measurements, for example, Powers' float test and the ASTM method (see Powers, 1968). In the field, levels of bleed above 0.5 per cent are relatively easily detected in any sample contained in a wide, low container, and in anchors the actual magnitude of bleed is less important than the fact of its existence.

Laboratory measurements of grout fluidity in terms of shear strength and viscosity are normally carried out with a rotating disc or coaxial cylinder viscometer. Two instruments which are commonly used in the field are the Colcrete flowmeter (which expresses fluidity in terms of horizontal slump) and the Portland Cement Association cone (in terms of low slump). Various specialists and researchers have calibrated these instruments in terms of standard grout parameters e.g. w/c ratio, but for particular grouts it is the authors' view that the most direct information on fluidity is still best obtained from field pumping tests. Nevertheless flowmeter and flow cone data can be useful in assessing efficiency of mixing.

Check measurements of water/cement ratio can be made on site by measuring the specific gravity of the grout using a Baroid mud balance (see Table XI). Hydrometers are not recommended since at low water/cement ratios larger errors are introduced due to the thixotropy and solid structure of the grout.

<table>
<thead>
<tr>
<th>TABLE XI. CALCULATED SPECIFIC GRAVITIES OF WATER/CEMENT GROUNTS</th>
<th>Specific gravity</th>
<th>Water/cement ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.10</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>1.95</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>1.84</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1.74</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>1.67</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>1.61</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>1.56</td>
<td>0.9</td>
<td></td>
</tr>
</tbody>
</table>

In most grouts the hydrogen ion concentration is of value as an indicator of chemical contamination; pH is therefore another parameter which can be a useful control in practice and where a large number of site tests are planned, a battery or mains pH meter can be used.

With regard to the strength development characteristics of cement grouts, Fig. 5 indicates the curing times required by a range of grout mixes made from Ordinary Portland and Rapid Hardening Cement to attain the minimum strength of 28N/mm² before stressing. The results were obtained from 150mm grout cubes but 75mm cubes should give reliable results in practice. Care must be exercised, however, when attempting to correlate 75mm and 150mm cube strengths. On demoulding larger cubes are invariably warmer, even when efficiently cured. In addition, the curing water takes longer to influence the centre of the larger cubes. Both these phenomena act to increase the early strength (1-7...
with the crucial grouting operation will be eased if the equipment is kept clean and in good repair, adequate supervision and skilled labour is provided, and unnecessary complications (e.g. small amounts of admixture) are avoided. Data relating to the operation should be carefully recorded—w/c, type of cement, and/or additives, type of mixing and pumping equipment, mixing and delivery time, grout fluidity and strength, source and chemistry of mixing water, length of grout line, pressure and quantity of grout injection, air temperature, and the names of the operating personnel. Such data will help to pinpoint reasons for anchor malfunction, should it subsequently occur.

It is strongly recommended that specific gravity checks as well as flow cone or flow meter testing should be used to supplement the results of conventional cube crushing programmes—a retrospective source of data.

**CORROSION AND CORROSION PROTECTION**

**Mechanisms and causes of corrosion**

The corrosion of prestressing steel is largely electrolytic and Longbottom and Mallett [1973] list the pre-requisites as (i) an electrolyte having interfaces with (ii) an anode and a cathode and also have (iii) direct metallic interconnection.

The electrolyte is usually aqueous, and a mere surface film is adequate. Reactions are initiated as a result of inhomogeneities or impurities in the steel or grout, or by the presence of chlorides or other salts in solution.

The cathode has a higher electrical potential relative to the electrolyte than the anode, which is a result of the electrochemical table. The more common elements are arranged as follows:

(stainless steel)  
\[
\begin{array}{c}
\text{Na} \\
\text{Al} \\
\text{Zn} \\
\text{Cd} \\
\text{Fe} \\
\text{Ni} \\
\text{Sn} \\
\text{Pb} \\
\text{H} \\
\text{Cu} \\
\text{Ag} \\
\text{O}_{2} \\
\text{passivated AI}
\end{array}
\]

Anodic \(\rightarrow\) Cathodic

The general rule is that electrolyte action will be more severe between electrodes which are widely separated in the table than between those which are closer.

There are generally held to be three major mechanisms of corrosion:

(1) **Corrosion by pitting**. Under conditions of chemical and/or physical inhomogeneity in the steel or electrolyte, ionisation will occur at both anode and cathode, constituting a bimetallic cell (Fig. 8a).

(2) **Corrosion involving crack formation under tension** ("hydrogen embrittlement"). This is more a physical corrosion, mainly affecting highly stressed carbon steels. The best known cause of brittleness is nascent hydrogen (Fig. 8b). The cathode reaction:

\[2H^+ + 2e^- \rightarrow H_2\]

is favoured by acid environments, and the hydrogen so produced tends to disrupt the structure of the steel.

From a survey of reports on hydrogen embrittlement it appears that oil quenched and tempered steels are far more susceptible to hydrogen embrittlement than drawn types. There is however no unanimous opinion about the susceptibility of prestressing steel to hydrogen embrittlement in highly alkaline grout.

(3) **Corrosion involving oxygen**. Local concentrations of oxygen at a cathode act to accelerate corrosion:

\[O_2 + 2H_2O + 4e^- \rightarrow 4OH^-\]

The reaction is favoured by alkaline conditions (see Fig. 8c) and oxygen concentrations at an anode lead to the formation of a protective, passivating layer of rust:

\[2Fe^{+++} + 2OH^- \rightarrow Fe_2O_3 + 2H_2O\]

In the alkaline environment provided by a good dense grout, steel is passivated in this way. As Portier [1974] noted, however, rust so formed is easily removed by the circulation or infiltration of water, thus leading to progressive dissolution of the steel.

There are two main chemical controls on these reactions—water, and electrochemical potentials.

(i) **Water**. Regardless of the type of corrosion, it can only occur in an ionic medium, and, under natural conditions, water is the most widespread bearer. The renewal of water increases the risk, while humidity is an even more dangerous parameter. The two factors are closely interdependent: the supply of oxygen; the intensification of the microcell effect by the formation of a cathode at the water/air interface; and the action of hydrogen embrittlement.

(ii) **Electrochemical potentials**. With respect to Fig. 9, in Region I there is formation of ferrous ions, and generalised dissolution. Hence it would appear that to avoid corrosion, it suffices to remain within pH 8.5—13.5, i.e. in the range created by grouts. However...
this protection is very inadequate since it is known that (Region II),
delamination and activating action of
\( FeO \), formation, there may be corrosion
by pitting under the influence of ions such as \( Cl^- \) when present in the cement. Also, Region III, corrosion within cracks formation may occur.

Thus, although no domain is abso-

lutely safe, the risks of corrosion can be simply reduced by:

(a) creating a \( pH \) environment of 9-12 in the grout. Chloride, sulphide, sulphate, and iodide ions tend to lower the \( pH \) of the grout, enhancing electrolytic action,

(b) avoiding the possibility of harmful ions. e.g. chlorides, sulphides, sulphites, contacting the steel surfaces,

(c) selecting steels with low susceptibility to corrosion under tension, and eliminating from grouts anions which favour the passage of hydrogen e.g. \( SH\cdot, NO_2^-\), \( CN^-\), and

(d) preventing, as far as possible, the circ-

ulation of water.

Corrosion is thus aided by porous grout or concrete, and Rehm [1968] has found that in certain cases a cover of 25mm is insufficient. Therefore in anchors the porosity of the grout is not simply its thick-

ness of cover, should be stipulated.

Pressurising the steel may accelerate the rate of intensity of corrosion, although the elastic and strength properties of non-

stressed steel are similarly affected. Quenched and tempered steels are far more susceptible to stress corrosion than cold drawn carbon steels of the type used in the UK for strand. Stress corrosion is more acute than ordinary corrosion for three main reasons,

(1) Stressing and releasing, if repeated, constantly deforms any protective oxide film,

(2) Stressing facilitates the development of micro-fissures, and

(3) Prestressing steel is, a priori, more susceptible than ordinary steel.

There is an increasing realisation that the failure of highly stressed materials under the influence of corrosion may be complex and may be precipitated by factors specific to the conditions which will or will not give rise to stress corrosion. The only safe principle to follow is that if conditions could be dangerous—as in permanent ground anchorage—then the whole design of the system should be orientated towards ensuring complete protection of the prestressing steel.

Whilst many of the problems of corro-
sion protection in prestressing systems in general are present in ground anchorage works Portier [1974] has pointed out that there are a number of corrosion problems specific to ground anchors, namely—

(i) Risks due to uplift pressure. Anchors may exert uplift pressure on the shafts, generally located underneath the water table and hence liable to uplift pressure. The slightest orifice serves as a drain cock and water may then flow along the tendon. This is the most hazardous for tendon an-

chors, although Solutanche Co Ltd., now use an epoxy pitch which is claimed to penetrate the tendon core and ensure abso-

lute imperviousness, and British strand manufacturers are confident about the penetration of corrosive resistant greases used at present with polypropylene sheathing.

(ii) Sealing. There are two contrary trends—either the risks are considered great and attempts made to protect the steel (as described below) or the risks are thought insufficient and the tieback is im-

mersed in the cement grout.

The latter method is older, and about 90 per cent of existing permanent anchors appear to have been so constructed, and whilst no failures have been observed no systematic records of corrosion have been taken.

(iii) The free length. This usually consists of a steel sleeve, or more often a plastic sleeve which may easily be re- 

ferred impervious at the joint. The ten-

don which passes inside is already pro-
tected by this sleeve, and also has addi-
tional protection from the cement filling the space between the sleeve and bore-

hole wall. A problem is to prevent the formation of longitudinal paths (along which water can flow) along the axis of the sleeve. Various substances have been used for filling as cement grout does have certain disadvantages, and recent trends are towards synthetic substances which can impregnate the core of the tendon, while being at the same time flexible.

(iv) The head. While often being the most susceptible zone, it invariably receives least attention. It is vulnerable for many reasons: grout settling affects it, leaks emerge through it, mechanical and heat stresses create electric couple out of proportion with those of the sealing, and it is in contact with the potentially corro-
sive atmosphere. One possibility is to en-
sure that on completion of the final grout-

ing operation the top anchorage is com-
pletely encased in concrete. This how-

ever pre-empts the possibility of restress-

ing the anchor at a future date. An alter-

native is to enclose the top anchorage in a steel or rigid plastic cover filled with grease or bitumen, again after final stress-

ing. The PCI Recommendations [1974] ad-
vocate the “asphaltic painting” of all top anchorage hardware.

Classification of groundwater aggressiveness

It has been demonstrated that certain ions, both in the ground and in the ground-

water initiate and sustain corrosion. Quan-
titative limits on aggressiveness of environ-
ments have been drawn up by Bureau Securitas [1972] and FIP [1973]. Ground and mixing waters classed as aggressive are:

(1) Very pure water. It is termed aggressive if the concentration of \( CaO \) is less than 300mg per litre. Such waters dissolve the free lime and hydrolyse the silicates and aluminates in the cement.

(2) Acid waters. If \( pH \) is less than 6.5, they are considered aggressive as they may attack the lime of the cement. They are normally industrial waters, water with dissolved carbon dioxide, or water contain-

ing humic acids.

(3) Waters with a high sulphate content. These react with the tricalcium aluminate of the cement to form salts which dis-

arrange the cement by swelling. Among these are (a) selenious water, with a high content of dissolved sodium sulphate, and (b) magnesium water, with a high content of dissolved magnesium sulphate. Waters with these salts are classed as very aggressive when the concentration of the salts exceeds 6.5g/litre for selenious water and 0.25g/litre for magnesium water. It is noteworthy that these values refer to stagnant water, and for flowing water the concentrations are 40 per cent of the above values.

Recommendations also refer to the aggressivity of the grout towards the steel of the tendon. In order to avoid “stress corrosion” of the tendon, the cement must not have a chlorine content, from chlor-

ides, which exceeds 0.02 per cent by weight, and sulphur from sulphides, which exceeds 0.10 per cent by weight. These are provisional limits only.

Any admixtures used must likewise con-
tain no elements aggressive towards the steel or cement, and so the use of calcium chloride is forbidden.

Degree of protection recommended in practice

Methods used to protect rock anchor tendons reflect the following factors; the intended working life, the aggressiveness of the environment and the consequences of failure due to corrosion. Systems should be capable of effective protection against mechanical damage, as well as chemical, and should not therefore be impaired by the operations of fabrication, installation or stressing.

Three different situations can be deline-

ated for the purposes of discussion, but in practice their distinction is often diffi-
cult.

(a) Temporary anchors in a non-aggres-

sive environment. It is normally safe to assume that the cement grout will protect the fixed anchor length and the specified
minimum cover for this type of anchor is not normally very large. Figures quoted by various engineers indicate a range of values for this type of anchor from 5 to 20mm. The need for some form of protection over the free length is not now disputed although it is not always enforced. White [1973] states that in the United States often no protection is provided even for a temporary anchor with a working life up to three years. Generally, however this is not so, and a combination of grease and tape is common practice. FIP [1973] recommend a grout cover of at least 5mm.

(b) Temporary anchors in an aggressive environment. The fixed anchor zone can still be satisfactorily protected with a good quality grout cover. However, the minimum cover now becomes more important and Matt [1973] has recommended that a minimum value of 30mm should be guaranteed. Greater importance is also placed on the assurance that this grout is not cracked: if this possibility cannot be excluded some additional protection system should be included. Protection of the free anchor length is still only a single protective system in most cases, plastic sheathing or greased tapes being the usual solution although grout or other protective coatings are also possible. The risk of failure due to corrosion of the tendon is greatly reduced if components of diameter in excess of 7mm are used. A minimum grout cover of 5mm is again recommended by FIP at present.

(c) Permanent anchors. These should always have protective systems designed assuming an aggressive environment: environmental changes during the life of the anchor cannot be anticipated and the possibility that the anchor will be exposed to an aggressive environment cannot therefore be excluded. It is now widely held that permanent anchors should be provided with a double corrosion protection system. It is recommended that, as far as possible, the protection should be made and checked under workshop or equivalent conditions. The chosen protection system should not adversely affect the handling of the tendon or the behaviour of the bond.

Over the fixed length, there is always a considerable bond, but it is common to provide an additional coating. The coating may be a high strength epoxy or polyester resin but any suitable material which has a proven resistance to the existing aggressivity and does not adversely affect the bond may be used. Sometimes it is considered sufficient to pregurt the anchor zone and inspect it before homing the tendon. The cover recommended by FIP is 5-10mm minimum.

The free anchor length is similarly doubly-protected. Grease packed plastic sheaths fitted under factory conditions are becoming a popular method. Various other elastic substances can also be used within a plastic tube; for example, bituminastic compounds like buto rubber, or greased tapes used within the sheath. The annular space outside the plastic tube is normally cement grouted but in some cases bitumen enriched grout is used.

**Corrosion protection systems employed in practice**

Numerous systems of protection against corrosion have been used—and in some cases abandoned—for rock anchors. Fundamentally, a distinction is drawn between systems for pre-protection and post-protection. The former are employed prior to homing, whereas the latter are effected after tendon installation.

With respect to systems of pre-protection sheathing is currently the most common method. PVC sheathing, or water resistant or greased tape is now almost standard protection for rock anchors. Greased tape in particular is easy to handle and apply with a 50 per cent overlap, and although the risk of damage during tendon installation is high, it does form an extremely efficient barrier to chemical attack. The grease should be supple to allow subsequent tendon extension during stressing without causing large friction losses, or being destroyed, and should thoroughly penetrate the tendon. With reference to sheathing, PVC or polypropylene sheathing may now be delivered to site already on the individual steel wires or strands, or it can be introduced in a separate process on site (Littlejohn & Truman-Davies, 1974).

Other pre-protection systems, which are described in an excellent article by Portier [1974] include:

(a) coatings providing cathodic protection,
(b) cathodic protection by electric current,
(c) synthetic, semi-rigid films,
(d) rigid synthetic anchor plugs, and
(e) metal casings under compression or tension.

Systems of post-protection are also numerous and consist basically of filling in situ a sleeve over the free length, after tensioning. The substances used range from fluids, such as oils or water containing lime, to bitumens and cement, and the various materials have been described

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**Fig. 11. Cementation Long Life Anchor**  
(after Goldier Brauer, 1973)


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**Fig. 12. Temporary anchor construction of Type A**  
(after Ostermayer, 1974)

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**Fig. 13. Permanent anchor constructions;**  
(a) Type A with coated tendon;  
(b) Type A with ribbed plastic tube;  
(c) Type B with pressure pipe  
(after Ostermayer, 1974)
and classified in some detail by Bureau Securitas [1972] according to duration of protection and aggressivity of the surrounding medium.

An interesting illustration of the development of corrosion protection systems is provided by comparing the anchors used at Cheurnas, in 1934 with a modern counterpart, as shown in Fig. 10 in which the former, bitumen was thermally employed, and the wires were galvanised (except in the fixed length). A claim (Khava et al, 1969) that about 11 per cent of the total tendon cross area in these was still free from corrosion after 30 years has been discredited recently by Portier [1974].

A sophisticated modern type is the Cementation Long Life Anchor (Fig. 11) in which the tendon requires to ensure complete protection of the fixed tendon length, but contributes a "deadman" effect to the whole anchorage system. The free length of the tendon consists of stranded "near pruchbarkeit" with a plastic grout and covered by polypropylene sheathing.

Osterneyer [1974] discusses the classification of the sophisticated bar anchors most commonly used. German temporary, Type A (Fig. 12) is generally used with only one stage of protection (sheath on the free length and at least 20mm of grout over the fixed length). The necessity of head protection and recommends that at least one coat of paint be applied to the head and the tendon above the sheathing.

Anchors of Type A (fixed under tension, Figs. 13a, 13b, and 15) and Type B (fixed anchor under compression, Fig. 13c) are used in permanent works. Such anchors have double protection — against both mechanical damage and chemical corrosion. In Type C anchor protection can be applied and tested under factory controlled conditions without difficulty. The protection on the whole length is examined electrically and then covered with a sheath of plastic (or steel) to limit the reaction of the grout with the tendon. A leaking joint, a relatively elastic material can be used and paste or grease pressed into the annular space between sheath and tendon may be considered adequate.

Anchors of Type C protection which remains undamaged during construction and stressing is difficult. For the anchors shown in Fig. 13a a synthetic coating is desirable which not only has an excellent bond with the tendon, in addition, must also be flexible and strong enough to carry high bond stresses over a long period. When the coating is thick, the danger exists that the fixed anchor will be subjected to bursting stresses. A spiral reinforcement is therefore provided to resist these stresses.

For the Type A anchor in Fig. 13b, the tendon is inside a ribbed plastic sheath. The annular space is filled with cement. Although this cement will crack, as in all type A anchors, the criterion of corrosion protection is considered to be fulfilled when the cement in the annular space is less than 4mm thick. When a ribbed plastic sheath is used, the danger of material fatigue is less than in cases where a protective coating has been directly applied to the tendon. Effective means of double corrosion protection are also met at the anchor head.

It is generally concluded that whilst the protection of rock anchors is a serious problem, it does not represent a crucial one at present and responsible engineers are clearly corrosion conscious. Nevertheless there is a growing need to establish standards of corrosion protection which will be accepted and used widely by contracting and contractors.